Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies

Editors:

Jan F. Feenstra
Ian Burton
Joel B. Smith
Richard S.J. Tol

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vrije Universiteit *amsterdam*

Institute for Environmental Studies

Preface

The United Nations Environment Programme (UNEP) took the initiative for the development of this "Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies" as part of UNEP's participation in the development of guidelines and handbooks for Climate Change Country Studies. The project is also part of the World Climate Impact Assessment and Response Strategies Programme (WCIRP) and as such contributes to the International Climate Agenda.

Climate Change Country Studies can be divided into four related activities:

1. Greenhouse Gas Emission Inventories;
2. Mitigation Studies (Greenhouse Gas Emission Reduction Studies);
3. Impact Assessment and Adaptation Studies; and
4. National Communications.

Guidelines for national Greenhouse Gas Emission Inventories have been developed by IPCC/OECD/IEA with assistance from UNEP/GEF. These Guidelines have been adopted by the first Conference of Parties (CoP) to the United Nations Framework Convention on Climate Change (UNFCCC).

Guidelines for Mitigation Studies are being developed by UNEP Collaborating Centre on Energy and Environment, Risø, Denmark, in co-operation with several developing countries and countries with economies in transition in a series of UNEP/GEF funded country studies.

Guidelines for National Communications have been developed by the UNFCCC.

It is emphasised that in no way should the development of this Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies suggest that adaptation to climate change is considered to be of greater importance than mitigation. Only mitigation can prevent climate change and its consequences. However, since we are already committed to some climate change and since it is unlikely that the reduction of greenhouse gas emissions will be sufficient to prevent climate change, it is better to be prepared than to leave it for future generations to live with.

The project for development of this version of the handbook was funded, through UNEP, by the Governments of Denmark and The Netherlands. The project was co-

ordinated by the Institute for Environmental Studies, Vrije Universiteit, Amsterdam. All communications between the editors and the lead authors were carried out by the convening editor Ian Burton, who took also the lead in the generic chapters introduction and getting started written by the editors.

The last version of this handbook (version 1.3; October 1996) was used by several country study teams in developing countries conducting impact and adaptation assessments. The handbook was tested specifically by the country study teams of Antigua and Bardua, Cameroon, Estonia and Pakistan in the UNEP/GEF project "Country Case Studies on Climate Change Impacts and Adaptations Assessments". Their comments, recommendations, and suggestions for improvement have been incorporated in this version. Apart from this, internationally recognised experts (see acknowledgements) reviewed, on request of the editors, the sectoral chapters. These reviews were compiled by the convening editor and sent to the lead authors for consideration. The editors are convinced that the above input, together with a new organisation, especially in the generic issue chapters, has improved this version of the handbook substantially.

This Handbook on Climate Change Impact Assessment and Adaptation Strategies is made available by UNEP to the Parties to the UNFCCC.

Although significant effort has been put into making this handbook more useful and better applicable for developing countries and countries with economies in transition than the last version, it is likely that it can be improved further. The country study teams (and other readers) that will use this handbook are therefore encouraged to comment candidly on the format and content and if possible give recommendations for improvement. **The users and readers of this handbook are invited to send their comments to either Jan F. Feenstra at the Institute for Environmental Studies, Amsterdam, or Alex Alusa at UNEP Headquarters, Nairobi.**

Jan F. Feenstra
Institute for Environmental Studies (IVM)
Vrije Universiteit
De Boelelaan 1115
1081 HV Amsterdam
The Netherlands
Tel. +31-20-444 9550
Fax +31-20-444 9553
E-mail: Jan.Feenstra@ivm.vu.nl

Alex Alusa
UNEP Headquarters
Atmosphere Unit
P.O. Box 30552
Nairobi
Kenya
Tel. +254-2-623 4551
Fax +254-2-623 410
E-mail: Alex.Alusa@UNEP.Org

List of lead authors

John M. Balbus	Department of Environmental & Occupational Medicine, George Washington University, 2300 K. St., NW #20120037 Washington DC, USA. Phone: +1 202 994 2614, e-mail: eohjmb@mail.gwumc.edu
Barry Baker	Ecosystems Research International, 305 W. Magnolia Street 262 Fort Collins - CO 80521-2801, USA. Phone: +1 970 493 4004, e-mail: barry@heavy.gpsr.colostate.edu
Michael Brody	US Environmental Protection Agency, Office of Planning, Analysis and Accountability (2710), 401 M St. SW Washington DC 20460, USA. Phone: +1 202 260 7558, e-mail: brody.michael@epamail.epa.gov
Ian Burton	Atmospheric Environment Science, Environment Canada, 4905 Dufferin Street, Downsview, Ontario M3H 5T4, Canada. Phone: +1 416 739 4314, e-mail: ian.burton@ec.gc.ca
Stewart J. Cohen	Environmental Adaptation Research Group (EARG), Environment Canada, located at Sustainable Development Research Institute, University of British Columbia, B5-2202 Main Mall, Vancouver, BC, Canada V6T 1Z4. Phone: +1 604-822-1635, e-mail: scohen@sdri.ubc.ca. Homepage: http://www.tor.ec.gc.ca/earg
Jan F. Feenstra	Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands. Phone: +31 20 444 9550, e-mail: jan.feenstra@ivm.vu.nl
Ihor Hlohowskyj	Environmental Assessment Division, Argonne National Laboratory, 9700 S. Cass Ave, Argonne, Illinois 60439, USA. Phone: +1 630 252 3478, email: ihor@anl.gov

Mike Hulme	Climate Research Unit, University of East Anglia, Norwich NR4 7TJ, UK. Phone: +44 1603 593162, e-mail: m.hulme@uea.ac.uk
Ana Iglesias	Intesca, Uniersidad Politecnica de Madrid, 28040 Madrid, Spain. Phone: +34 91 336 5832, e-mail: iglesias@ppr.etsia.upm.es
Richard J.T. Klein	Potsdam Institute for Climate Impacts Research, Telegrafenberg C4, P.O. Box 601203, D-14412 Potsdam, Germany, Phone: +49 331 2882500, e-mail: klein@pik-potsdam.de
Stephanie Lenhart	Stratus Consulting Inc., P.O. Box 4095, Boulder CO 80306-4059, USA. Phone: +1 303 381 8000, e-mail: slenhart@stratusconsulting.com
Sune Linder	Swedish University of Agricultural Sciences, Department of Ecology and Environmental Research, P.O. Box 7042, S-750 07 Uppsala, Sweden. Phone: +47 18 672440, e-mail: sune.linder@emc.slu.se
Jay R. Malcolm	Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada M5S 3B3. Phone: +1 416 978 5480, e-mail: malcolm@larva.forestry.utoronto.ca
Robert J. Nicholls	Flood Hazard Research Centre, School of Social Science, Middlesex University, Queensway, Enfield EN3 4SF, U.K. Phone: +44 181 3625569, e-mail: robert14@mdx.ac.uk
Martin L. Parry	Jackson Environment Institute, University College London, 5 Gower Street, London WC1E 6HA, U.K. Phone: +44 171 813 5206, e-mail: parryml@aol.com
Cynthia Rosenzweig	NASA/GISS, 2880 Broadway, New York, NY 10025, USA. Phone: +1 212 678 5591, e-mail: crosenzweig@giss.nasa.gov
Robert J. Scholes	Division of Water, Environment and Forest Technology CSIR, P.O. Box 395, Pretoria 0001, South Africa. Phone: +27 12 841 2045, e-mail: BScholes@csir.co.za
Joel B. Smith	Stratus Consulting Inc., P.O. Box 4095, Boulder CO 80306-4059, USA. Phone: +1 303 381 8000 x218, e-mail: jsmith@stratusconsulting.com

Frank Stern	Hagler Bailly Consulting, Inc., P.O. Drawer O, Boulder, CO 80306-1906, USA. Phone: +1 303 449 5515, e-mail: fstern@habaco.com
Kenneth M. Strzepek	University of Colorado, Civil, Environmental and Architectural Engineering, University of Colorado , ECOT-5-28, Campus Box 428, Boulder, CO 80309-0428, USA. Phone: +1 303 492 7111, e-mail: strzepek@spot.colorado.edu
Richard S.J. Tol	Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands. Phone: +31 20 444 9503, e-mail: richard.tol@ivm.vu.nl

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Jan F. Feenstra
Ian Burton
Joel B. Smith
Richard S.J. Tol

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Acronyms and abbreviations

ADM	Adaptation Decision Matrix
AEEI	Autonomous Energy Efficiency Improvement
AIM	Asian-Pacific Integrated Model
ALS	Airborne laser scanning
ANPP	Aboveground net primary production
AVV	Aerial videotape-assisted vulnerability analysis
ASE	Adaptation Strategy Evaluator
BLS	Basic Linked System
CCC	Canadian Climate Centre
CGE	Global computable general equilibrium model
CIKARD	Center for Indigenous Knowledge for Agriculture and Rural Development
COSMIC	Country Specific Model for Intertemporal Climate
COSMO	Coastal Zone Simulation Model
DO	Dissolved oxygen
DSS	Decision support system
EASM	Egyptian Agricultural Sector Model
ENSO	El Nino/Southern Oscillation
EPIC	Erosion Productivity Impact Calculator
ETS	Effective temperature sum
FAO	Food and Agricultural Organization
GCM	General circulation model
GCOS	Global Climate Observing System
GDP	Gross domestic product
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographic information system
GISS	Godard Institute for Space Science
GNP	Gross national product
GOOS	Global Oceans Observing System
GTOS	Global Terrestrial Observing System

HSI	Habitat Suitability Index
IA	Integrated assessment
IAM	Integrated assessment model
ICASA/IBSNAT	International Consortium for Application of Systems Approaches to Agriculture - International Benchmark Sites Network for Agrotechnology Transfer
ICZM	Integrated coastal zone management
IEA	International Energy Agency
IGBP	International Geosphere-Biosphere Programme
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LOICZ	Land-Ocean Interactions in the Coastal Zone
MARA/ARMA	Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique
MBIS	Mackenzie Basin Impact Study
MEI	Morphoedaphic index
MIASMA	Modelling framework for the health Impact Assessment of Man-induced Atmospheric changes
MINK	Missouri, Iowa, Nebraska, Kansas
MPI	Max Plank Institute
NEB	Northeast Brazil
NCAR	National Center for Atmospheric Research
OECD	Organisation for Economic Co-operation and Development
RCM	Regional climate model
RFF	Resources for the Future
SADC	Southern African Development Community
SCM	Simple climate model
SRF	Systematic Reconnaissance Flight
SST	Sea surface temperature
TEAM	Tool for Environmental Assessment and Management
UD	Upwelling-diffusion
UKMO	United Kingdom Meteorological Office
UNFCCC	United Nations Framework Convention on Climate Change
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USCSP	US Country Studies Program
USEPA	US Environmental Protection Agency
WHO	World Health Organization
WMO	World Meteorological Organization
WRI	World Resources Institute

Introduction

Authors
Ian Burton [1]
Jan F. Feenstra [2]
Joel B. Smith [3]
Richard S.J. Tol [2]

The uses of this handbook

In many countries, governments are seeking advice from a wide range of disciplines on the potential impacts of climate change on the environment and their society and economy. This handbook is designed to help those conducting research supporting such advice. Underlying the research are two fundamental questions: "What does climate change mean to us?" and "What might be done about it?" This handbook is designed to provide newcomers to the field of climate impact and adaptation assessment with a guide to available research methods, particularly for answering the first question. The handbook will also serve as a ready reference for many others currently engaged in impacts and adaptation research.

The situations in which climate impact assessment are required can be quite varied. A common situation is that studies are needed at the national or country level, among others as inputs for the National Communications as required by the United Nations Framework Convention on Climate Change (UNFCCC). So-called "Country Studies"

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[1] Atmospheric Environment Science, Environment Canada, Downsview, Ontario, Canada.

[2] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands.

[3] Stratus Consulting Inc., Boulder CO, USA.

have been supported through the UN Environment Programme, the governments of the Netherlands, the United States, and others. Typically in these studies some key sectors of the economy are selected for special attention. In other instances specifically vulnerable regions are selected for study. Impact studies are not necessarily con-fined within the boundaries of one country. International river basins have been the subject of climate impact studies and so have ecological regions such as deserts, grasslands, mountains, and small islands.

This handbook is essentially as an introduction to a wide range of methods that can be used to design assessment studies of climate change impacts and related adaptation strategies. It does not serve as a "stand-alone", step-by-step, or "how to do it" document. It is not prescriptive nor does it describe only a single method by sector. The intent of providing an overview of methods is to give readers enough information to select the method most appropriate to their situation. However, not enough information is given to apply a method. To carry out an impact assessment, reference must be made to more detailed literature, software and data may need to be obtained from elsewhere, and in many instances individual or small group training and consultation sessions will be required.

The designs are likely in most cases to include detailed workplans that specify methods to be used; the time, financial resources, and skills that will be allocated and brought to bear; and the related operational and logistic support. To develop research designs and workplans the users need to understand enough about the methods to make reasoned choices appropriate to their circumstances, including the target audience or clients. This clearly requires an appreciation of the various methods, including the amount of detail, the accuracy, and the reliability of their output. An important consideration is the assumptions that it is necessary to make in order to carry out any particular impact study. Users also need to be able to judge the requirements that must be met in order to make effective use of the methods.

What is climate change impact assessment?

Climate change impact assessment refers to research and investigations designed to find out what effect future changes in climate could have on human activities and the natural world. Climate change impact assessment is also frequently coupled with the identification and assessment of possible adaptive responses to a changing climate. To the extent that adaptation can reduce impacts, the assessment of adaptation measures is part of impact studies. Thus impacts may be described as "gross" or unmodified impacts, and as "net" impacts after adaptation has been taken into account. Climate change impact studies are necessarily conjectural. That is to say, impacts cannot usually be experimentally confirmed or verified. Clearly it is not possible to conduct a controlled experiment by changing the global atmosphere to test the effects of changes on human and natural systems.

In the absence of controlled experiments, other ways have to be developed to try to find out what the impacts of climate change may be. There are five approaches which have been applied as investigative techniques to try to cast more light on the potential impacts of future climate change:

1. Palaeological, archaeological, or historical studies of how climate changes and climate variations in the past have affected human and/or natural systems.

2. Studies of short term climatic events which are analogous to the kind of events that may be expected to occur with human induced climate change, such a droughts, and floods. This approach (the use of climate analogies) has been developed into a formal method called “forecasting by analogy”.

3. Studies of the impact of present day climate and climate variability.

4. The creation of models , often quantitative of the relationship between climatic variables and selected impacts sectors to try to answer the “what if” kinds of question.

5. Expert judgement, which refers to a variety of methods whereby especially well informed and experienced specialists are brought together to develop a consensus view.

Models are the method used most frequently in impacts assessments, and it is to the description and evaluation of such models that this handbook is primarily devoted. Inevitably these studies are predicated upon a number of assumptions many of which are themselves likely to be proved wrong with the passage of time . Forecasting, or telling the future, by whatever method used, is notoriously unreliable. The first three approaches listed (historical climate impacts, analogue impacts, and contemporary climate impacts) are therefore important as inputs to the assumptions made in models, and serve as the best ‘reality check” available. The fundamental problem that all of these methods face is that all approaches are based on observations and experience with climate change and climate variability. Climate change may introduce new conditions that have not been seen and that are not understood. While the results of these assessments may be the best information we have on potential impacts of climate change, they should not be interpreted as reliable forecasts of the future.

Why do we need climate impact assessments?

Over the past three decades, since 1970 or even earlier, the scientific evidence for human induced climate change has become steadily stronger. By 1995 the international scientific community of atmospheric and related scientists, organised in the Intergovernmental Panel on Climate Change (IPCC), was able to conclude in a cautiously worded statement that “the balance of evidence suggests that there is a discernible human influence on the climate” (IPCC, 1996). With all the appropriate qualifiers and

scientific caveats, this means that human induced climate change has been detected. Climate change is a present reality.

This leads to two further questions:

1. How important or serious are the impacts of human induced climate change likely to be?

2. What can and should be done to prevent and modify these impacts, and when and how should it be done?

The answer to the second question has been construed in the UNFCCC as falling into two main dimensions, mitigation (or sometimes limitation) and adaptation. Methods for the study of greenhouse gas emissions and their mitigation have been fully described elsewhere. This handbook focuses upon the second category of response, adaptation.

Information about climate impacts is needed both to help decide upon both the urgency and the desirability of mitigative and adaptive measures, actions, and policies, and their appropriate combinations. Since climate change is a global problem, decisions with respect to both mitigation and adaptation involve actions or choices at all levels of decision-making, from the most local and community level (including families and individuals) to the broadest international levels, involving all national governments and many transnational bodies as well. The intended target audience or client for impact studies therefore is also very wide ranging, and this will affect the design if the study in many ways.

The guidance literature

There are three important references in the guidance literature that research teams may wish to consult at the design stage of a study. The antecedents of the present volume were designed for different purposes but the authors of this handbook have, where appropriate, drawn on this earlier work.

The first in time was the SCOPE report (Kates et al., 1985) This edited volume of papers describes climate impacts in a number of sectors and is especially strong in its consideration of socio-economic impacts and responses. The second is the IPCC Technical Guidelines for Assessing Climate Change Impact and Adaptations (Carter et al., 1994).This document lays out a general approach to impacts and adaptation assessment, and in particular proposed seven steps that can be followed in a study design. These are also described in Parry and Carter (1998).

The third is the guidebook prepared for the US Country Studies Program, which follows the IPCC approach and presents a detailed, step-by-step guide to a few model-based methods per sector for country-level assessments (Benioff et al., 1996). To strengthen comparability of studies, a limited set of models is presented (usually one per

sector). By comparison this handbook is designed to address a wider range of needs, and is addressed to a wider range of potential users.

Handbook organisation

Clearly impact and adaptation studies can be designed for such a variety of circumstances, addressed to such a variety of clients, and focused on anything from a very specific impact on one small part of the socio-economic or natural system to a broad, multi-sectoral, integrated study at a national or regional level, that it is practically impossible to specify a design that can serve all purposes. This handbook is organised in two parts: Part I treats generic and cross-cutting issues, and Part II presents methods for studying impact and adaptation in the selected sectors of water, coastal resources, agriculture, rangelands, health, energy, forests, biodiversity, and fisheries.

Part I includes a "getting started" chapter, which deals with issues, methods, and consideration common to all impact and adaptation studies. The next two chapters discuss how to design and where to obtain scenarios. Chapter 2 treats scenarios of climate change, and Chapter 3 treats scenarios of the socio-economic context in which climate change impacts and adaptation may occur. Chapter 4 describes the need for integration across sector studies and interaction with stakeholders, and suggests ways of establishing such integration and interaction. Chapter 5 treat adaptation to climate change, the sort of options that exist and how to evaluate them.

In order to maintain some comparability among the chapters in Part II, dealing with methods in specific sectors, the authors were asked to follow a common format insofar as their subject matter permits. Therefore each of the chapters begins with a brief introduction that defines and describes the scope of the problem. The likely or known climate change impacts in the sectors are briefly described. Against this background an array of the various methods is presented. The purpose of this presentation of a selected number of methods is to illustrate the range of different levels of complexity in the methods. Some of the less demanding methods, in terms of data, modelling requirements, and the like, are presented alongside the more complex and demanding methods. The aim is always to be user friendly, and to provide enough information to permit users to make a more informed choice in the design of impact studies, as well as to begin identification and preliminary assessment of adaptation.

References

Benioff, R., S. Guill, and J. Lee (eds). 1996. *Vulnerability and Adaptation Assessments: An International Guidebook.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Department of Geography, University College, London.

Kates, R.W., J. Ausubel, and M. Berberian (eds). 1985. Climate Impact Assessment. Studies of the Interaction of Climate and Society. Scientific Committee on Problems of the Environment. SCOPE Report No. 27. John Wiley and Sons, Chichester, United Kingdom.

IPCC. 1996. *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds). Cambridge University Press, Cambridge, United Kingdom and New York, 880 pp.

Parry, M. and T. Carter. 1998. *Climate Impact and Adaptation Assessment: A Guide to the IPCC Approach.* Earthscan Publications, London.

1 Getting Started

Authors
Ian Burton [1]
Jan F. Feenstra [2]
Joel B. Smith [3]
Richard S.J. Tol [2]

At the beginning of an assessment of climate change impacts and adaptation strategies, a number of important questions should be addressed. It is the purpose of this chapter to identify these questions, and to suggest some of the factors that may enter into their resolution. It is not the intent of this chapter or of the handbook to prescribe answers. The proper design of an assessment can be achieved only by those who will carry it out in consultation with the potential users or clients.

Too often decisions are made quickly in the interests of "getting started" which later come to be regretted. This is because the design decisions entail commitments to inclusions and exclusions which are difficult, costly, and often impossible to change at a later date. For that reason it is often better to take a little extra time, and exercise a little patience, at the outset to make sure that the choices have been made as wisely and with as much understanding and forethought as practicable.

This chapter provides a list of questions that should be widely discussed at the outset, and to which satisfactory answers should be agreed by all the main parties, including

[1] Atmospheric Environment Science, Environment Canada, Downsview, Ontario Canada.

[2] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands.

[3] Stratus Consulting Inc., Boulder CO, USA.

the sponsors (those providing the funds), the researchers (those carrying out the research and those directing it), and the affected community (those who may be affected by climate change or response to it and thus have a stake in the analysis).

It is unlikely that the questions can be fully resolved at the outset of the assessment. It may be a good idea, therefore, to provide for a periodic reassessment of these questions, to ensure that the objectives agreed at the outset are still being met.

How is the problem to be defined?

At the outset it is important to have a good sense of the definition of the problem to be studied. Each of the sectoral chapters which follow (Chapters 6 to14) begins with a general statement of the problem. While this will not be sufficiently specified in site-specific terms, it is intended to point in the general direction suggested by current knowledge and research results. Study designers and users of this handbook will want to develop more specific problem statements for themselves.

Many of the succeeding questions may be viewed as part of the problem definition. Thus problem definition may be treated in a holistic manner, where a brief problem statement can serve as a focus and criterion against which to judge the relevance of specific ideas. Problem definition may also be broken into some component parts as suggested in the following questions.

What are the goals of the assessment?

Often the goals of the assessment are specified by the client (sponsor) or are strongly set or implied by the circumstances of the assessment. It is important to clarify the objectives at the outset, since they determine to a large extent the problem definition, scope, and boundaries of the assessment.

Many climate impact assessments have been designed to serve the policy interests of national governments. Other levels of jurisdiction, from local to regional, may also be interested in the results. Often there are multiple objectives, where, for example, a national government may wish to have impact research results to inform its own policy, and at the same time contribute to an international assessment (for example, meeting a government’s obligations under Article 3 of the UNFCCC to reduce vulnerability to climate change).

What time? What space?

The decision with respect to the spatial extent of the assessment and the length of time into the future that will be considered clearly depends on the factors previously discussed.

One crucial question is the sort of climate changes to be considered. This topic is covered in detail in Chapter 2, Climate Change Scenarios. It is common practice to think of climate change as long-term changes in means, for example, that mean global temperature may rise globally by 1.0 to 3.5 C by 2100 and precipitation may vary by plus or minus 10 to 20 percent (IPCC, 1996), and by equivalent regional changes in means, where these can be derived from GCMs.

What are the assessment boundaries?

At first it may appear relatively straightforward to place boundaries around a climate impact assessment. For example, “We are going to assessment the impact of sea level rise on mangrove forests”, or “We are going to study the impact of climate change on agriculture”. The question of boundaries will come up in at least two related ways: geographic boundaries and study depth.

Geographic boundaries

The matter of geographic boundaries of the assessment is important. Countries are often faced with the choice of studying the entire country or a region such as province, river basin, or ecological zone. For small countries, this issue is not typically relevant as the whole country can readily be studied. For large or even medium-sized countries, this issue can be challenging. Focusing on a region or a river basin allows for more in-depth analysis. In these cases the compatibility and integration issues will be very important. For instance, it is of limited use to study irrigated agriculture in one region while water availability is studied in another region. Studying the entire country gives results that appeal to a broader audience and allow national policy issues to be more readily addressed, but it may be harder to fully integrate large geographic scale studies. Typically the trade-off is between depth and breadth.

The depth of the assessment

A difficulty that is quickly encountered is that the impacts in most sectors are connected to other impacts in other sectors, and themselves have secondary tertiary and N order effects. Where is the analysis to stop? For example, damage to mangrove forests may affect breeding of fish species, which in turn affects fish populations, which affect coastal fishing communities, which affect local and perhaps regional nutrition, which affects human health and raises demands for alternative food supplies from agriculture, which is itself under climatic stress, and so forth. To assess the importance of climate as a factor in the decline of fish populations, and the importance of fish in nutrition, it is important to know what other factors may be affecting the fish population (such as overfishing), and how costly fish is compared with alternative protein supplies.

Such ramifications of climate impacts can spread throughout an ecosystem, throughout a socio-economic system, and from a local impact to regional and wider geographical

areas. It is tempting to think that such expanding ripple effects get progressively weaker proceeding away from the initial focus in time and in space. This is not necessarily the case. It depends in part of the condition of the systems or targets impacted. Where these are vulnerable, or their adaptive capacity is reduced for other reasons, the impacts may actually become more severe with distance.

Any assessment team should therefore engage in a discussion during the "getting started" phase of the boundaries of the assessment, and how these are to be determined and then followed.

What sectors and areas are to be included in the assessment?

The choice of the scope of the assessment is crucial. Clearly this is dependent upon the objectives, but it is commonly found that the researchers themselves have ideas about the most appropriate sectors to include. The focus of an assessment can be as small as a single cultivar (the impact of climate change on wet rice production), or extend to a whole agricultural system, or to all the socio-economic and natural systems in a specific country or region. Sometimes another spatial unit of analysis may be selected, such as an island, (Antigua and Barbuda), a river basin, (the Indus), an ecosystem (savannah), or other features such as lakes, mountains, and so forth.

The choice of the content of the assessment is often constrained by the availability of financial and other resources. It is in the nature of the climate impacts problem for a wider scope to be preferred, especially at this stage of development of the field where there are so many unknowns. Both the science and the policy requirements tend to lead to studies designed to gain a broad overview, rather than to providing precise answers to narrow and hypothetical questions.

In those many cases where all related sectors cannot be studied, the researchers should point out potentially important interactions in their report.

How can we ensure comparability?

It is always tempting for researchers to follow their own inclinations and hunches, and to allow the nature of the problem as they see it to determine the choice of methods, and the ways in which they are applied. Often such curiosity-driven research can be highly productive and innovative. In research that is aimed at providing understanding which will serve a policy process, this often conflicts with the need for the research results from one subject area to be comparable with those in other areas. This requirement is important if the results of individual component studies are to add up to something more than the sum of their separate parts. This tension applies both within studies and between studies. For example, in a country assessment of the impacts of climate change, the results will not be comparable or compatible if the various sector

components (e.g., water, agriculture, health, biodiversity) use different scenarios of climate change or different assumptions about the future state of the economy. Consistency is essential in these matter. The same applies outside the assessment, for example, if the results of an impact assessment in one region are to be comparable with those in another region, or an adjacent country, which may share the same river basin.

How can the project be sufficiently integrated?

The domain of climate impact studies is so broad that the tendency for individual component studies to be conducted in relative isolation is very strong and hard to resist. The question of integration is not the same as the question of comparability. Integration refers to a much closer examination of the ways in which sectors and regions interact. The complex issue of integration is discussed in Chapter 4. Assessment teams are invited to read Chapter 4 at the outset and to try among themselves to resolve the question of how much integration is to be attempted and in what way.

How should adaptation be addressed?

The magnitude of climate change impacts estimated from a assessment is often very sensitive to the assumptions made about adaptation. It is difficult to predict exactly how people will respond to climate change. Will they continue their behaviour from the past because they do not understand climate change and its implications or will they know exactly what to do to efficiently adapt? Studies have made very different assumptions about adaptation, and thus have yielded very different estimates of impacts. It is therefore important to consider adaptation at the design phase of the assessment and to decide how it is to be brought into the impacts research at an early stage. Where a assessment is being organised by sectors, it can be helpful to select one person from each of the sectoral groups to serve as members of a cross-cutting group specifically devoted to the adaptation questions. These and related issues are addressed in Chapter 5.

Should we carry out a pilot project?

The questions raised above are all issues of assessment design. They are crucial. Decisions made at the beginning of the analysis can determine the shape and content of the research, arbitrary or hasty decisions may be regretted later. Where studies are to be conducted in a national or broad regional context, it may therefore be useful to carry out a preliminary assessment to help guide the choice.

Instead of simply bringing the members of a assessment team together to try to resolve the “getting started” questions, it may be helpful to carry out a preliminary pilot exercise. A quick and inexpensive way to do this is to draw together a wider group of experts (not restricted to the assessment team) from the different sectors and regions, together with specialists in climatology, social and economic studies, insurance, disaster

research, and so forth. By pooling their knowledge and experience, it may be possible to arrive at a consensus view or a collective expert judgement of priority sectors or regions and results. Given the natural tendency for experts to stress the importance of their own subjects of research or expertise, it is also helpful to include some persons in such an exercise who have a broad perspective and are not associated with any particular sector or region, and who have a less direct stake in any outcome of the preliminary assessment.

What plans should be made for the communication and use of results?

During a preliminary assessment there may also be an opportunity to take into consideration the wider context of the assessment. Questions that assessment designers may wish to address include the following:

- What outputs will be most useful to policy makers? How will the results of the assessment be made available to the policy and decision-making process? How will the results of the assessment be communicated to a wider audience and the general public, as well as those most at risk?

- How will the assessment be related to national economic and social development strategy and plans?

What types of method and tools should be used?

There is a range of different approaches or methods that can be used in the assessment of climate change impacts. These include quantitative and predictive models, empirical studies, expert judgement, and experimentation. Each of these approaches has it own advantages and weaknesses, and a good strategy may be to use a combination of approaches in different parts of the assessment or at different stages of the analysis. In addition to formal modelling approaches, consideration should also be given to methods of stakeholder involvement, and the use of expert judgement. In some cases empirical studies of current climate impacts may be useful. There are also other tools that may be used, such as geographic information systems (GIS) and remote sensing. Each of these is briefly described below. Consideration should be given to using these approaches in appropriate combinations.

The sectoral chapters of the handbook (Chapters 6 -14) present details of a range of these methods and approaches. The purpose of this discussion is to provide a guide to the sectoral chapters, so that users will be forewarned and forearmed in what to look for. The treatment of the different methodological approaches is not uniform or standard across the chapters, however, because the sectors are quite different in their susceptibility to different kinds of analysis, and in some sectors (e.g., agriculture and water) modelling approaches are much more highly developed that in others (e.g.,

human health and energy). In such sectors other approaches are more commonly in use and seem better suited to the kind of data and the kinds of problem to be addressed.

For a more detailed discussion of the types of assessment methods, see the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994).

Quantitative models

Where feasible, it is desirable to use models where the variables can be expressed in quantitative terms, so that a variety of tests can be carried out (e.g. sensitivity tests), and so that results can be expressed in more precise terms. However, one has to keep in mind that the results generated by these models may look very precise, but should be handled with caution since the underlying assumptions – not only climate and socio-economic scenarios but also assumptions about processes – can be rather weak or incorrect.

Assessment designers can use the following sectoral chapters in this handbook to provide a quick picture of the available models. In many cases it will be preferable to adopt an existing model and modify it as necessary to meet specific assessment needs. A crucial test in the choice of modelling approach and specific model is data needs. Often the data needs are high and difficult to meet, and this may lead to simplification of the model or even in some cases the development of a new model or models.

The choice of model is best conducted by experienced modellers, since detailed foreknowledge of the problems likely to be encountered is especially valuable. Where experience with climate impacts modelling itself is not available, experience with other types of modelling can be of great help.

This discussion deals with impact models. These are to be distinguished from climate scenarios, and socio-economic baseline models or scenarios. They are also to be distinguished from the decision-making and choice models discussed in Chapter 5, Adaptation.

There are broadly three kinds of quantitative models that can be used in climate impacts studies: biophysical models, socio-economic models, and integrated system models. The ideal that is being sought is a model or models which deal with climate and socio-economic and natural systems in an interactive way. Many of the available models, however, are simple cause and effect models, in which one or more climatic variables are changed and the consequences predicted and measured. In reality we are dealing with an interactive system in which one set of cause and effect relationships leads to another. The integrated systems models represent an on-going effort to deal with this complexity.

It should be noted that models do not do everything. Models that address only one sector or aspect of a system may simulate that sector or aspect well. But they may not

include interactions from important related sectors or other aspects of the system. Models that integrate across sectors or systems may capture interactions and be useful for assessing broader scale effects. But their simulations of specific sectors or aspects of systems may be less reliable than the sector or aspect-specific models. Thus, the choice of a model should depend in part on what questions are being asked, that is, whether they are broad or narrow questions. Users of this handbook should recognise the weakness of any model they choose before using the model and interpreting the results.

Biophysical models

Biophysical models are used to analyse the physical interactions between climate and an exposure unit. Details of specific models together with their merits and shortcomings are provided in the sectoral chapters.

There are basically two types of biophysical models, empirical statistical models and process based models. Empirical statistical models are based on the quantitative relationship between climate and the particular sector or system under current climate. The models can be quite useful for simulating effects of climate within the existing range of observed climate and assuming other critical factors do not change. When these models are used to simulate climate change, it is implicitly assumed that the statistical relationship between climate and the sector does not change. Thus a linear relationship based on observations is assumed to continue to be linear outside the observations.

In contrast, process based models are based on physical laws, first principles about the workings of a system, or assumedly universal regularities. In principle, these can be applied outside of the geographic area or climate zone in which they were developed. In reality, there is much uncertainty about the exact biophysical processes under climate change, especially when other factors are included. For example, we are uncertain how the CO2 fertilisation effect will work in field or natural conditions, especially if there is severe drought from climate change (for more discussion see Carter et al., 1994).

Economic models

Most of the impact models of the kinds introduced above are concerned with the prediction of first-order impacts of climate change on such variables as crop yield, run-off, or the range of insect and disease vectors. To estimate second-order effects and beyond, such as those on production of cereals, on water supply, or on industrial output, can require, among other things, the use of economic models. A more detailed discussion of economic models can be found in Carter et al. (1994). The chapters in this Handbook do not give full consideration of economic models, although such they are a necessary addition to first order impact studies if the socio-economic assessment of climate impacts is to be complete.

It is important to distinguish three types of models, which depend on the scale of analysis. At the finest scale, economic models describe the behaviour of a single actor, such as a farmer or a firm. They can be used to estimate how an individual actor may respond to climate change. For example, a farm level model can be used to determine whether a farmer might add irrigation, switch crops, or abandon farming in response to yield changes. Actor (or micro-) level models do not simulate changes in consumer demand or in prices; so a key factor for the individual actor, prices, is assumed to be unchanged.

Sector (or meso-level) models simulate behaviour in a sector of the economy. Economic models of agriculture may simulate the agricultural economy of a country or the world. Such models can simulate changes of behaviour in all actors in a sector, including consumers. Agriculture models can estimate changes in production and trade patterns. These models do not simulate interactions between the sector and the rest of the economy.

Economy wide (or macro-level) models simulate economic activity across all sectors of the economy. They can estimate changes in total production, employment, and other macro-economic variables. Like biophysical models, economic models can be divided among empirical statistical models and process based models. Empirical statistical economic models are based on observed empirical relationships between economic variables. As with biophysical models, these types of economic models may have limitations with regard to estimating conditions outside of the observed data or when there is a significant change in basic economic conditions. In contrast, general equilibrium models are based on laws of economics and can be thought of as process based models. They may be more appropriate for simulating economic activity when there is a basic change in economic conditions. The empirical statistical models tend to be static whereas the process based models can be dynamic. Economy wide models tend to have less detail about individual sectors than do sector-based models.

Integrated systems models

Most of the methods and models described in this handbook are designed for specific sectors. Assessments based upon single sector studies, or even single sector studies added together, fail to address the interactive complexity of climate impact phenomena, for instance, through competitive land and water use. For this reason, research attention is being devoted to the development of integrated systems models. The design of integrated studies and integrated models is discussed in Chapter 4. Although interactions between sectors can be crucially important, building an integrated systems models is typically beyond the means of a climate change impact and adaptation assessment. Instead, adjusting sector studies for first-order interaction is often feasible and a reasonable approximation to full interactions.

Empirical studies

Empirical observations of the interactions of climate and society and natural systems can be of value in anticipating future impacts. This is commonly achieved through analogue methods, in which variations over space or past time can substitute for future changes. Three kinds of analogue can be identified: historical events, historical trends, and regional or spatial analogues of present climate.

A particular advantage of empirical studies emerges as they are extended into the area of adaptation because it becomes possible to ask decision makers, stakeholders, and those impacted directly about how they adapt or have adapted in the past. It is also possible to confirm their responses through direct observations.

Empirical studies can be combined effectively with quantitative model scenarios. Such a combination of approaches permits modelling work to be solidly grounded in experience, and permits the extension of empirical studies into the future.

Expert and stakeholder judgement and participation

A useful method of obtaining a rapid assessment of the state of knowledge concerning the likely impacts of climate change is to solicit the judgements and considered opinions of experts in this and related fields. The use of expert judgement may be especially appropriate in preliminary or pilot studies, as discussed above. Expert judgement may therefore be used in anticipation of other types of approach, and be an aid in the design of such studies.

There are many ways of organising inputs to studies by expert judgement. Often this is done informally in committees and small group discussions. While the most highly regarded experts may be drawn upon in this way, such approaches tend to lack transparency, and there is always the possibility that a different group of experts would have arrived at different conclusions. The use of expert judgement can also be formalised into a quantitative assessment method, by classifying and then aggregating the responses of different experts to a range of questions.

More recently, decision support systems that combine dynamic simulation with expert judgement have emerged as promising tools for policy analysis. Here subjective probability analysis is required where simulation empirical models are lacking.

Remote Sensing and GIS.

Remote sensing from aircraft and satellites is the science and art of collecting data about objects located at the earth’s surface by using sensors mounted on observation aircraft and satellites and of interpreting the data to provide useful information. The main civil application areas of remote sensing are cartography, agriculture, food security, forestry, environment, geology, water resources, marine resources, atmospheric quality, and regional planning.

Remote sensing can very effectively be used in combination with GIS, which is a computer system capable of holding digital maps called geographical layers or spatial information (represented by points, lines, and polygons) and their associated statistical and/or descriptive data called attribute data. The development of GIS has allowed geographically referenced data to be analysed in complex ways. GIS facilitates the analysis of multiple layers of data and allows statistical analysis of multiple factors while maintaining their spatial representation. A very important advantage of the use of GIS is that such systems facilitate the future collection of relevant data as well as future, more complex analyses.

The data requirements for effective use of GIS are high. Data need to be geographically referenced using compatible systems, and it is important that the spatial resolution of the various layers be as similar as possible. Such detailed and compatible data often do not exist, and therefore the costs of developing such a database can be very high. Other specific limitations include the cost of the software (although less expensive products are available) and the need to train technicians to use the software.

There are many GIS software packages available on the market such as IDRISI (Clark University), GRASS (US Army Corps of Engineers), Arc/Info (ESRI), and others. All of these package vary widely in cost, sophistication, ease of use, and manner of handling spatially referenced data.

The application of a GIS in impact assessments includes (1) depicting past, present, or future climate patterns; (2) using simple indices to evaluate present-day regional potential for different activities based on climate and other environmental factors; (3) mapping changes in the patterns of potential induced by a given change in climate, thus showing the extent and rate of shifts; (4) identifying regions that may be vulnerable to changes in climate; and (5) considering impacts on different activities with the same geographical region so as to provide a basis for comparison and evaluation (Carter et al., 1994). GIS can also been used in conjunction with general circulation models (GCMs), biophysical simulation models, and integrated databases to conduct regional and global impact analyses.

GIS can also be a valuable tool in integrated impact assessment for storing, combining, and analysing the geographic information used and developed by the different assessment teams. If country assessment teams decide to use GIS in their studies, it is essential that all assessment teams use the same or at least compatible systems.

How do we keep on track and assess progress?

Climate impact assessment and adaptation studies are complex, multidisciplinary enterprises. There are bound to be strong centrifugal forces operating which send assessment participants in different directions. If the assessment is to retain coherence, it is important to create at the outset a procedure for periodic review and assessment of progress and to be prepared to make “course corrections”. Therefore it is suggested that meetings of the study team be held at frequent enough intervals to permit collective

assessments of progress to be made, and to ensure that the agreed answers to this list of questions remain valid and are providing sufficient guidance to the component studies. Where this turns out not to be the case, appropriate adjustments should be made under the guidance of the project leadership.

References

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Department of Geography, University College, London.

IPCC. 1996. *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds). Cambridge University Press, Cambridge, United Kingdom and New York, 880 pp.

2 Socio-Economic Scenarios

Lead Author
Richard S.J. Tol [1]

2.1 Introduction

The world on which climate change will have its impact will not be the same as the world of today. Many things will change, some even faster than climate. Populations and economies figure prominently among these. In many countries, population is projected to double or even triple over the next century. In some countries, the economy is flourishing and growing very fast. In others, growth is less. In some, the economy is actually shrinking. These changes will have a variety of effects. Higher populations implies more people to be affected by climate change. It also implies a higher demand for food, for water, for places to live, for energy. More prosperous people will have more to lose to climate change, but will also have more to spend to protect themselves. They will be less dependent on agriculture, and have better health care. Changes in population and economy will not only alter the impact of climate change on human systems, but also have ramifications for natural systems through, for example, altered land use and environmental pollution.

For such reasons, it is important to have an idea of how populations and economies will develop over the coming century and how this will affect the impacts of and adaptation to climate change. This is commonly done with scenarios, reflecting expert knowledge

[1] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands.

and output of extensive models. This chapter discusses how such scenarios can be developed and to what use they can be put. It also provides a further background to socio-economic scenarios in the context of climate change impact research. Box 2.1 illustrates many of the points raised, drawing on the scenarios build for the Pakistan country study (Pakistan Ministry of Environment, Local Government and Rural Development, 1997).

Box 2.1 Socio-economic scenarios for Pakistan.

Socio-economic scenarios were developed in the UNEP country study for Pakistan (Pakistan Ministry of Environment, Local Government and Rural Government, 1997). The scenarios comprise a range of issues, and are intended to be used in all impact and adaptation analyses for Pakistan (the first step toward integrated assessment, cf. Chapter 4). Quantitative scenarios were constructed for total and urban population, total and sectoral economic activity, total and crop-specific agricultural production, total and sectoral energy demand, and total and activity-specific industrial output. In addition, a suite of issues was addressed in a more qualitative manner (although supported with numbers in many cases). These include literacy, health care, import tariffs, forest cover, and infrastructure. As a result, a reasonably complete characterisation of future Pakistan emerges, with sufficient detail to analyse the more subtle effects of socio-economic development on the impacts of climate change and the ability to adapt.

Three scenarios were developed, with two “anchor” years: 2020 and 2050. For the period up to 2020, the scenarios are borrowed from existing sources, scenarios developed for various planning studies in and for the country. The period 2020-2050 was developed, with less detail, for the purpose of the impact and adaptation study. The business-as-usual scenario is based on a projection of observed trends, corrected for recent structural reforms. A high scenario is based on more optimistic assumptions about developments in economy and policy. Similarly, a low scenario is based on more pessimistic assumptions.

2.2 Background

2.2.1 Definition

A scenario is “a coherent, internally consistent and plausible description of a possible future state of the world”, according to Carter et al. (1994). Webster’s New Dictionary and Thesaurus (1990, p. 487) more modestly defines a scenario as “an outline of future development”. The definition of Carter et al. is the ideal, Webster’s version is the practice. The development and use of scenarios has a long tradition, going back to at least De Jouvenal (1967) and Kahn and Wiener (1967).

A scenario differs from a forecast in that a scenario is a plausible future, whereas a forecast is the most likely future. Being only a plausible future, a scenario is ideally part of a set of scenarios, which together span the range of likely future developments. Scenarios and forecasts have in common that they are internally consistent.

A scenario differs from a projection in that a scenario is a plausible future of a suite of interrelated variables, whereas a projection often is a simple extrapolation of current

trend, and often only concerns a single variable. Internal consistency is not a necessary property of projections.

2.2.2 The scope of socio-economic scenarios

Climate scenarios are scenarios of climatic conditions. They are treated in Chapter 3. Socio-economic scenarios are scenarios of the state and size of the population and economy, in the broadest sense of the words. Socio-economic scenarios comprise the number of people in a country, as well as their age, health, gender, values, attitudes, religion, education, where and how they live, and so on. Socio-economic scenarios comprise the gross domestic product, as well as income distribution, relative importance of economic sectors, imports and exports, unemployment, savings, land and water use, and so forth. Socio-economic scenarios also comprise technology, legislation, culture, processes of decision-making, etcetera. In short, socio-economic scenarios comprise everything that shapes a society. Arguably, they also comprise environmental changes associated with socio-economic changes. Examples are land use change, land degradation, eutrophication, and nature preservation.

Of course, it is impossible to make a scenario of everything, particularly within the framework of a country study. Socio-economic scenarios can comprise almost everything, but for practical reasons they should comprise only the elements that are crucial for a climate change impact analysis; not more and not less. Table 2.1 lists the impact categories as used in this Handbook and gives a selection of the socio-economic parameters that influence impacts. Note that Table 2.1 is only for illustration. Countries may well differ from the broad picture described here. The decision of which socio-economic variables are needed can be made only after an understanding has been acquired of how sensitive the system or sector under study is to changes in these variables, and how fast these variables are likely to change. Besides gaining general knowledge and insights from the first steps in an impacts and adaptation study, brainstorming with appropriate experts and surveying the literature may help identify the crucial socio-economic variables that are liable to change significantly over the coming decades, and that have a profound influence on the sensitivity and adaptability of the system or sector under consideration.

2.3 Scenario development

2.3.1 Background

Developing scenarios of socio-economic conditions is both easy and difficult. It is easy in that a scenario is a description of a plausible future, a quantified description of a yet-to-become reality in which assertions cannot be checked against data. No scenario has ever come true. This is not to say that any scenario is as good as any other. Scenarios need to be possible (i.e., not violate known constraints such as land acreage); plausible (i.e., in line with current expectations); and interesting (e.g., a scenario that projects a bright future without problems is appealing but not necessarily

Table 2.1 Possible socio-economic scenarios needed for climate change impact and adaptation analysis, per sector or system.

Sector/system	Variables needed for scenario
General	Population growth Economic growth
Water resources	Water use for agriculture, domestic, industrial and energy sectors Land use (for run-off) Adaptation capacity (economic, technological, institutional)
Coastal zones	Population density Economic activity and investments Land use Adaptation capacity (economic, technological, institutional)
Agriculture	Land use Water use Food demand Atmospheric composition and deposition Agricultural policies (incl. international trade) Adaptation capacity (economic, technological, institutional)
Human health	Food and water accessibility and quality Health care (incl. basic) Demographic structure Urbanisation Adaptation capacity (economic, technological, institutional)
Energy	Population Economic structure Power-generation structure Adaptation capacity (economic, technological, institutional)
Forestry	Land use Water use Timber demand Atmospheric composition and deposition Nature preservation policies Adaptation capacity (economic, technological, institutional)
Livestock and grasslands	Land use Water use Meat and diary demand Atmospheric composition and deposition National and international markets and policies for meat and diary Adaptation capacity (economic, technological, institutional)
Wildlife and biodiversity	Land use Water use Atmospheric composition and deposition Tourism Nature preservation policies
Fisheries	Fishing (practice and intensity) Land use (particularly in coastal zones) Water use (particularly for freshwater) Atmospheric deposition

interesting for policy analysis).[2] Therefore, scenario development is also difficult. A scenario is a single realisation of an infinite number of equally plausible developments. A good scenario is consistent with current understanding of reality without assuming that the future will resemble the past and the present. A good scenario does not say that the future will be "more of the same". The future will differ both quantitatively and qualitatively from the present, just as the present differs both quantitatively and qualitatively from the past. Scenario development thus requires a combination of a thorough understanding with an eye for crucial details, a broad overview of and insight about historical trends and international comparisons, creativity, and boldness.

Such a combination of talents is rare. Fortunately, in most cases, scenarios do not have to be developed from scratch. Scenarios can be borrowed or adapted from the literature. A variety of research institutes create scenarios on a variety of issues, with regional or even global coverage. Table 2.2 provides an overview of common sources for scenarios of socio-economic conditions. It is strongly advised to rely on existing scenarios, for convenience, to save time, and to be comparable to and consistent with related studies. New scenarios should be developed only if it is truly necessary, for instance, for variables that are not projected in existing scenarios.

Many countries have developed country-specific scenarios to assist national policy-makers in developing long-term strategies. Specificity to the circumstances of the country may well be very important. If one goal of the study is to inform domestic stakeholders about the impacts of climate change and possible adaptation options to it, the use of existing scenarios has as additional advantages that the study's audience is already familiar with the scenarios and that adaptation policies can readily be placed in the context of other policies. It is therefore recommended that national scenarios be used where possible. National scenarios are likely to have been developed in the context of development plans, agricultural plans, infrastructure plans, and so on. The likely sources or contacts are the appropriate ministries or perhaps a specialised planning office.

Note, however, that national scenarios (which have been developed for different purposes) seldom reach the second half of the 21st century, which is the relevant time for climate impact research. However, a long-term scenario for the country can, with a modest effort, be based upon an existing national scenario for the medium term, and an existing regional scenario for the long term.

It is also recommended that the scenarios used for impact and adaptation assessment be consistent with the scenarios used for greenhouse gas emission studies. The main overlaps are the assumed population and economic growth rates. Mitigation scenarios may also project agricultural production and deforestation. Scenarios used for the

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[2] Unless there are identified interventions of how to reach such a future. A possible application to a climate change impact study would be a scenario with strategic adaptation (e.g., land tenure reform) which would nullify the impact of climate change.

Table 2.2 Existing socio-economic scenarios.

Parameter	Period	Number scenarios	Geographical coverage	Remarks
Intergovernmental Panel for Climate Change (IPCC), WMO, and UNEP				
Population	1990-2100	3	World, 7 regions	based on World Bank and United Nations
Income	1990-2100	4	World, 7 regions	
Energy production and consumption	1990-2100	6	World, 7 regions	
Deforestation	1990-2100	4	World	
Source: Leggett et al., 1992. Electronic source: Limited distribution on diskettes.				
World Population Projections, World Bank				
Population (gender, age, migration)	1990-2150	1	World, regions and countries	
Source: Bos et al., 1994. Electronic source: Commercial distribution on diskettes.				
IMAGE 2, RIVM				
Population (total and urban)	1990-2100	1	World, 13 regions	based on IS92a and WRI (1990)
Income	1990-2100	1	World, 13 regions	based on IS92a
Economic activity	1990-2100	1	World, 13 regions	
Land use	1990-2100	4	World, 13 regions, 0.5^0x0.5^0	
Source: Alcamo et al., 1994. Electronic source: --				
International Institute for Applied Systems Analysis (IIASA)				
Population (gender, age, migration)	1990-2100	5	World, 13 regions	
Source: Lutz, 1997. Electronic source: http://www.iiasa.ac.at/				
World Health Organization				
Mortality (age, gender, cause)	1990-2020	1	World, 8 regions	
Source: Murray and Lopez, 1996 Electronic source: --				
Food and Agriculture Organization				
Land use	1990-2010	1	World, various regions	
Production (crop-specific)	1990-2010	1	World, various regions	
Source: Alexandratos, 1995. Electronic source: --				

impact of climate change on energy production and consumption show considerably more overlap with the scenarios for emissions reduction.

It is important that scenarios are consistent across sector studies. Indeed, this is the first step toward integration (Chapter 4). In this case, ensuring consistency actually saves work. First, scenarios that apply to most of the sectors in the country should be developed. Such scenarios are likely to include population growth, economic growth, and other generic variables. Population growth rates may need to be region-specific. Economic growth rates may need to be sector-specific. Sector-specific scenarios could include age distribution of the general population and number of doctors for health, and international wheat prices and land tenure reforms for agriculture. Note that some elements of a scenario may be applicable to more than one sector. Examples are acid deposition (managed and unmanaged terrestrial and aquatic ecosystems); water demand by households (water resources, agriculture); and diet (agriculture, health). It is therefore recommended that all scenarios (including the sector-specific ones) be developed by one team, or that the development of sector-specific scenarios be strictly co-ordinated.

2.3.2 Building scenarios

Scenarios are often based on a combination of expert judgement, extrapolation of trends, international comparisons, and model runs. Historical developments are a good guide for future developments. However, simple extrapolation should be avoided. Understanding the phenomena underlying the observed trends and the forces that shape the past developments is necessary for adequate extrapolation.

The situation in countries in a later stage of a transition may inspire an estimate of future developments in a country currently in earlier stages. An obvious example is the demographic transition, which describes how human mortality and fertility rates fall with improved health care and growing prosperity. Another transition is that of economic structure, with agriculture as the dominant economic sector in the early stages of development, succeeded by industry, and then by services. People tend to consume more meat when lifted from poverty, but tend to reduce their meat intake when more affluent. Such transitions describe broad tendencies of average behaviour. It may well be that countries are different. For instance, religion may interfere with fertility rates or dietary preferences, although secularisation may counteract this. Or governments may choose to steer economic structure toward, for instance, the tourist sector.

Models play an important role in scenario development for well-established relationships, for example, demographic structure and population growth, or price-induced changes and economic structure. Models cannot be used to generate a complete scenario. Instead, models help to fill in details of scenarios. For instance, a demographic model could help translate a projection of mortality and fertility rates into age distribution. The projection of mortality and fertility rates would need to come from

another source, which may be another model. Similarly, the resulting age distribution could feed into a model which projects the prevalence of diseases.

Expert judgement is needed for the gaps that cannot otherwise be filled, to blend the pieces into a coherent and plausible scenario, and to generate a plausible and interesting range of scenarios. Expert judgement plays a crucial role in interpreting the results of historical, international, and model studies. If time is short, or the budget limited, expert judgement may even replace such studies, or fill in gaps. Models, historical trends, and international comparisons may yield inconsistent, sometimes even conflicting results. Experts would be needed to restore consistency, and to choose between results. Further, expert judgement is essential for picking a set of scenarios, each of which is plausible and interesting, that span the range of possible futures.

Expert judgement may be the only reliable source where the situation is very uncertain, for instance, because of drastic break in the economic system (as, for example, in the countries of the former Soviet Union) or in the political situation (as in certain parts of Africa).

2.3.3 Multiple scenarios

The future is uncertain. A single scenario for future developments may transmit a false sense of certainty to the study's audience. The audience may accept a single scenario either because it places too much trust in the abilities of scientific research, or because it does not want to accept the additional complexities and responsibilities that come with uncertainty. Therefore, multiple scenarios, at least three, should always be used.

Multiple scenarios have the additional advantage that a better understanding of the system under consideration is obtained. Using multiple scenarios is in fact a sophisticated sensitivity analysis. Multiple scenarios can show how different development paths may affect vulnerability differently.

Multiple scenarios arise if crucial parameter values (e.g., fertility rate) are varied between middle, high, and low values. A range of parameter values can be obtained from the literature, from empirical studies, or from expert judgement. A rich scenario is based on many parameters. Even with substantial resources, it may be impossible to investigate all combinations of middle, high, and low values. Ideally, one should generate many scenarios, based on random parameter values, and select those that span the range of outcomes for further study and application. This may be too elaborate. If time or budget is limited, attention should be given to the most important parameters, that is, those that have the highest uncertainty and the largest influence on the outcomes. These should all be varied such that the outcome — population, income — is increased, or decreased, in all cases. To get a high population scenario, for example, mortality would be set at its low value, and fertility at its high value. This will generate three scenarios, a low, a middle, and a high one. If time permits, intermediate scenarios could also be generated. In generating multiple scenarios, it is essential to keep an eye

on plausibility and internal consistency. For instance, high per capita income growth often leads to low fertility and mortality rates.

Besides varying parameters, different, yet plausible assumptions on certain processes can be made. This is at a more advanced stage of scenario development. It is particularly relevant for the more qualitative aspects of scenario building. For example, it may be desirable to contrast a scenario with a well-protected domestic market to a scenario in which the economy is open and all sectors compete at the world market. A scenario with strictly regulated water resources could be compared to a scenario with a market for water rights. Such scenarios are structurally different, so it is impossible to classify these as high or low.

2.4 Use of scenarios

Socio-economic scenarios are used to provide the context in which climate change will have its impact. An impact analysis usually starts with an analysis of a sector or system (e.g., agriculture, health) in the current situation. Next, climate is perturbed and the impact on the sector or system (e.g., higher yields, more malaria) is analysed. Socio-economic scenarios are used to perturb other-than-climatic influences on the sector or system; see Figure 2.1.

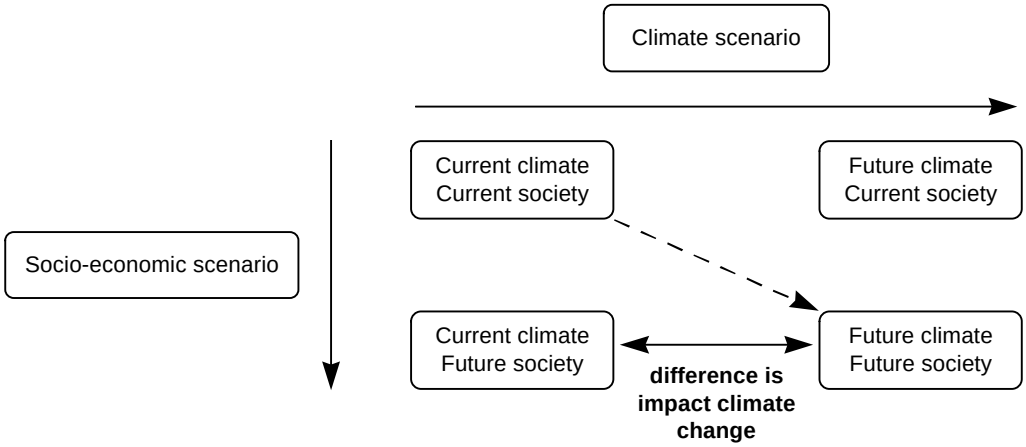

Figure 2.1 Climate and socio-economic scenarios.

Figure 2.1 displays four combinations of current or future climate and current or future society.[3] The upper left corner is the current situation: climate is as it is at present, and society is as it is at present. Consider a climate-sensitive activity such as water resources management or agriculture. Suppose we are interested in flood damage, or

[3] In reality, climate and society do not develop independently of each other. Viewing climate as a resource or a constraint, human decisions are constantly affected, including those concerning long-term development. Human land use affects regional climate, and greenhouse gas emissions after global climate.

crop yield. Now, if only climate changes, we move from the upper left corner to the upper right corner. Flood damage or crop yield changes because of climate change. This change is the impact that climate change would have on the current situation. However, society also changes. If climate were to remain as it is today, we move to the lower left corner. Flood damage or crop yield would change, for instance because of new investments, new regulations, or new technologies. This is the impact of socio-economic change. If both climate and society change, we move to the lower right corner. Flood damage or crop yield would change further. This is the change that will be observed. It is the combined effect of climate and other changes. The situations with current climate and future society, or future climate and current society are counterfactual: they exist in only theoretical exercises, not in reality.

Obviously, one should not go to the trouble of using, let alone developing, socio-economic scenarios if the impact of climate change on a future society is expected to be similar to the impact of climate change on the current society. That is seldom the case, however. It is true that a particular cultivar of maize reacts similarly to a certain change in climate, whether it is 1997 or 2057. In the intervening years, however, that particular cultivar is likely to be replaced by another cultivar, or maize by wheat, or cropland by industrial development for reasons other than climate change.[4] Similarly, the farmer that currently lacks the ability to adapt may have been succeeded by one that has the capital to buy different seeds or machinery, or irrigate the land (although the currently abundant water may have been taken or polluted by novel industrial development). A population currently vulnerable to malaria may have benefited from a successful health care programme. The trend may also be in the opposite direction. Regions which nowadays control malaria may lose the race in the future because of ever more resistant strains of the malaria parasite. In general, it is better to assume that socio-economic developments have a substantial effect on sensitivity to climate change than to assume that the effect is trivial.

For instance, Mekonnen and Hailemariam (1998) describe a socio-economic baseline scenario for climate change impact assessment in Ethiopia. In addition to the obligatory population and economic growth, the scenario also considers urbanisation, agriculture encroaching on grasslands, and expanding mining and industrial activities. Furthermore, the scenario considers further strengthening of institutions and environmental legislation, which would result in, for example, improved soil management and forest preservation.

So, such factors have to be included in a climate change impact study.[5] The question is how. The previous section describes how to develop scenarios of socio-economic parameters. The scenarios have to then be linked to the impact analysis. Below, a number of examples by sector are given of how this has been handled in the impacts

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[4] If it is because of climate change, that is adaptation, the subject of Chapter 5.

[5] Recall that first the crucial socio-economic variables need to be identified. A study of the impacts of climate change on the present situation may be very informative for that.

and adaptation literature. Of course, these examples are not perfect solutions. Nor are they prescriptions of how it should be done. Rather, they are illustrations of how socio-economic scenarios can be incorporated, meant to illuminate and inspire the user on how the issue can be tackled.

2.4.1 Water resources

More people will use more water. Perhaps not per capita, but the population in total will likely use more water. At the same time, water resources are under pressure all over the world, with reserves falling and conflicts between competing users looming. This implies that, in many places in the world, water resources management will look drastically different in fifty years' time, as current practices cannot be sustained.

A drastic change to a river is building a dam. If there is good reason to assume that one or more dams will be built in the river that is the subject of the study, this should be incorporated into the analysis. Another likely change is that the demand for river water (for irrigation, cooling, or household consumption) will be different, so that downstream discharges change as well. A part of the consumed water is put back into the river, it is perhaps enriched by other substances. Further, peak floods may increase because part of the catchment is deforested or paved. In that case, the nature of floods changes, with higher, more rapid, and shorter peak flows.

Investigating the impact of such changes requires rather detailed scenarios of land and water use in the catchment of study. Time may be too short to develop these, while the detail required may not be found in existing scenarios. Besides, scenarios are good for broad pictures. The details of scenarios are not very reliable, and sometimes the details can have very important consequences. For instance, there may be a good reason to expect that the river will be dammed, but where the dam will be placed and how big it will be is hard to foresee, yet very important for the hydrological regime. It may therefore be better to use "analogue parameterisations".

The models described in Chapter 6 have been used for many studies. After calibrating the chosen model to the river catchment, consider looking at other calibrations. If the river is about the same as a river 200 miles north, the main difference being that deforestation has progressed much further there, then the runoff parameters of that catchment give an idea of what runoff will look like in this river catchment after deforestation. This should be done with great care, as no river is the same.

2.4.2 Coastal zones

Sea level rise affects coastal zones, which tend to be highly dynamic both ecologically and economically. This has important consequences for the impacts of sea level rise. An obvious change is the size of coastal systems at risk. The Global Vulnerability Assessment (Hoozemans et al., 1993), for instance, finds 61 million people at risk of a 1-meter sea level rise world-wide if populations are held constant at their 1990 values.

This number grows to 100 million as a result of 30 years of population growth and migration to the coast. Conversely, 169,000 square kilometres of coastal wetlands are potentially at loss if the current situation is maintained. This number is projected falls to 154,000 square kilometres in 30 years' time, because other pressures on coastal systems reduce the acreage of wetlands.

Hoozemans et al. (1993) also point out that richer countries have more financial resources to invest in coastal protection (cf. also Fankhauser, 1995; Nicholls et al., 1995).

Being a global study, Hoozemans et al. (1993) is understandably scarce on details. The study by the Comision Nacional Sobre el Cambio Global (1998) describes a scenario for coastal development in Uruguay. In addition to the obligatory population and economic growth, they also considered the impact of currently planned infrastructure. It is planned to connect Buenos Aires in Argentina and Colonia in Uruguay by a bridge. This is likely to spur considerable growth in Colonia and neighbouring San Jose. Similarly, a road is planned along the north coast, bridging the lagoons. Opening this area is likely to lead to additional coastal development.

2.4.3 Agriculture

Future agriculture will be as different from current agriculture as that is of past agriculture. Since World War II, the world has witnessed a tremendous growth in population and income, decolonisation, the "Green Revolution", the Common Agricultural Policy in Europe, and, most recently, the freeing of international trade. All of these have had a significant impact on agriculture, not only on its output but also on the way it is practised and organised.

The most obvious change is population growth. Demand for food will be greater and more varied, and therefore production needs to be greater, and also more diverse and specialised. There are three basic options for increasing food supply, namely expansion of agricultural lands, increased productivity per acre, and increased net food imports. Expansion invariably means expansion into lands less suitable for agriculture. Crops on marginal lands tend to be more sensitive to climate change (or any other stress) than crops on richer lands. An impact study needs to take this into account. More varied agricultural production would reduce sensitivity to climate change (through diversification), but at the same time would increase the information needed for successful adaptation (assuming that each crop needs to be investigated individually).

Increasing productivity per acre can be done in a variety of ways, by improving soils, water and nutrient availability, cultivars, and management practices. High-yield strains are often more susceptible to disturbance and disease than their lower-yield predecessors. If rain-fed crops are converted to irrigated crops, producers' vulnerability to drought shifts from local (the field) to regional (the watershed), bringing in competitive users for the irrigation water. At the same time, increasing productivity per acre is often accompanied by an expansion of resources, notably capital, information,

and alternative sources of income. As a result, the farmer (not the crop) could become less vulnerable to climate change.

Increasing food imports would imply that agriculture becomes less sensitive to climate change in the country itself, but more sensitive to climate-change-induced price shocks at the world food market. Increasing food imports or reducing exports of food and non-food agricultural products would have ramifications for the balance of payments and the exchange rate.

At the national level, the impacts of climate change on the agricultural sector also depend on the assumed economic and population growth rates. Countries with low population growth will have fewer mouths to feed. Countries with high economic growth will have more resources to support a smaller agricultural sector. Vulnerabilities will be very different if a country seeks rapid industrialisation, takes food imports for granted, seeks self-reliance in food production, or chooses a path of agricultural export-led growth. Vulnerabilities will also be different if a country chooses to protect and support its farmers, or let them face the whims of the market and the weather on their own strength.

2.4.4 Rangelands and livestock

The issues raised with regard to arable agriculture also pertain more or less to rangelands and livestock. Rangelands and the livestock living on them are affected by changes in water and land use, deposition of eutrophying and acidifying substances, soil erosion and land degradation, and management practices. The demand for meat and dairy products, which depends on the number of people and their dietary preferences, is also important. The intensity of farm management is another factor that may influence the response of rangelands and livestock to climate change. Extensive farms may be most sensitive to changing weather conditions. This sensitivity may decline if land is improved, feed is supplemented, and animal health care is improved. Bio-industry is largely insensitive to climate change, but may conflict with consumer preferences.

2.4.5 Human health

Human health is another area where large changes can be expected. Medical research concentrates on “diseases of affluence” (e.g., cardiovascular disorders), which may be less sensitive to climate change than “diseases of poverty” (e.g., infectious diseases). Breakthroughs in treatments for climate-sensitive diseases may not occur, and if they do, their timing is highly uncertain. Further, the effect these have on vulnerability is trivial. For instance, in the unlikely event of the development of an effective and cheap malaria vaccine, the effect of climate change on the disease will be negligible.

Access to basic health care is often important to vulnerability to climate-sensitive diseases. With some effort, this can be derived from scenarios on per capita incomes. Other variables such as income distribution and national or international health care

programmes are also important. These could be derived by extrapolation or be the subject of a sensitivity analysis. In any case, people tend to care about their health, and if they are able, they will take care of their health. So, increasing incomes implies better health care and reduced vulnerability to diseases, including those sensitive to climate change.

Although a rise in income may improve human health, economic growth and urbanisation will continue so that “rich” and “urban” diseases will gain in importance relative to “poor” and “rural” diseases. Two prominent categories are cardiovascular diseases (related to heat and cold) and respiratory disorders (related to heat, cold, and air quality). The urban heat island effect makes heat waves in cities much worse than at the countryside. Air conditioning helps only those who have it. And air conditioning actually contributes to the heat outside. Urban air quality also tends to be worse than rural air quality, and particularly so during hot weather.

The impact of heat waves depends on adaptation. Once air conditioning is wide-spread (including in shopping malls) and cooling water bodies or forests are nearby, vulnerability will decrease. A similar thing may happen to urban air quality. Once the dirtiest traffic is banned, and the dirtiest industries moved to the outskirts of the city, air quality will improve and vulnerability decline.

Scenarios for population, per capita income, and urbanisation are readily available for most countries (see Table 2.2). Scenarios for other variables are not so readily available.

2.4.6 Energy

Energy production and consumption are likely to change in ways that affect their sensitivity to climate change. On the production side, biomass, solar energy, and, particularly, hydropower are directly influenced by climate. These sources of energy may well gain in importance in the future, so that the number of potentially affected units (biomass plantations, hydropower plants, wind turbines) grows. Energy production and the composition of energy supply are subject to substantial study, largely in the context of mitigation studies of climate change. It is recommended that the scenarios used for mitigation studies also be used to study the impact of climate change on energy production and consumption.

Climate effects on energy consumption are largely confined to heating and cooling. Demands for heating and cooling depend on the number of people and their housing situation. Particularly important is the spread of air-conditioning. Note that climate change may speed up the introduction of air-conditioning. Building design, urban planning, family size, age distribution, and working hours may also significantly affect energy demand for heating and cooling.

Besides energy supply and demand, technologies are also bound to change. New power generating techniques may be more or less sensitivity to weather conditions, or sensitive

to other weather circumstances than current techniques. For instance, new power plants may use less cooling water, or new photovoltaic cells may be less sensitive to overcast skies. Technological change may also influence the energy demand side. For instance, the energy demand of more efficient air conditioners is less sensitive to climate than is the demand of less efficient air conditioners.

2.4.7 Forests

Besides by climate change, forests are affected by changes in water and land use, deposition of eutrophying and acidifying substances, timber demand, and management practices. These factors affect both the size of the forest sector and the species composition in the stands. The latter would imply a qualitative shift in the impact of climate change, since different species react differently. Trees stressed by, say, an acid environment also react differently to climate change than trees in a healthy environment, as do trees in an environment artificially enriched by nutrients. Foresters would behave differently if the land tenure system were to change, or if the demand for “sustainably grown” timber were to increase. Forest acreage would decrease if other types of land use became relatively more attractive, for instance because of extensions of nature reserves, increased demand for agricultural produce, or greater timber supply on the international market.

2.4.8 Biodiversity

Biodiversity is affected by changes in water and land use, deposition of eutrophying and acidifying substances, soil erosion and land degradation, and recreation. In some cases, management practices are also influential. All of these factors influence the way in which biodiversity reacts to changes in the climate. Perhaps the most influential factor is the area of human disturbance. The area that is left untouched by humans, whether this is scattered or well-connected, confined to marginal grounds and so on, is a significant driver of vulnerability to climate change. Also, whether adjacent lands are used for eco-tourism, extensive farming, or industrial development is influential. Further, access of indigenous people or poachers may be important. Inflow of contaminating or fertilising substances via air or water may also affect an ecosystem and its reaction to climate change.

2.4.9 Fisheries

The most crucial factor determining the impact of climate change on fisheries is the harvesting of the world’s fish stocks for human consumption. A further increase in the reach and accuracy of fishing fleets would lead to more stress on more fish populations, leaving them more vulnerable to climate change. Technologies enabling fishermen to catch only desirable species, and regulations restricting access to certain waters, times, or species, would reduce stress and increase resilience to climate change.

Another important factor is human influence on hatcheries, nurseries, and food resources such as coastal wetlands and coral reefs. A further increase in the stress on these systems would leave fish stocks more vulnerable to climate change, and decreasing stress would have the reverse effect.

A third factor that may be worth looking at is the spread of aquaculture. If fish supply were to rely more heavily on "farmed" fish than on wild stocks (because of market forces or government intervention), stress on the latter would decrease and the influence of climate change on the former would be greater. A change in dietary preferences for fish would change demand, and thus would affect the supply and stress of fish populations.

2.5 Concluding remarks

The socio-economic circumstances of the world on which climate change will have its impact will be very different from today's circumstances. The future system or sector of the study is likely to differ not only in size but also in structure. Therefore, the impacts on and adaptation of the future system or sector may well differ quantitatively and qualitatively from the impacts and adaptation of the current system. In one way or another, the analysis needs to take this into account.

As a first step, the crucial elements that are likely to change should be identified. Is it the size of the population, water use upstream, or agricultural policy? As a second step, a scenario of how these crucial elements might change over the next decades needs to be developed or, preferably, obtained. As a third step, the impact and adaptation analysis must be combined with the socio-economic scenario.

The second step is probably the easiest. Do not develop scenarios; instead borrow them from the literature. If no scenarios are available, use historical trends and geographical analogues to inspire scenario development. If time permits, use more than one scenario.

The first and third step are specific to the situation of a country study. General guidelines are either too vague to be helpful or too specific to be applicable to each case. Using appropriate experts will probably help. The literature on climate change impacts and adaptation is rapidly expanding, and full of examples how others have tried to solve this problem. This chapter also provides a number of examples, but these are only examples; different problems would need different solutions.

References

Alcamo, J., G.J. van den Born, A.F. Bouwman, B.J. de Haan, K. Klein Goldewijk, O. Klepper, J. Krabec, R. Leemans, J.G.J. Olivier, A.M.C. Toet, H.J.M. de Vries, and H.J. van der Woerd. 1994. "Modelling the Global Society-Biosphere-Climate System: Part 2; Computed Scenarios." *Water, Air and Soil Pollution*, 76 (1-2), 37-78. Reprinted in J.

Alcamo (ed), *IMAGE 2.0: Integrated Modeling of Global Climate Change.* Kluwer Academic Publishers, Dordrecht.

Alexandratos, N. (ed). 1995. *World Agriculture: Towards 2010 — An FAO Study*. Wiley, Chichester.

Bos, E., M.T. Vu, E. Massiah, and R.A. Bulatao. 1994. *World Population Projections*. John Hopkins University Press, Baltimore and London.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka, 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Intergovernmental Panel on Climate Change, Geneva.

De Jouvenal, B. 1967. *The Art of Conjecture*. Basic Books, New York.

Fankhauser, S. 1995. *Valuing Climate Change - The Economics of the Greenhouse*. EarthScan, London.

Mekonnen, A. and K. Hailemariam. 1998. *Baseline and climate change scenarios for Ethiopia*. Presented at the Conference on National Assessment Results of Climate Change: Impacts and Responses, held in San Jose, Costa Rica, March 25-28. National Meteorological Services Agency, Addis Ababa, Ethiopia.

Comision Nacional Sobre el Cambio Global. 1997. *Uruguay Climate Change Country Study: Assessment of Climate Change Impacts in Uruguay, Final Report*. Prepared with the US Country Studies Program as the International Cooperation Agency. Montevideo.

Hoozemans, F.M.J., M. Marchand, and H.A. Pennekamp, 1993. *A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production and a Global Scale (second, revised edition)*. Delft Hydraulics, Delft, The Netherlands.

Kahn, H. and A.J. Wiener. 1967. *The Year 2000: A Framework for Speculation on the Next Thirty-Three Years.* MacMillan, New York.

Leggett, J., W.J. Pepper, and R.J. Swart. 1992. "Emissions Scenarios for IPCC: An Update." In J.T. Houghton, B.A. Callander and S.K. Varney (eds), *Climate Change 1992 -- The Supplementary Report of the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

Lutz, W. (ed). 1997. *The Future Population of the World: What Can We Assume Today?* EarthScan, London.

Ministry of Environment, Local Government and Rural Development. 1998. Study on Climate Change Impact and Adaptation Strategies for Pakistan. Government of Pakistan, Islamabad.

Murray, C.J.L. and A.P. Lopez (eds). 1996. *The Global Burden of Disease.* Harvard University Press, Cambridge.

Nicholls, R.J., S.P. Leatherman, K.C. Dennis and C.R. Volonté. 1995. Impacts and responses to sea-level rise: qualitative and quantitative assessments. *Journal of Coastal Research*, Special Issue 14: 26-43.

Webster's New Dictionary and Thesaurus. 1990. Concise Edition. Geddes & Grosset, New Lanark.

3 Climate Change Scenarios

Lead Authors
Joel B. Smith [1]
Mike Hulme [2]

Contributing Authors
Jaak Jaagus, Estonia
Sirje Keevallik, Estonia
Ademe Mekonnen, Ethiopia
Kinfe Hailemariam, Ethiopia

3.1 Introduction

This chapter addresses the important and often controversial topic of climate change scenarios. The choice of climate change scenarios is important because it can determine the outcome of a climate change impacts analysis. Extreme scenarios can produce extreme results, and moderate scenarios can produce moderate results. The selection of scenarios is controversial because scenarios are often criticised for being too extreme, too moderate, too unreliable, or not considerate of important factors such as changes in variability.

This chapter does not provide instructions on which types of climate change scenarios to use or how to construct them. Rather, it discusses the options for selecting scenarios, the issues that need to be considered in selecting scenarios, and the advantages and disadvantages of different approaches. The design and application of specific scenarios will require additional research and may require technical assistance.

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[1] Stratus Consulting Inc., Boulder, Colorado, USA.

[2] Climate Research Unit, University of East Anglia, Norwich, UK.

This chapter begins by addressing why climate change scenarios should be used and postulating criteria for selecting types of scenarios. Generic options for selecting scenarios are described, followed by a discussion of issues to be considered when selecting scenarios. The chapter then discusses issues in the use of general circulation models (GCMs[3]) in climate change scenarios and gives examples of scenario selection. (Chapter 2 discusses why it is important to use scenarios to examine the potential implications of uncertain future conditions such as climate change.)

More than one scenario should be used to show that there is uncertainty about regional climate change. Using one scenario can be misinterpreted as a prediction. Using multiple scenarios, particularly if they reflect a wide range of conditions (e.g., wet and dry) indicates some of the uncertainty about regional climate change.

Climate change scenarios have been typically developed for a particular point in the future. Many climate change scenarios examine the climate associated with a doubling of carbon dioxide levels in the atmosphere over pre-industrial levels ($2xCO_2$).[4] This will most likely happen in the last half of the twenty-first century. These could be considered static scenarios because they are based on the (false) presumption that a stable climate will be reached in the future. This assumption is made to simplify analysis, not because it is widely believed that climate will reach a static condition. In contrast, transient scenarios examine how climate may change over time. They typically start in the present day and cover a number of decades into the future.

A range of scenarios can be used to identify the sensitivity of systems to climate change and to help policy makers decide on appropriate policy responses. It must be explained to policy makers, journalists, and the public that climate change scenarios are not predictions of the future in the way that weather forecasts are. Rather, they are plausible indications of what the climatic future could be like, given a specific set of assumptions. The range of plausible climate change scenarios is much greater than that determined by uncertainties in climate models alone, and depends to a considerable extent on future global demographic and technological change, land utilisation, and ecological adaptation. Thus, prediction is too ambitious a term for such a tentative and provisional exercise of looking into the future (Henderson-Sellers, 1996).

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[3] GCM can also stand for “global climate models.” However, one-dimensional and two-dimensional models of global climate can be considered to be global climate models. Models of the general circulation of the atmosphere or atmosphere and oceans need to be three-dimensional. Thus here GCM only refers to these three-dimensional models.

[4] These CO_2 doubling scenarios usually mean the “effective doubling” of CO_2, that is, when the warming potential of all greenhouse gases, such as methane, nitrous oxide, and the halocarbons as well as carbon dioxide, equals the doubling of CO_2 alone.

3.2 Climatological baseline

It is typical in impacts assessment to use a period of years of observed meteorological data to define a "current climate baseline". This set of years can be used to calibrate impacts models and to quantify baseline climate impacts, e.g., crop yields under current climate. A 30-year continuous record of recent climate data is widely used for creating a baseline climate (e.g., Rosenzweig and Parry, 1994). A 30-year period is likely to contain wet, dry, warm, and cool periods and is therefore considered to be sufficiently long to define a region's climate. The 30-year "normal" period as defined by the World Meteorological Organisation (WMO) is recommended by the Intergovernmental Panel on Climate Change (IPCC) for use as a baseline period (Carter et al., 1994).

The current WMO normal period is 1961-1990. This period best defines current climate because it is recent. Since the quality and quantity of weather observations tend to improve over time, this period is likely to contain a more extensive network of observing stations and to record more variables than earlier periods. One problem with use of the 1961-1990 period, however, is that the 1980s were, globally, the warmest decade this century (Jones et al., 1994), although in some regions the 1980s were not warmer than prior decades. On average, therefore, using 1961-1990 as a base period could introduce a warming trend into the baseline, which could bias the results of some impact assessments, particularly transient assessments that combine observed baseline climate with an underlying trend in climate variables. The trend is not a problem if one is reporting only averages and variances. Another recent 30-year period such as 1951-1980, which has no trends or less distinct trends, could perhaps be used. But earlier periods are more likely to have less comprehensive and poorer quality data. On balance, it is preferable to use the most recent period.

In many cases, the baseline data set may contain insufficient variables or periods of missing data. In addition, there may be a need to create a baseline period that is much longer than 30 years to create more reliable statistical results (e.g., Lin, 1996). One way to remedy these situations is to use stochastic weather generators (see Table 3.3) (e.g., Richardson and Wright, 1984). These simulate daily weather at a site based on historical statistical relationships between variables. Using a weather generator to generate longer and more complete baseline data sets may require substantial amounts of observed weather data, which can be costly, or the data may be difficult to obtain.

3.3 Conditions for selecting climate change scenarios

Climate change scenarios selected for impact assessment should meet the following four conditions:

Condition 1. The scenarios should be consistent with the broad range of global warming projections based on increased atmospheric concentrations of greenhouse gases, e.g., 1°C to 3.5°C by 2100 (Houghton et al., 1996),

or 1.5°C to 4.5°C for a doubling of CO_2 concentrations (IPCC, 1990). Regional changes in climate variables may be outside the range of global average changes, but should be consistent with what climate change theory and models conclude may happen.

Condition 2. The scenarios should be physically plausible; that is, they should not violate the basic laws of physics. It is not plausible, for example, to assume that a country with as large an area as Russia or Brazil would have a uniform increase or decrease in precipitation. However, such a scenario could be plausible for smaller areas. In addition, changes in variables need to be physically consistent with each other. For example, days with increased precipitation will most likely have increased cloudiness.

Condition 3. The scenarios should estimate a sufficient number of variables on a spatial and temporal scale that allows for impacts assessment (Smith and Tirpak, 1989; Viner and Hulme, 1992). Many impacts models need scenario data for a number of meteorological variables such as temperature, precipitation, solar radiation, humidity, and winds. In addition, daily or more frequent information may be needed for some studies.[5]

Condition 4. The scenarios should, to a reasonable extent, reflect the potential range of future regional climate change. For example, a set of scenarios that examines only a relatively large or small amount of warming, or only wet or dry conditions, will not help identify the full range of sensitivities to climate change

In assessing options for creating climate change scenarios, it is important to meet as many of these conditions as possible. Where conditions are not met, the shortcoming should be acknowledged in reporting the results of analyses that use the scenarios.

3.4 Generic types of climate change scenarios

There are three generic types of climate change scenarios: scenarios based on outputs from GCMs, synthetic scenarios, and analogue scenarios. All three types have been used in climate change impacts research, although probably a majority of impacts studies have used scenarios based on GCMs. This section briefly describes each type

[5] Those creating climate change scenarios need to discuss data needs with the groups assessing impacts on each sector. The sectoral groups need to identify the variables they need and the necessary spatial and temporal resolution (e.g., 100 square kilometres at a daily time step). The climate change scenarios group needs to determine what can reasonably be provided.

of scenario and its relative advantages and disadvantages.[6] The section closes with a discussion of a fourth possibility of using a combination of two or more options. These different approaches, among others, have been summarised in Table 3.3.

3.4.1 General circulation models

GCMs are mathematical representations of atmosphere, ocean, ice cap, and land surface processes based on physical laws and physically-based empirical relationships. Such models have been used to examine the impact of increased greenhouse gas concentrations on future climate. GCMs estimate changes for dozens of meteorological variables for grid boxes that are typically 250 kilometres in width and 600 kilometres in length. Their resolution is therefore quite coarse. The most advanced GCMs couple atmosphere and ocean models and are referred to as coupled ocean- atmosphere GCMs; see Gates et al. (1996) for an evaluation of coupled GCMs.

Two types of GCM runs can be useful for impact assessments. Almost all GCMs have been used to simulate both current (1 CO_2) and future (2 CO_2 or occasionally 4 CO_2) climates. The difference between these simulated climates is a scenario of how climate may change with an effective doubling (or quadrupling) of atmospheric CO_2 concentrations. These are referred to as equilibrium experiments since both the current and future climates are assumed by modellers to be in equilibrium (i.e., stationary). GCMs used for equilibrium experiments generally have only a very simple representation of the oceans.

To be sure, climate is never in equilibrium. Greenhouse gas concentrations are not held constant, because of human activities or other reasons. The assumption of a stable climate makes it easier, however, for climate modellers to estimate the effect of increased greenhouse gases on climate and for impact assessors to examine potential impacts.

The second type of experiment is called a transient experiment. Here, a coupled GCM is used to simulate current (1 CO_2) climate and then future climate as it responds to a steady increase in greenhouse gas concentrations beyond 1 CO_2 concentrations (e.g., Manabe and Stouffer, 1995; Mitchell et al., 1995). A typical forcing scenario in a transient experiment is a 1 percent per year increase in CO_2 concentration, but many different forcing scenarios could in principle be used. The model is typically run for 100 years or more into the future. Tables 3.1 and 3.2 display attributes of some transient coupled atmosphere-ocean GCMs. An important limitation of many transient scenarios from GCMs is the so-called “cold start” problem (Hasselmann et al., 1993). This occurs when a transient GCM simulation fails to reflect the climate change that arises because of historical greenhouse gas emissions (i.e., those before the baseline period; Kattenberg et al., 1996). When this occurs, GCMs usually underestimate the change in

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[6] Section 3.5 also discusses advantages and disadvantages of GCM based scenarios.

climate in the first few decades beyond the present. More recently, a few "warm start" transient experiments have been successfully completed in which historical emissions of greenhouse gases back to the nineteenth century have been used to force the model (e.g., Mitchell et al., 1995; Mitchell and Johns, 1997). Many impact assessment studies have used GCMs as the basis for creating scenarios (e.g., Parry et al., 1988; Smith and Tirpak, 1989; Rotmans et al., 1994; Strzepek and Smith, 1995). These studies combined average monthly changes between 2×CO_2 and 1×CO_2 climates from equilibrium GCM experiments with 30 years of observed climate data. The use of the observed climate data provides greater spatial, and sometimes temporal, variability than can be provided by the GCM (thus helping meet Condition 3), although it assumes that these aspects of climate do not change from current conditions.

Table 3.1 Sample of global, mixed-layer, atmosphere-ocean general $_2$ simulations) used for impact assessment studies.

Group	Horizontal resolution (number of waves or lat. × long.)	Global surface air temperature change (°C)	References
GFDL	4.4° × 7.5°	3.2	Wetherald and Manabe, 1988
GFDL	4.4° × 7.5°	4.0	Manabe and Wetherald, 1987
GFDL	2.2° × 3.8°	4.0	Wetherald and Manabe, 1988
OSU	4° × 5°	2.8	Schlesinger and Zhao, 1989
MRI	4° × 5°	~4.3	Noda and Tokioka, 1989
NCAR	4.4° × 7.5°	4.0	Washington and Meehl, 1990
CSIRO4	3.2° × 5.6°	4.0	Gordon and Hunt, 1994
CSIRO9	3.2° × 5.6°	4.8	Whetton et al., 1993; Watterson et al., 1997
GISS	8° × 10°	4.8	Hansen et al., 1984
UKMO	5° × 7.5°	5.2	Wilson and Mitchell, 1987
UKMO	5° × 7.5°	3.2	Mitchell and Warrilow, 1987
UKMO	2.5° × 3.75°	3.5	Mitchell et al., 1989
CCC	3.75° × 3.75°	3.5	Boer et al., 1992; McFarlane et al., 1992
MPI	1.25° x 1.25° [a]	—	Bengtsson et al., 1996

[a] Time-slice experiments with atmosphere-only ECHAM3 T 106 model.

Source: Watson et al., 1998

Until the last few years, equilibrium GCM experiments were more readily available. This is because it takes less computing time to run a static experiment than a transient experiment. Many impacts studies have relied on static experiments and typically estimate the effects of CO_2 doubling on a sector. Thus, they estimated the potential effects of climate change in the latter half of the twenty-first century. With increased computing power it has become less expensive to run transient experiments. In recent years, the output from transient experiments has been used more frequently in climate change impacts studies. Thus, potential impacts over successive decades can also now be estimated.

The major advantage of using GCMs as the basis for creating climate change scenarios is that they are the only tool that estimates changes in climate due to increased greenhouse gases for a large number of climate variables in a physically consistent manner.[7] The GCMs estimate changes in a host of meteorological variables, e.g., temperature, precipitation, pressure, wind, humidity, solar radiation (Schlesinger et al., 1997), that are consistent with each other within a region and around the world, and thus they fully meet Conditions 1 and 2, and partially satisfy Condition 3.

[7] Although the variables within a GCM are all determined using physical laws, or empirical relationships based on physical laws, validation studies show that the internal relationships between these model variables may not necessarily be the same as the relationships observed in the real world. This is because of deficiencies in the GCM.

Table 3.2 Sample of global coupled atmosphere-ocean general circulation models (transient simulations) used for impact assessment studies.

Group	Model name[a]	Horizontal resolution (number of waves or lat. × long.)	Greenhouse gas scenario[b] (percent/year)	Global surface air temperature change at CO_2 doubling (°C)	References
BMRC	—	3.2° × 5.6°	1	1.35	Colman et al., 1995
GFDL	—	4.4° × 7.5°	1	2.2	Manabe et al., 1991, 1992
MRI	—	4° × 5°	1	1.6	Tokioka et al., 1995
NCAR	5° Ocean	4.4° × 7.5°	1	2.3	Meehl et al., 1993
NCAR	1° Ocean	4.4° × 7.5°	1	3.8	Meehl, 1996; Washington and Meehl, 1996
UKMO	UKTR1	2.5° × 3.75°	1	1.7	Murphy, 1995; Murphy and Mitchell, 1995; Senior, 1995
UKMO	HADCM2	2.5° × 3.75°	1 + aerosols	~2.5	Mitchell and Johns, 1997
MPI	ECHAM1+LSG	5.6° × 5.6°	1.3	1.3	Cubasch et al., 1992
MPI	ECHAM3+LSG	5.6° × 5.6°	1.3 + aerosols	not available	Hasselmann et al., 1993
CSIRO	—	3.2° × 5.6°	1	2.0	Gordon and O'Farrell, 1997
CCC	CGCM1	3.75° × 3.75°	1	2.6	Reader and Boer, 1998 ; Flato et al., 1997
GISS	—	4° × 5°	1	1.4	Russell et al., 1995

[a] If different from group name.

[b] The greenhouse gas scenario refers to the rate of increase of CO_2 used in the model experiments; most experiments use 1 percent per year, which gives a doubling of CO_2 after 70 years (IS92a gives a doubling of equivalent CO_2 after 95 years).

Source: Watson et al., 1998.

A major disadvantage of using GCMs is that, although they accurately represent global climate, their simulations of current regional climate are often inaccurate (Houghton et al., 1996). In many regions, GCMs may significantly underestimate or overestimate current temperatures and precipitation (see Table 3.3). Another disadvantage of GCMs is that they do not produce output on a geographic and temporal scale fine enough for many impact assessments (Condition 3). GCMs estimate uniform climate changes in grid boxes several hundred kilometres across, and although they estimate climate on a daily or even twice daily basis, results are generally archived and reported only as monthly averages or monthly time series. An additional disadvantage of GCM-based scenarios is that a single GCM, or even several GCMs, may not represent the full range of potential climate changes in a region (Condition 4).

Although GCMs have clear limitations for scenario construction, they do provide the best information on how global and regional climate may change as a result of increasing atmospheric concentrations of greenhouse gases. Some of the ways of creating climate change scenarios using GCM output are described in Section 3.5.

3.4.2 Synthetic scenarios

Synthetic scenarios, sometimes referred to as arbitrary scenarios, are based on incremental changes in such meteorological variables as temperature and precipitation. For example, temperature changes of +2°C and +4°C can be combined with precipitation changes of −10 percent or 20 percent or no change in precipitation to create a synthetic scenario (e.g., Poiani and Johnson, 1993; Mendelsohn and Neumann, in press). These incremental changes are usually combined with a baseline daily climate database to yield an altered 30-year record of daily climate.

Synthetic scenarios usually assume a uniform annual change in temperature and other variables over a study area, although some studies have introduced temporal and spatial variability into synthetic scenarios. Robock et al. (1993) developed different synthetic scenarios for annual average change in temperature and precipitation in wet and dry years in the Sahel and Venezuela. Kalvová and Nemešová (1995) developed different seasonal changes in temperature and precipitation patterns for the Czech Republic, but again applied them uniformly across the region. Rosenthal et al. (1995) used different uniform changes in winter and summer temperature across climate zones of the United States. Thus, they included some temporal and spatial variability. All three studies based the selection of synthetic scenarios on outputs from GCMs.

The main advantages of synthetic scenarios are their ease of use and transparency to policy makers and other readers of impacts studies. In addition, synthetic scenarios can capture a wide range of potential climate changes (Condition 4). One can examine small changes in climate (e.g., 1°C) up to large changes in climate (e.g., 5°C to 6°C), and one can examine increased and decreased precipitation scenarios. In addition, because individual variables can be changed independently of each other, synthetic scenarios also help identify the relative sensitivities of sectors to changes in specific meteorological variables. A further advantage of synthetic scenarios is that different studies can use the same synthetic scenarios to compare sensitivities (although assuming the same synthetic scenario across different sites may well violate Condition 2, internal consistency). Synthetic scenarios are inexpensive, are quick and easy to construct, and generally require few computing resources.

A major disadvantage of synthetic scenarios is that they may not be physically plausible (Condition 2), particularly if uniform changes are applied over a very large area or if assumed changes in variables are not physically consistent with each other. As noted above, uniform changes in temperature, and particularly precipitation, are not plausible over large areas. It is important to not arbitrarily select changes in variables such as temperature, precipitation, wind, clouds, and humidity that are not internally consistent with each other. For example, increased precipitation would normally be associated

with increased clouds and humidity.[8] Synthetic scenarios may not be consistent with estimates of changes in average global climate (Condition 1). This last limitation can be overcome by using the outputs of GCMs to guide the development of synthetic scenarios, as was done in each of the three studies cited above.

3.4.3 Analogue scenarios

Analogue scenarios involve the use of past warm climates as a scenario of future climate (temporal analogue scenario), or the use of current climate in another (usually warmer) location as a scenario of future climate in the study area (spatial analogue scenario).

3.4.3.1 Temporal analogue scenarios

Temporal analogue scenarios come from one of two sources: the instrumental record (weather observations) or the paleoclimatic record. A major study of climate change impacts in the United States, the Missouri-Iowa-Kansas-Nebraska (MINK) study (Rosenberg, 1993), used the instrumental record from the 1930s, a very dry and hot period in the upper Midwest (approximately 1°C warmer than 1951-1980), as an analogue for climate change. An advantage of using the instrumental record as the basis for a climate change scenario is that climate change data are available on a daily and local scale (Condition 3), which is a finer temporal and spatial resolution than that usually provided or archived by GCMs.

Some researchers have suggested using warm periods from the paleoclimate record to create scenarios of climate change (e.g., Shabalova and Können, 1995). The advantage of using paleoclimate data over instrumental data for climate change scenario construction is that temperature differences in the distant past compared to current climate tend to be greater than those within the instrumental record, and may therefore be more consistent with potential changes in average global temperature over the next century (Condition 1). However, collecting or collating the relevant paleoclimate data for the required region may be a costly and time-consuming exercise.

The major disadvantage of using temporal analogue climates for climate change scenarios is that the changes in past climates were unlikely to have been caused by increased greenhouse gas concentrations. It is more likely that these changes were caused, for example, by changes in the Earth's rotation around the sun. The reasons for the warming in the 1930s are uncertain. Thus, these scenarios are not based on human-induced increases in greenhouse gas concentrations (Condition 1). A potential

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[8] The more meteorological variables being used in a scenario, the more care is needed when relying on synthetic scenarios. Arbitrarily assigning values to many variables risks selecting a set of outcomes that is not physically plausible. Climate models may be more attractive to examine larger sets of climate variables.

disadvantage of analogue scenarios based on instrumental records is that complete instrumental records for the period in question may not exist in many countries. A further disadvantage of paleoclimate scenarios is that data are generally available only for seasonal changes in temperature and precipitation. In addition, paleoclimate data are not available in many locations, particularly in tropical areas. Furthermore, temporal analogue scenarios (except those from millions of years ago, which have very low resolution of data) tend to be at the low end or even below the range of potential future climate warming, thus violating Condition 4.[9]

3.4.3.2 Spatial analogue scenarios

Some studies used other regions with warmer climates than the area of study as a spatial analogue of climate change. For example, Parry et al. (1988) used Scotland as a spatial analogue for the potential future climate in Iceland and Kunkel et al (1998) transposed warmer climates from south and south-west of the Great Lakes over the Great Lakes to investigate changes in runoff and lake thermal structure. An advantage of spatial analogues is that they can be used to examine how social and natural systems have adapted to different climates (Parry et al., 1988; Mendelsohn et al., 1994). Such scenarios can be particularly helpful in examining the potential for adaptation to minimise adverse effects of climate change. They also provide an often graphic means of communicating the broad significance of climate change to the public. Spatial analogues can also introduce changes in spatial and temporal variability (Kunkel et al., 1998). The disadvantage of spatial analogue scenarios is that, because of geographical and other differences, the future climate in the study area is unlikely to be the same as the current climate in another location (Carter et al., 1994), even if the average annual temperature may be similar. Thus, the level of detail available from an analogue site may give a false sense of precision and may violate Conditions 1, 2, and 4. Furthermore, extensive continental or global climate data sets are necessary to search for an analogue region, and such data sets may not be easy to obtain.

3.4.3.3 Final thoughts on analogue scenarios

Since temporal analogues of global warming were not caused by anthropogenic emissions of greenhouse gases and because spatial analogues are unlikely to be plausible scenarios of future climate change, the climate change impacts assessment literature has generally recommended that these types of scenarios not be used (IPCC, 1990; Carter et al., 1994). If they are used, they should be used only under two conditions. The first is that the limitations of this approach should be clearly explained, pointing out that analogue scenarios may not be accurate representations of greenhouse gas induced climate change. The second is that other approaches such as synthetic or GCM based

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[9] Scenarios with relatively low levels of temperature change can be useful in identifying potential climate change impacts early in the next century.

scenarios are also used in the same study. This will help ensure that a broader range of climate changes is included in the scenarios.

3.4.4 Combinations of options

None of the above options fully satisfies all four scenario selection conditions. Sulzman et al. (1995) therefore recommend using a combination of scenarios based on outputs from GCMs and synthetic scenarios. They advocate using GCM-based scenarios because they are the only ones explicitly based on changes in greenhouse gas concentrations. Synthetic scenarios complement GCM scenarios because they allow for a wider range of potential climate change at the regional level and are easier to construct and apply. Harrison et al. (1995) also use both GCM and synthetic scenarios in their assessment of climate change and agriculture in Europe, arguing that synthetic scenarios allow the sensitivity of the impact models (in their case crop models) to climate change to be more clearly established than do GCM scenarios. GCM scenarios were subsequently used in their study to determine a more plausible range of climate change impacts.

Table 3.3 Table of scenario construction methods and requirements[a] .

Scenario method	Assumptions	Type of result[a]	Limitations	Required data	Cost[b]	Time demand	Computing demand	Required analyst skill
Non-model based								
Synthetic	A sensitivity scenario; result may be implausible	Typically, uniform climate change across a region and seasons	Climate will most likely not change uniformly across regions and seasons	Need to obtain observed data (min 30 year)	Zero	Low	Zero	Low
Analogue — spatial	Climate in another location can serve as a plausible scenario of future climate	Description of mean M climate	Topography is unimportant in shaping climate	Extensive continental or global climate data	Low	Low/medium	PC	Some understanding of climate diagnostics
Analogue — temporal	Historical or paleoclimate periods can serve as scenarios of climate change	Description of climate patterns and D or M variability	Past warm periods not caused by human activities, e.g., greenhouse gas emissions	Extensive historic climate data series for the region concerned	High for collecting paleoclimate data; low for historical record	Low for historical data, can be high for paleoclimate data		
Model-based								
Simple climate models (SCMs)	Reduced-form models can mimic the behaviour of GCMs	Global-mean temperature and sea-level	SCMs do not give regional variation	Combine with 30 years observed data	Very low	Low	PC	Low
General circulation	The model simulates the	300-600 kilometres	Grid boxes have	Maybe some data for validation	Low/medium	Medium	PC or workstation	Modest

models (GCMs)[c]	important climate processes well	resolution; M or D data; mean or time series	low resolution	purposes; combine with 30 years observed data	(maybe large data storage requirement)

Table 3.3 Table of scenario construction methods and requirements[a] (continued).

Scenario method	Assumptions	Type of result[a]	Limitations	Required data	Cost[b]	Time demand	Computing demand	Required analyst skill
Regional climate models (RCMs)[d] — existing	The models have higher resolution than GCMs so they simulate the important climate processes well	25-100 kilometres resolution; M or D data; mean or time series	RCMs use boundary conditions from GCMs, so may not correct for errors	May be some data for validation purposes; may need to combine with 30 years observed data	Low/medium	Medium	PC or workstation (maybe large data storage requirement)	Modest
Regional climate models (RCMs)[d] — new	The models have higher resolution than GCMs so they simulate the important climate processes well	25-100 kilometres resolution; M or D data; mean or time series	RCMs use boundary conditions from GCMs, so may not correct for errors	Extensive data for initialisation and validation; may need to combine with 30 years observed data	Very high	Very high	High; workstation or mainframe computer	Extensive knowledge of climate modelling
Empirical downscaling[d]	Use existing relationships to calculate small-scale climate	Site or catchment specific time series; D or M data	Synoptic-scale relationships are constant over time	Extensive D or M series of synoptic and/or surface climate variables	High, if data to be purchased	High	Substantial; PC or workstation	Some understanding of climate dynamics
Weather generators (WGs)[d]	Weather can be described as a stochastic process	Site or grid specific time series; D data		Extensive D weather series for sites and/or grids	High, if data to be purchased	Medium/high	PC	Some understanding of the statistical properties of weather series

[a] D = daily data; M = monthly data.

[b] Costs for obtaining observed data are generally low to medium.

[c] It is assumed that people will use existing GCM results, and not run their own.

[d] These methods must all be used in conjunction with GCM results.

3.5 Issues in selecting and designing climate change scenarios

A number of issues beyond the four conditions introduced in Section 3.3 should be considered when selecting or designing climate change scenarios. Consideration of these issues may affect the selection of a generic option from the alternatives described in the previous section. Table 3.3 summarises some of the advantages and disadvantages of these and other approaches.

3.5.1 Using GCMs for scenario construction

3.5.1.1 Equilibrium experiments

Climate change scenarios obtained from equilibrium GCM experiments describe an average climate of the future. These scenarios assume an abrupt change in climate conditions between "now" and many decades in the future, often when 2×CO_2 concentrations are reached. In many cases, observations in the baseline climate data set are perturbed by adding to them, or multiplying them by, changes in monthly or annual temperature and precipitation derived from the equilibrium GCM experiment (an equilibrium scenario can also include a change in interannual climate variability; see Section 3.5.3). An example of where equilibrium climate change scenarios have been used is provided in Section 3.6.1.

There are two distinct disadvantages of equilibrium scenarios, particularly those derived from 2×CO_2 experiments using GCMs. The first is that the equilibrium climate change caused by CO_2 doubling will probably not be realised for many decades (Kattenberg et al., 1996). Indeed, under some emissions scenarios such doubling may be delayed until the twenty-second century, or may never occur (Wigley et al., 1996). These scenarios would only be realised well beyond the time horizon of most policy makers. The second disadvantage is that it is unlikely that atmospheric greenhouse gas concentrations will ever remain at a level constant enough to enable an equilibrium climate to be reached. Climate will always be adjusting to different forcing factors, and an equilibrium climate will be the exception, not the norm. Indeed, if greenhouse gas emissions go unabated, it is probable that atmospheric concentrations of greenhouse gases will eventually substantially exceed 2×CO_2 levels (Wigley et al., 1996).

3.5.1.2 Transient experiments

These two problems with equilibrium scenarios may be addressed by using results from transient climate model experiments. Climate change scenarios derived from transient experiments describe how climate may change over time. A transient scenario would typically start with current (baseline) climate and estimate year-by-year changes in climate for up to 100 years into the future. Again, observations in the baseline climate

data set are perturbed by adding to them, or multiplying them by, changes in monthly or annual temperature and precipitation derived from the transient GCM experiment. Under transient scenarios, the climate is never assumed to be in equilibrium with greenhouse gas concentrations, and the possible climate for each year through the twenty-first century is described. Transient scenarios can therefore be used to examine the potential effects of climate change over time and potential impacts within shorter planning horizons.

Transient scenarios also have some disadvantages, however. If results are taken from a "cold start" transient experiment (see Section 3.4.1), then it is not realistic to attach specific calendar years to the model years because such experiments underestimate climate change in the first decades of the experiment. Some adjustment technique is necessary to make this conversion (see Section 3.5.1.3 for an example of such a technique). Also, it is harder to define the "true" greenhouse gas signal from a transient climate change experiment than from an equilibrium experiment. This is because the natural variability of climate is better simulated in a transient GCM, and this can obscure the greenhouse gas signal for many decades (Santer et al., 1996; Mitchell et al., in press). Whether or not this is important for climate change scenario purposes depends on whether it is desired that the scenario contain both natural variability and greenhouse signal.

3.5.1.3 Attaching calendar years to GCM scenarios

An alternative approach to using the output from equilibrium or transient GCM experiments directly in a climate change scenario involves using the results from experiments performed with simple one-dimensional models, often called upwelling- diffusion (UD) or simple climate models (SCMs). This approach involves three stages (Hulme et al., 1995): defining the standardised pattern of change using a GCM experiment (i.e., regional changes in meteorological variables such as temperature and precipitation are divided by the global warming of that model experiment yielding a ratio); defining the magnitude of global warming from an SCM; and then scaling the pattern by this global warming value. An example of this approach to scenario construction is described in Section 3.6.3 and Box 3.1. The example shows how the scenario tool SCENGEN can be used to create scenarios for the middle of the twenty-first century.

The advantage of this linked-model approach to scenario construction is its versatility. Any range of emissions scenarios can be entered into the SCM to yield a range of global warming projections over the next 100 years or so, thus satisfying Conditions 1 and 4. By selecting the required time horizon (e.g., 2050, or the average of the period from 2030 to 2060), the transient global warming estimate or range of estimates can be extracted. This global warming value is then used to scale the standardised pattern of regional climate change that has been extracted from a GCM experiment (or number of GCM experiments to satisfy Condition 4) to yield a derived transient scenario of climate change for a given year or period. This scenario can then be added to the

baseline climatology, ensuring that the global warming value has been calculated from the correct baseline (e.g., 1951-1980 or 1961-1990).

Box 3.1 Using SCENGEN to construct climate change scenarios for Estonia.

SCENGEN was used to construct climate scenarios for Estonia for the UNEP country vulnerability study. The SCENGEN CD-ROM was prepared by the Climatic Research Unit at the University of East Anglia, United Kingdom, and requires a Pentium PC running Windows 95. The version of SCENGEN used contained results from a set of 14 GCMs and the one-dimensional integrated simple climate model MAGICC, which consists of a carbon cycle and other greenhouse gas modules, an UD climate module, and ice melt modules.

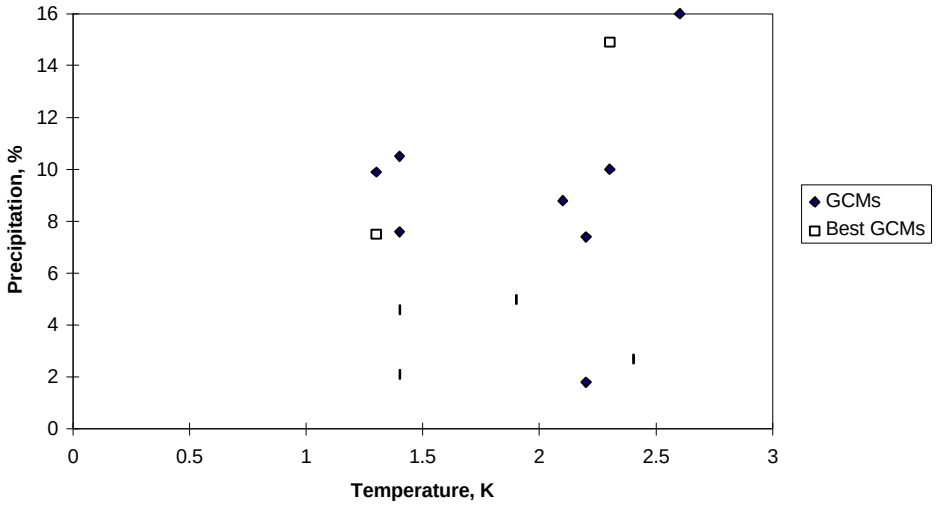
Estonia is situated between $57^0$30'N and $59^0$40'N and between $21^0$46'E and $28^0$13'E. The 25^0 meridian divides the country into two nearly equal parts that fall into different $5^0 \times 5^0$ grid boxes. Since the area of Estonia is only 45,215 square kilometres, climate change scenarios were considered to be uniform over the whole country. They were obtained by averaging the SCENGEN estimates of the two grid boxes. When necessary, linear interpolation was used for spatial downscaling.

For hydrological and agricultural modelling, knowledge of the annual cycle of meteorological elements is essential, so all climate scenarios were constructed with a monthly resolution. From the eight meteorological elements offered by SCENGEN, mean temperature and precipitation changes were chosen. All changes were given for 2085-2115 (i.e., 2100) with respect to 1961-1990. For some scenario users, shorter time horizons (e.g., with a resolution of 10 years) were also made available.

Once time horizons and spatial-temporal resolution are decided, SCENGEN offers the user three choices: Which emissions scenario? Which MAGICC model parameters? Which GCMs? The first two choices together determine the global warming projections. Although a variety of emissions scenarios with some measures of environmental regulation are available, only three IPCC scenarios were used: IS92c as a low emissions scenario, IS92a as a central scenario, and IS92e as a high emissions scenario. MAGICC presents an uncertainty range for the following parameters: CO_2 emissions from land-use changes, indirect aerosol radiative forcing, ocean upwelling rate, and climate sensitivity. By combining these ranges of input parameters and the three emissions scenarios, a central estimate (2.1 K) and two extremes (0.8 and 5.5 K) of global mean annual warming by 2100 with respect to 1961-1990 are obtained. The extremes were rejected, however, and instead a minimum warming was determined from a combination of low emissions (IS92c) and low climate sensitivity (1.5 K), and maximum warming was determined using the high emissions scenario (IS92e) and the high climate sensitivity (4.5 K). Other MAGICC parameters were kept at their default values, although only constant aerosol forcing was allowed. These emissions and parameter choices gave a range of global warming of 0.9 to 4.7 K by 2100, a range that meets Condition 1. This range differs from the 1.5 to 4.5 K range for the climate sensitivity because CO_2 doubling occurs at different times for different emissions scenarios. MAGICC also gives a range of CO_2 concentrations and sea-level rise estimates for these emissions and parameter choices and these values were used directly in the regional climate change assessments.

The selection of the GCMs was made with the help of the histogram shown here and considering the criteria for GCM selection discussed in Section 3.4.1. To construct the histogram, the central global warming projection for 2050 was used (IS92a emissions and a climate sensitivity of 2.5 K). As a result, two GCMs were selected: HADCM2, representing a less warm and less wet scenario, and ECHAM3TR, representing a warmer and wetter scenario for Estonia (Condition 4). The seasonal changes of mean temperature and precipitation in Estonia by 2100 with respect to 1961-1990 are shown in the table.

Most probable annual changes in Estonia by 2050 with respect to 1961-1990 according to 14 global climate models



Changes in annual mean temperature and precipitation by 2036-2065 (i.e., 2050) with respect to 1961-1990 for Estonia according to the 14 general circulation models used in SCENGEN. The two selected GCMs are marked in red as the 'best' GCMs
Seasonal changes in mean temperature and precipitation for Estonia by 2100 with respect to 1961-1990 according to the selections chosen in SCENGEN.

Season	Temperature change (K)			Precipitation change (percent)		
	Minimum	Central	Maximum	Minimum	Central	Maximum
HADCM2						
Winter	0.9	2.8	5.2	5	15	27
Spring	0.8	2.4	4.4	5	13	25
Summer	0.6	1.8	3.4	6	16	30
Autumn	0.9	2.4	4.5	5	14	26
ECHAM3TR						
Winter	1.9	5.2	9.8	12	35	65
Spring	1.3	3.8	7.0	14	39	73
Summer	0.9	2.6	4.9	2	6	12
Autumn	1.5	4.4	8.2	10	28	52

These scenarios show the climate of Estonia getting warmer and wetter. The warming is greater than the global mean and strongest in winter and autumn. Little can be said about the annual cycle of precipitation change, since there is little agreement between the seasonal results of the two GCMs.

It should be noted that this version of SCENGEN does not take into account the cooling effect of aerosols on regional climate. The projections in the table are therefore probably overestimated, since Estonia is situated in a region where anthropogenic aerosol emissions, and hence climatic effects, are likely to be significant.

This approach makes one or two assumptions about the nature of greenhouse-gas-induced climate signals. It assumes that the pattern of anthropogenic climate change can be adequately defined from a 10- or 30-year period of a GCM experiment, whether

equilibrium or transient; and it then assumes that this pattern remains constant over time (i.e., the magnitude is scaled by the global warming but the pattern is constant).

This is an assumption that is difficult to test and may violate Condition 2. Furthermore, many transient experiments have not displayed a consistent pattern in change variables such as precipitation. The pattern of precipitation and temperature often changes over the transient simulation. In some cases the sign of precipitation change may change over the simulation. On the other hand, the assumption has formed the basis for recent climate change fingerprint detection studies, which have yielded evidence that anthropogenic forcing of climate can be detected in the observations (Santer et al., 1996). These issues of changing patterns over time have been explored by Mitchell et al. (in press).

3.5.2 Which GCMs to select?

Many climate change experiments have been performed using GCMs: between 25 and 35 equilibrium experiments and about 10 transient experiments (see Gates et al., 1992; Kattenberg et al., 1996). If a GCM-based scenario is to be constructed, selecting which GCMs to use from this population of experiments may be difficult. In some cases the choice may be limited by which GCMs have archived their results in an accessible and public form and whether the required climate variables are included. But, assuming that the user is in a position to choose from this population, which GCMs should be chosen? A number of criteria can be used to make this decision.

3.5.2.1 Vintage

Results from GCM climate change experiments performed as long ago as 1983 are still in circulation. It may be argued that owing to developments in the science and modelling of climate change, only the most recent experiments should be used. But this is an arbitrary criterion to apply, and does not adequately reflect the nature and development history of different climate models.

3.5.2.2 Resolution

As climate models have developed, there has been a general tendency toward increased spatial resolution. Some of the early GCMs operated at a resolution of 800 kilometres, whereas some of the more recent GCMs are now operating at about 300 kilometres. Although higher resolution GCMs yield results that contain more spatial detail, they are not necessarily always superior to the lower resolution versions. For example, in areas of complex topography, such as mountainous areas like the Himalayas or the Andes, or areas with large lakes, such as equatorial East Africa, even high resolution GCMs do not adequately simulate regional climate patterns.

3.5.2.3 Validity

A stronger argument than either vintage or resolution may be to select the GCM that simulates the present climate of the study region most accurately, on the assumption that this GCM would also yield a more accurate representation of future regional climate. This approach has been used in a number of scenario construction exercises, e.g., Benioff et al. (1996); Box 3.2 describes how the Ethiopian country studies team selected GCMs for their assessment of climate change impacts based on how well the models simulate current climate patterns over Ethiopia. Note that the Ethiopians also used model resolution as a factor in their selection. The control climate of a number of GCMs is compared with the observed baseline climate — means, climatic spatial patterns, monthly variability — and the GCMs that are closest to reality are then used to generate the scenario. One convenient measure of similarity between two climates (e.g., a model and an observed climate) is the spatial pattern correlation coefficient.

This provides an objective measure of how well a GCM can reproduce the regional or global observed pattern of climate (e.g., Smith and Pitts, 1997). Note, however, that this criterion does not guarantee that the GCMs selected will yield the most reliable results.

3.5.2.4 Representativeness of results

A further criterion that can be used when selecting GCMs is to consider the representativeness of each GCM's results. Thus, for example, if three GCMs are to be selected for a scenario construction exercise, one might choose a GCM that gives a magnitude of change fairly typical of the population of GCM experiments, together with GCMs that give results at the low and high end of the range of results (Box 3.1 describes how the Estonian country studies team used SCENGEN to develop a range of climate change scenarios). This may be particularly relevant when examining precipitation changes, since the climate change patterns of this variable show the greatest differences from model to model. Thus, a GCM that shows a drying pattern over the region, together with ones that show little change and a wetting pattern, may be chosen deliberately to meet Condition 4. This combination of GCMs can be used even though the selected GCMs may not necessarily be the "best" models. This approach to choosing GCMs was adopted in the regional impacts assessment for southern Africa (Hulme et al., 1996). Here, the "core" scenario was based on the GCM that, out of the sample of 11 GCMs examined, correlated best with the observed climate (i.e., using the validity criterion), and two other GCMs were chosen to capture the extreme range of regional precipitation changes simulated by the 11 experiments (i.e., using the representativeness criterion).

Box 3.2 Climate change scenarios for Ethiopia.

Ethiopia participated in the U.S. Country Studies Program (Dixon et al., 1996) and conducted a study on vulnerability and adaptation of agriculture, water resources, and forests. Five GCM models were examined for use in the study: Canadian Climate Centre Model (CCCM; Boer et al., 1992); Geophysical Fluid Dynamics Laboratory R-30 model (GFDL-R30; Wetherald and Manabe, 1988); Geophysical Fluid Dynamics Laboratory's transient model (GFDL-transient; Stouffer et al., 1989); United Kingdom Meteorological Office (UK89; Mitchell et al., 1989); and Goddard Institute for Space Since (GISS; Hansen et al., 1983). The baseline climate was developed using 1961-1990 climate data. The climate variability study used computing averages, standard deviation, moving averages and identification of dry and wet years for rainfall, and averages and moving averages for temperature.

Evaluating and Creating the GCM Scenarios

GCM output was evaluated on a seasonal basis. The 1961-1990 climatological data from selected stations were organised to develop climatological maps in compatible units of measurement. For example, a rainfall baseline map was prepared in mm/day. The evaluation involved comparison of the current model simulation with the observations to test performances. GCM outputs provided by the NCAR were analysed in a 0-20□N and 30-50□E window. Models that better reflect the observed climate were then selected by adopting the following criteria.

Comparison of results of current simulation with average climate (temperature and rainfall). Grads software (Doty, 1992) was used to produce $1xCO_2$ GCM output maps for the region being studied. Observed data and $1xCO_2$ outputs from the GCMs were compared based on the location, the magnitude (how significantly the GCM under or overestimates climate), and the numbers of maxima and minima. The gradient and how accurately the model simulates the marginal areas (the boundary between the lowlands and the highlands) were also examined.

Model resolution. Most models have low resolution, do not parameterise the physiographic nature of different places well, and use a generalised topography. Since Ethiopia has different types of terrain, the low resolution models give exaggerated estimates.

Trend match. In addition, validation was done on a station-by-station basis. Interpolated GCM outputs were used for selected stations. GCM outputs were compared to actual climate data. Trends and the trend match between the two results were studied (see figure).

Validation assessment was done for Kiremt (June-September), Belg (February-May), and Bega (October-January) on a seasonal basis.

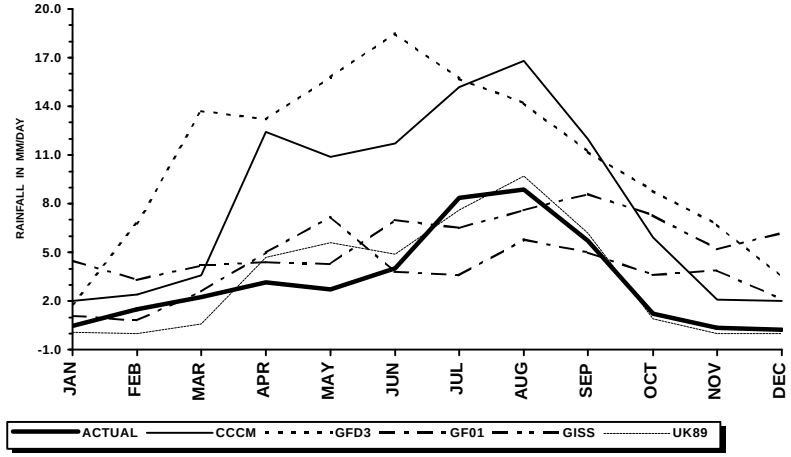
General Observations:

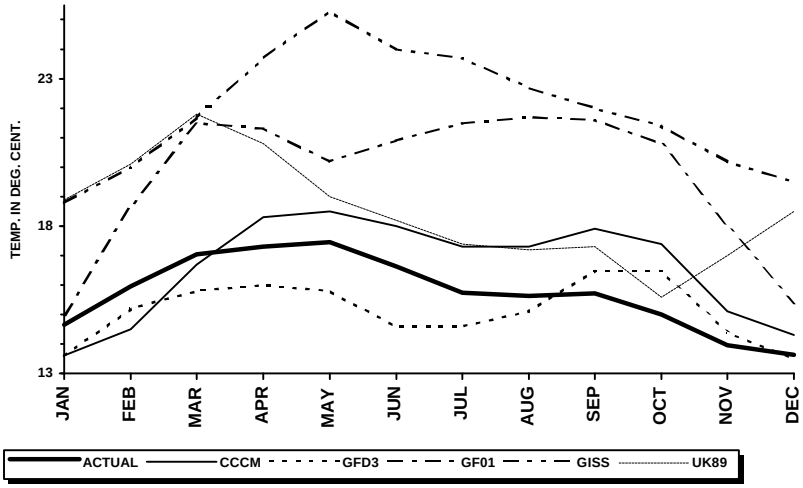
- All models simulated only one rainfall maximum for the country whereas the actual shows three to four high rainfall pocket area.
- None of the models could discriminate between the lowlands and the adjoining highlands. This may be because of the inherent problem of the models using smoothed topography.
- All models were weak in identifying the high rainfall zone in the eastern highlands and overestimated the rainfall of the northern Rift Valley.
- All models overestimated the rainfall over the north-western and south-eastern lowlands, particularly for the Belg season.
- Most models could not discriminate the temperature gradient between the lowlands and the adjoining highlands.

- Most models underestimated the simulations of the northern Rift Valley and the south-eastern lowlands.

All model simulations show increasing temperature trends from the central highlands toward the east.

Comparison of Observed and GCM Estimates of Current Climate Rainfall and Temperature for Addis Ababa





Conclusions

One transient and two equilibrium GCM models that best simulate the mean climate were selected: CCCM, GFDL-1989, and GFDL-transient. UK89 and GISS were not used.

In developing scenarios, the G*ridpti* program (developed by NCAR; interpolates between the four nearest grid points in a GCM to develop an estimate for a specific location, and grid points are weighted based on the inverse of distance) was used to extract temperature differences and rainfall ratios from the GCMs selected for all stations. Equilibrium GCM scenarios were then prepared by combining the difference between $2xCO_2$ and $1xCO_2$ and observed data for temperature, and by combining the ratios of $2xCO_2$ to $1xCO_2$ and observed data for rainfall. Transient GCM scenarios were also developed by combining the decadal differences with the observed data for both rainfall and temperature. Synthetic (incremental)

scenarios were developed by assuming 2°C and 4°C increases to the observed mean for temperature and by adding -20, -10, 0, +10, and +20 percent changes to the observed mean for rainfall.

3.5.3 Changes in mean versus changes in variability

Most studies of potential climate change impacts have assumed changes in average climate conditions, but not in climate variability. These scenarios assume that only average annual or average monthly variables, such as temperature and precipitation, change. Each day within a month or year is assumed to have the same absolute change in temperature and the same percentage change in precipitation. Thus, the pattern of daily climate and the interannual variability of climate stays approximately the same.

These scenarios are commonly used for two main reasons. First, there is uncertainty about how climate change will affect the temporal variability of climate. Perhaps the biggest source of interannual climate variability in the tropics and elsewhere is the El Niño/Southern Oscillation (ENSO) phenomenon. It is still unclear whether ENSO events will change character in response to climate change (e.g., see Trenberth and Hoar, 1996). Elsewhere, there are some advances in the scientific understanding about changes in climate variability (see Kattenberg et al., 1996). Second, changes in average climate only are used in a scenario since they are relatively easy to apply (e.g., Benioff et al., 1996). The average temperature change for a particular month is added to all the observed temperatures in that month in the climate baseline, and the change in precipitation (e.g., 1.1 for a 10 percent increase) is multiplied by the days with observed precipitation.

Although hard to specify, it is most likely that climate variability will change as a response to greenhouse gas forcing. For example, Whetton et al. (1993) examined a number of GCM experiments and found that precipitation intensity and flooding increased over most of Australia; Hulme et al. (1996), in their scenario for southern Africa, included changes in interannual rainfall variability. Changes in climate variability can have a more dramatic effect on many agriculture and water resource systems than changes in the mean alone. Mearns et al. (1996), for example, found that wheat yields in the Great Plains of the United States are very sensitive to changes in interdaily temperature and precipitation variability. Ideally, therefore, climate change impacts studies should consider changes in both interannual and interdaily variability.

One way in which changes in daily climate variability can be incorporated into a scenario is through the use of a weather generator (e.g., Wilks, 1992). A weather generator is calibrated on the baseline climate data. The parameters of the generator, including the variability parameter, are then altered in a way that is consistent with the climate scenario, whether it is derived from GCMs or from analogue or synthetic sources. Using the new, altered, parameters, a new sequence of daily scenario weather is created in which the daily variability of climate is now changed. This approach has been followed in a number of studies, including Semenov and Barrow (1997) in their assessment of climate change impacts on European agriculture. Weather generators

require large historical daily weather data sets, which may be difficult to acquire, and constructing scenarios using them can be quite time consuming.

One aspect of climate variability that weather generators cannot yet capture is changes in the interannual or interdecadal variability of climate. These low frequency aspects of climate are not well simulated by stochastic generators, and therefore changes in these frequencies are difficult to incorporate into climate scenarios. Mearns et al. (1992) examined the effect of changes in monthly variability on crop yields in Kansas. They modified interannual variability of a historical record (1951- 1980) of monthly temperature and precipitation and developed a monthly time series with double, quadruple, one-half, and one-quarter the observed interannual variance. Daily changes in precipitation were adjusted to be consistent with the monthly changes.

3.5.4 Spatial variability

There are a number of options for manipulating the spatial variability of a climate change scenario. Some scenarios contain only a uniform change in climate over an area. For example, Mendelsohn and Neumann (in press) used a synthetic scenario and assumed a uniform change in temperature and precipitation over the United States. Other studies use the regional changes in climate defined by GCM grid boxes, each of which may be between 250 and 600 kilometres. Because of the lack of precision about regional climates in a GCM, Von Storch et al. (1993) advocate that in general the minimum effective spatial resolution should be defined by at least four GCM grid boxes. The skill of GCM simulations for an individual grid box will depend, however, on the spatial autocorrelation of the particular weather variable. Smith and Tirpak (1989) assumed uniform changes within each GCM grid box, whereas Smith et al. (1992) interpolated between the four nearest GCM grid points down to 0.5° latitude/ longitude (about 50 kilometres) pixels. This latter technique is the simplest form of downscaling from a GCM resolution to the sort of spatial resolution more commonly used in impacts studies.[10]

3.5.4.1 Downscaling

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[10] Smith et al., (1992) interpolated on the basis of linear averaging by the inverse of distances between the specific point and the GCM grid points. The basic formula for temperature is

$$\frac{\sum_{i} 1(i/D_i)}{\sum_{i} 1(1/D_i)} \cdot T_{i1x} \ ,$$

where

D_i is the distance from the site to grid point i, and

More sophisticated downscaling techniques calculate subgrid box scale changes in climate as a function of larger-scale climate or circulation statistics. The two main approaches to downscaling have used either regression relationships between large- area and site-specific climates (e.g., Wigley et al., 1990) or relationships between atmospheric circulation types and local weather (e.g., Von Storch et al., 1993). When applied to daily GCM data, these techniques offer the prospect of generating daily climate change scenarios for specific sites or catchments and therefore meet Condition 3 for a climate change scenario. The disadvantage of downscaling approaches is that they require large amounts of observed data to calibrate the statistical relationships and can be computationally very intensive. Such methods are also very time consuming since unique relationships need to be derived for each site or region. Downscaling methods are also based on the fundamental assumption that the observed statistical relationships will continue to be valid in the future under conditions of climate change. This assumption may violate Condition 2 for a climate change scenario.

3.5.4.2 Regional models

Downscaling techniques are statistical methods for generating greater spatial variability in a climate change scenario. An alternative approach involves the use of high resolution regional climate models (RCMs; also called limited area models, LAMs). Regional climate models are typically constructed at a much finer resolution than GCMs (often 50 kilometres), but their domain is limited to continents or subcontinents. Although RCMs yield greater spatial detail about climate, they are still constrained at their boundaries by the coarse-scale output from GCMs. To an extent, therefore, the performance of an RCM can only be as good as that of the driving GCM. A number of RCM climate change experiments have now been performed over North America (e.g., Giorgi et al., 1994; Mearns et al., 1997), Europe (e.g., Jones et al., 1995), Australia (Walsh and McGregor, 1997), and parts of Asia (e.g., India; Bhaskaran et al., 1996), but their performance in relation to downscaling techniques has not yet been fully evaluated. The costs of establishing a regional climate model for a new region and running a climate change experiment are extremely high, both computationally and in terms of human resources. For the moment, it remains premature for regional model output to be used extensively in climate impacts assessments, at least for most regions.

3.5.5 Simulations of greenhouse gas forcing alone and in combination with other factors

Until the last few years, GCMs did not consider the regional effects of sulphate aerosols in their simulations of future climate. They modelled only the effect of increased greenhouse gas concentrations on global and regional climate. It has now become evident that aerosols from fossil fuel consumption and from biomass burning can have a

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$T_{i\ 1x}$ is the $1XCO_2$ value for the temperature at grid point *i*.

significant cooling effect in some regions of the world (Charlson et al., 1992; Taylor and Penner, 1994).

A small number of climate change experiments have attempted to simulate the combined effect of greenhouse gas increases and aerosol changes on global climate. For example, Mitchell and Johns (1997) found that some regional climate changes, both temperature and precipitation, are considerably different when aerosol effects are included. This is an important new development in our understanding of climate change, but the full implications of this for climate change scenario construction have not yet been worked through.

Model experiments that incorporate other significant forcing factors such as aerosols are likely to yield more plausible scenarios of climate change. Model development is likely to lead to further refinements in the simulation of future climate change, such as including the effects on climate of stratospheric ozone depletion or by treating each greenhouse gas separately rather than as CO_2 equivalents, which has been the case until now. The first such GCM experiments will be completed during 1998.

3.5.6 Consistency in scenarios of CO_2 concentrations, change in climate, and sea level rise

One of the conditions for selecting a climate change scenario is that it be internally consistent. This concerns not only the relationships between climate variables, but also the relationships between other important scenario variables such as sea level rise and atmospheric CO_2 concentration. Ideally, a climate change scenario should also include estimates of changes in these two variables since they are likely to have important environmental impacts (e.g., on coastal regions and on vegetation).

Atmospheric CO_2 concentration is one of the drivers of climate change. A climate change scenario will therefore have assumed, either implicitly or explicitly, a CO_2 concentration. Synthetic scenarios of CO_2 concentration can be created (e.g., 600 ppmv), but it can be difficult to make the CO_2 concentration consistent with the synthetic climate and sea level changes. If a GCM-based scenario is being used, there is usually an explicit assumption of the CO_2 concentration. For example, in an equilibrium experiment, the CO_2 concentration usually doubles from, say, 300 ppmv to 600 ppmv, or in a transient experiment, the concentration may increase by 1 percent per year. In GCM experiments, however, these are strictly speaking equivalent-CO_2 concentrations (i.e., the combined forcing effect of all greenhouse gases); the actual CO_2 concentration will be less than that stated. Many studies make the mistake of assuming that actual doubling of CO_2 concentrations and (equivalent) doubled CO_2 climate are the same.

Since sea level rise is predominantly a result of global warming, the scenario of sea level rise should be consistent with the scenario of global climate change. Warrick et al. (1996) predicts that eustatic sea level (i.e., without considering subsidence or uplift of regional shorelines) will rise by between 15 and 95 cm by 2100. This range of values is based on the same greenhouse gas and aerosol emissions scenarios used by the IPCC to

estimate changes in global average temperatures (Warrick et al., 1996). Impacts researchers should be careful to ensure that scenarios of sea level rise are consistent with their scenarios of climate change.

One way of ensuring such consistency between CO_2 concentration, climate change, and sea level rise in a scenario is to use a simple integrated climate model (Hulme et al., 1995). This type of model, widely used by the IPCC (IPCC, 1997), typically comprises a UD climate model (see Section 3.5.1.3) together with a carbon cycle model and ice melt models. Such a model allows an emissions scenario to be defined by the user and then calculates, using reduced-form physical models of the climate system, the resulting CO_2 concentration, global warming, and global sea level rise for each year from 1990 to 2100. These estimates are fully consistent with each other and can subsequently form the basis for a GCM-based scenario. An example of this approach to scenario construction is described in Section 3.6.3 and Box 3.1. Alternatively, one could base the CO_2 concentrations, climate change, and sea level rise scenarios on a single integrated source such as Houghton et al. (1996).

3.6 Example approaches to scenario construction

In this section we summarise the approach taken to climate change scenario construction by three high profile impacts research activities, the U.S. Country Studies Program, Working Group II of the IPCC, and the various international impacts studies in which the Climatic Research Unit at the University of East Anglia have been involved.

3.6.1 US Country Studies Program

The US Country Studies Program (USCSP) provided financial and technical assistance to 55 countries studying greenhouse gas emissions, mitigation of greenhouse gases, and impacts and adaptation to climate change (Benioff et al., 1996). The USCSP suggested specific approaches for assessing impacts and adaptation. For the use of GCMs in constructing climate change scenarios, the following steps were suggested (Box 3.2; Smith and Pitts, 1997):

- obtain the 1×CO_2 results from the sample of GCM experiments held at the National Center for Atmospheric Research (e-mail address: datahelp@ucar.edu; home page address: http://www.scd.ucar.edu/dss/);
- compare the GCM results with the observed regional climate;
- select the three (or more) GCMs that best reproduce observed climate;
- define the regional patterns of change from these GCM experiments as the difference or ratio between the 2×CO_2 and 1×CO_2 simulations;

- combine these changes with a 30-year baseline climate data set (1951-1980 or 1961-1990);

- follow a simple interpolation procedure (based on the inverse of distance) to downscale the GCM results to individual sites using results from up to four GCM grid boxes.

Synthetic scenarios were also recommended to complement the GCM scenarios. The suggested synthetic scenarios combined changes in mean temperature of 2°C, 4°C, and 6°C with changes in precipitation of ±10 percent, ±20 percent, and no change. Thus, up to 15 synthetic scenarios could be applied to the baseline climate data set.

These USCSP scenario recommendations adequately addressed Condition 2 (the GCM scenarios were physically consistent); Condition 3 (GCM outputs for temperature, precipitation, and solar radiation were provided, and combining the outputs with the baseline climate data provided high spatial and temporal resolution sufficient for impacts models); and Condition 4 (three GCMs captured part of the range of potential changes and the synthetic scenarios captured the rest). The recommendations also suggested that particular applications might require the use of weather generators or more sophisticated downscaling methods. Most of the GCM scenarios were equilibrium ($2\times CO_2$) scenarios, and under some emissions scenarios would not be realised during the twenty-first century. Some of the GCMs provided information that is consistent with Condition 1. In some regions (e.g., low latitude), some of the synthetic scenarios (e.g., high temperature changes) may violate Condition 1.

3.6.2 IPCC Working Group II

As part of the IPCC Second Scientific Assessment in 1995, the Technical Services Unit of IPCC Working Group II commissioned a set of climate change scenarios for use by the 31 Working Group II writing teams. The purpose of these scenarios was to provide a common set of climate data to be used by these authors in their assessment of climate change impacts (Greco et al., 1994).[11]

The scenarios were GCM-based and made use of results from three transient GCM experiments: those performed at Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, USA; the Max Plank Institute (MPI) in Hamburg, Germany; and the Hadley Centre at the UK Meteorological Office (UKMO). The baseline period chosen was 1961-1990, and global maps of mean temperature and precipitation for this period were generated. Two time horizons were chosen for the scenarios: 2020 and

[11] For the Third Assessment Report of the IPCC, due in 2001, a climate scenario and related information data centre has been established to provide a common set of scenario information for impacts assessors. This Data Distribution Centre (DDC) is based jointly at UEA, Norwich, UK and at DKRZ, Hamburg, Germany. A web site with full information can be found at http://ipcc-ddc.cru.uea.ac.uk/.

2050. To overcome the “cold-start” problem of the GCM experiments and because the transient GCM experiments used different forcing scenarios, the GCM results were related to 2020 and 2050 in the following way. A simple UD climate model was used to simulate global warming from 1990 to 2100 assuming the IS92a emissions scenario (Leggett et al., 1992). This yielded global warmings of 0.53°C and 1.16°C by 2020 and 2050, respectively. The GCM results were then searched to find the decades in which these increments of global warming occurred in each experiment, and the three GCM patterns of climate change for these respective decades were extracted.

The WG II scenarios were consistent with the broad range of IPCC global warming projections and the patterns of change were physically consistent, being derived from GCMs (Conditions 1 and 2 were met). No downscaling techniques or weather generators were applied to the scenarios; the results were presented at the original GCM resolution. Only changes in mean temperature and precipitation were extracted, and no variability changes were defined, only changes in mean climate. Condition 3 was not therefore satisfactorily addressed. For this reason the scenario may be regarded as only an “entry-level” scenario. By selecting patterns from three different GCM experiments, some attention was paid to Condition 4, but the range of the WG II scenario changes probably did not reflect the full potential range of regional changes.

3.6.3 Scaling: A scenario generator from the Climatic Research Unit and COSMIC

The Climatic Research Unit at the University of East Anglia has developed a climate change scenario generator that runs on a desktop PC. This approach to scenario construction has been used in a large number of impacts assessments around the world. The software tool is called SCENGEN and is briefly summarised here (see also Hulme et al., 1995; SCENGEN).

SCENGEN allows users to generate global and regional scenarios of climate change based on GCM results of their own choosing. Options exist to select scenarios based either on single GCMs or on groups of GCMs,[12] and the scenarios may be presented simply as change fields for a given global warming or given period, or added to a baseline climatology. As a stand-alone module, SCENGEN is driven by built-in global warming projections derived from two greenhouse gas emissions scenarios. SCENGEN has been designed, however, to be used in conjunction with a UD climate model that contains a full set of climate and sea level models. SCENGEN therefore also generates estimates of future CO_2 concentration and sea level rise. When linked in this way, SCENGEN offers the user complete flexibility about the choice of emissions scenario, a

[12] Combining GCMs averages the regional results of more than one model. It is not necessarily clear that an average of several GCMs is more reliable than a single GCM. An argument can be made that averaging GCMs voids the internal consistency within individual models (Condition 2). Note that SCENGEN does not advocate averaging of GCMs.

range of global warming projections, and a choice about the origin of the global or regional climate change scenario generated. See Box 3.1 for an example of such a scenario developed for Estonia.

SCENGEN displays scenarios at two spatial scales: a global resolution of 5° latitude/longitude and, for a series of predefined regional windows, 0.5° latitude/longitude resolution. At the global scale, change fields of mean monthly, seasonal, and annual precipitation, mean surface air temperature, and mean cloudiness can be displayed at a 5° latitude/longitude resolution. These change fields can be superimposed onto a global baseline climatology to generate "actual" climatologies for future periods. Scenarios for the four regional windows are generated at a 0.5° latitude/longitude resolution using new 1961-1990 baseline climatologies constructed specifically for SCENGEN. Options are identical to those for the global scenarios above, except that a wider range of climate variables can be selected.

SCENGEN meets Conditions 1, 2, and 4 of the climate change scenario construction conditions, but only partially meets Condition 3. It is not clear, however, whether regional climate variables will change in constant proportion with average global changes in temperature. This approach can also be described as providing only entry-level scenarios. The use of downscaling techniques and weather generators would make SCENGEN more useful for many impact analyses.

In addition, the University of Illinois at Urbana-Champaign and the Electric Power Research Institute developed a scenario generator that runs on a desk top PC, called the Country Specific Model for Intertemporal Climate (COSMIC). It allows the user to choose between 7 sulphate emissions scenarios, 10 greenhouse gas stabilisation scenarios (based on the IPCC (Schimel et al., 1996) and the "WRE" stabilisation scenarios (Wigley et al., 1996), outputs from 14 GCM models. The model uses a energy-balance-climate/upwelling-diffusion-ocean model to calculate changes in mean global temperature and sea level on an annual basis out to 2200. COSMIC scales the GCM outputs to 0.5° cells and averages the changes in each 0.5° cell for each of 158 countries (Williams et al., in press). The scaling of the GCMs is done in the same fashion as SCENGEN, although COSMIC scales the difference in precipitation rather than the ratio (Larry Williams, EPRI, personal communication, 1998). Results for changes in temperature and precipitation are given for each month in up to the year requested by the user.

3.7 Conclusions

Table 3.3 summarises the options for creating climate change scenarios, and sources of GCM data, observed data, and climate models are given in Table 3.4. The options range from the rather simple one of using synthetic scenarios to more complicated ones of using analogue data or climate models. The choice should depend not only on the resources that are available, but also on how quickly impacts researchers need the scenarios. Whatever is done, the researchers selecting the scenarios should be sure to

choose a set of plausible scenarios that reflect the range of potential climate change consistent with increased greenhouse gas concentrations in the atmosphere and give the climate data necessary to carry out the impacts assessments.

The art of creating climate change scenarios is an evolving one. With improvements in GCMs and new techniques such as downscaling, RCMs, COSMIC, and SCENGEN, more sophisticated scenarios can be created. Nonetheless, there is fundamental uncertainty about regional climate change. The magnitudes and even direction of change of many important meteorological variables are uncertain. And there is even greater uncertainty about changes in variability and extreme events — changes that may be critical for climate impacts assessment. Users of this handbook should always remember that climate change scenarios do not yield predictions of the future, they only help us to understand the potential implications of climate change and the vulnerability of human and natural systems to this change.

Table 3.4 Sources of scenario information.

GCM Data	
IPCC Data Distribution Centre	Web: http://ipcc-ddc.cru.uea.ac.uk/ Dr. Mike Hulme Climatic Research Unit, University of East Anglia Norwich NR4 7TJ UK Tel: 44-1603-593162, Fax: 44-1603-507784 e-mail: m.hulme@uea.ac.uk Dr. Michael Lautenschlager Deutsches Klimarechenzentrum (DKRZ) 55 Bundestrasse, Hamburg, Germany Tel: 49-404-1173297; Fax: 49-404-1173400 e-mail: lautenschlager@dkrz.de
Hadley Centre model data	Climate Impacts LINK Project Climatic Research Unit University of East Anglia Norwich NR4 7TJ Web: http://www.cru.uea.ac.uk/link Tel: +44 1603 592089; fax: +44 1603 507784 email: d.viner@uea.ac.uk
Assorted GCM data	Roy Jenne/Dennis Joseph National Center for Atmospheric Research (NCAR) Data Support Section/SCD PO Box 3000 Boulder, Colorado 80307-3000 USA Tel: 1-303-497-1215; fax: 1-303-497-1298 email: jenne@ucar.edu Web: http://www.scd.ucar.edu/dss/pub/index.html (see "Country Studies")
MECCA model data	Charles Hakkarinen Manager, Atmospheric Sciences Environment Group Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94304-1344 USA Web: http://www.epri.com/ME2CA/about the CD.html Tel: 1-415-855-2592; fax: 1-415-855-1069

	email: mecca@www.epri.com
CSIRO model data	Roger Jones CSIRO Division of Atmospheric Research Private Bag No. 1 ASPENDALE VIC 3195 Australia Web: http://www.dar.csiro.au/pub/programs/climod/cml.htm Tel: +61 3 9239 4555; fax: +61 3 9239 4444 email: roger.jones@dar.csiro.au

Table 3.4 Sources of Scenario Information (continued).

GCM Data (continued)	
ECHAM Model Data	Deutsches Klimarechenzentrum GmbH Bundesstraße 55 D-20146 Hamburg Germany Web: http://www.dkrz.de/forschung/forschung.eng.html Tel: +49 40 41173 - 275; fax: +49 40 41173 - 400
Weather generators	
LARS weather generator	Micha Semenov IACR Long Ashton Research Station Department of Agricultural Sciences University of Bristol Long Ashton, Bristol BS18 9AF, UK Web: http://www.lars.bbsrc.ac.uk/model/larswg.html Tel: +44 1275 392 181; fax: +44 1275 394 007 email: mikhail.semenov@bbsrc.ac.uk
Richardson WG	Clarence Richardson Grassland Soil and Water Research Laboratory 808 E. Blackland Road Temple, Texas 76502, USA Tel: 817-770-6500; fax: 817-770-6561 email: richards@brcsun0.tamu.edu
Observed global climate data	
NCAR	Roy Jenne/Dennis Joseph National Center for Atmospheric Research Observed daily data can be obtained by contacting Roy Jenne or Dennis Joseph at the address listed above for “Assorted GCM Data” or through e-mail: Email: jenne@ncar.ucar.edu Email: joseph@ncar.ucar.edu
GHCN/CDIAC	GHCN v2 temp consists of monthly means of daily maximum, minimum, and/or mean temperature from 7,280 land surface weather stations. The earliest record is from 1701 and the latest record is from a few months ago. This release includes a wide variety of station metadata such as population and vegetation indicators. It may be obtained free of charge through anonymous ftp. See http://www.ncdc.noaa.gov/ghcn.html for details. GHCN is produced by the National Climatic Data Center/NOAA, the Office of Climatology Arizona State University, and the Carbon Dioxide Information Analysis Center/ORNL/DOE.
Climatic Research Unit	Mark New Climatic Research Unit University of East Anglia Norwich NR4 7TJ Web: http://www.cru.uea.ac.uk/~markn/carbon/ncrc.htm Tel: +44 1603 592702; fax: +44 1603 507784 email: m.new@uea.ac.uk
Simple climate models	
MAGICC	Mike Hulme Climatic Research Unit University of East Anglia Norwich NR4 7TJ Web: http://www.cru.uea.ac.uk/~mikeh/software/magicc.htm Tel: +44 1603 593162; fax: +44 1603 507784

email: m.hulme@uea.ac.uk

References

Bengtsson, L., K. Arpe, E. Roeckner, and U. Schulzweida. 1996. Climate predictability experiments with a general circulation model. *Climate Dynamics* 12, 261-278.

Benioff, R., S. Guill, and J. Lee (eds). 1996. *Vulnerability and Adaptation Assessments: An International Guidebook.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Bhaskaran, B., R.G. Jones, J.M. Murphy, and M. Noguer. 1996. Simulations of the Indian summer monsoon using a nested regional climate model: Domain size experiments. *Climate Dynamics* 12, 573-588.

Boer, G.J., N.A. McFarlane, and M. Lazare. 1992. Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model. *Bulletin of the American Meteorological Society* 5, 1045-1077.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Department of Geography, University College, London.

Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley, J.E. Hansen, and D.J. Hoffman. 1992. Climate forcing by anthropogenic aerosols. *Science* 255, 423-430.

Dixon, R.K., S. Guill, F.X. Makanda, and I. Hlohowskyj (eds). 1996. Vulnerability and adaptation of African ecosystems to global climate change. *Climate Research* 6(2) Special Edition.

Doty, B.E. 1992. Using the Grid Analysis and Display System (GRADS). Department of Meteorology, University of Maryland, College Park. mimeograph.

COSMIC. http://crga.atmos.uiuc.edu/COSMIC/announce.html

Gates, W.L., J.F.B. Mitchell, G.J. Boer, U. Cubasch, and V.P. Meleshko. 1992. Climate modelling, climate prediction and model validation. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Callander, and S.K. Varney (eds). Cambridge University Press, Cambridge, United Kingdom.

Gates, W.L., A. Henderson-Sellers, G.J. Boer, C.K. Folland, A. Kitoh, B.J. McAveney, F. Semazzi, N. Smith, A.J. Weaver, and Q.C. Zeng. 1996. Climate models — evaluation. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Callander, and S.K. Varney (eds). Cambridge University Press, Cambridge, United Kingdom.

Giorgi, F., C. Shields Brodeur, and G.T. Bates. 1994. Regional climate change scenarios over the US produced with a nested regional climate model. *Journal of Climate* 7, 375-399.

Gordon, H.B. and B.G. Hunt. 1994. Climatic variability within an equilibrium greenhouse simulation. *Climate Dynamics* 9, 195-212.

Greco, S., R.H. Moss, D. Viner, and R. Jenne. 1994. *Climate Scenarios and Socioeconomic Projections for IPCC WG II Assessment.* International Panel on Climate Change, Working Group II, Washington, DC.

Hansen, J. G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis. 1983. Efficient three-dimensional global models for climate studies: Models I and II. *Monthly Weather Review* 111, 609-622.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner. 1984. Climate sensitivity: Analysis of feedback mechanisms. In *Climate Processes and Climate Sensitivity, Geophysical Monograph Series,* Volume 29, J.E. Hansen and T. Takahashi (eds). American Geophysical Union, Washington, D.C. pp. 130-163.

Harrison, P.A., R.E. Butterfield, and T.E. Downing (eds). 1995. Climate Change and Agriculture in Europe. Research Report No. 9, Environmental Change Unit, University of Oxford, United Kingdom.

Hasselmann, K., R. Sausen, E. Maier-Reimer, and R. Voss. 1993. On the cold start problem in transient simulations with coupled atmosphere-ocean models. *Climate Dynamics* 9, 53-61.

Henderson-Sellers, A. 1996. Can we integrate climatic modeling and assessment? *Environmental Modeling and Assessment* 1:59-70.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). 1996. *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.

Hulme, M., S.C.B. Raper, and T.M.L. Wigley. 1995. An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy* 23, 347-355.

Hulme, M., J. Arntzen, T.E. Downing, R. Leemans, J. Malcolm, N. Reynard, S. Ringrose, and D. Rogers (eds). 1996. *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region.* CRU/WWF, Norwich, United Kingdom.

IPCC. 1990. *Climate Change: The IPCC Scientific Assessment.* J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds), Cambridge University Press, Cambridge, United Kingdom.

IPCC. 1997. *An introduction to Simple Climate Models used in the IPCC Second Assessment Report.* IPCC Technical Paper II, WMO/UNEP, Geneva.

Jones, P.D., T.M.L. Wigley, and K.R. Briffa. 1994. Global and hemispheric temperature anomalies — land and marine instrumental records. In *Trends '93: A Compendium of Data on Global Change,* T.A. Boden, D.P. Kaiser, R.J. Sepanski, and F.W. Stoss (eds). ORNL/CDIAC-65. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Jones, R.G., J.M. Murphy, and M. Noguer. 1995. Simulation of climate change over Europe using a nested regional climate model. Part 1: Assessment of control climate, including sensitivity to location of lateral boundaries. *Quarterly Journal of the Royal Meteorological Society* 121, 1413-1449.

Kalvová, J. and I. Nemešová. 1995. Czech Republic Climate Change Scenarios. Charles University, Prague. Mimeograph.

Kattenberg, A., F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, and T.M.L. Wigley. 1996. Climate models — Projections of future climate. In *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change,* J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). Cambridge University Press, Cambridge, United Kingdom.

Kunkel, K.E., S.A. Changnon, T.E. Croley II, and F.H. Quinn, 1998. Transposed climates for study of water supply availability on the Laurentian Great Lakes. *Climate Change* 38, 387-404.

Leggett, J., W.J. Pepper, and R.J. Swart. 1992. Emissions scenarios for IPCC: An update. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* J.T. Houghton, B.A. Callander, and S.K. Varney (eds). WMO/UNEP Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Lin, E. 1996. Agricultural vulnerability and adaptation to global warming in China. *Journal of Water, Air & Soil Pollution* 92, 63-73.

Manabe, S. and R.T. Wetherald. 1987. Large scale changes in soil wetness induced by an increase in carbon dioxide. *Journal of Atmospheric Sciences* 44, 1211-1235.

Manabe, S. and R.J. Stouffer. 1995. Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature* 378:165-167.

Manabe, S., M.J. Spelman, and R.J. Stouffer. 1992. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part II: seasonal response. *Journal of Climate* 5, 105-126.

Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan. 1991. Transient response of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part I: annual mean response. *Journal of Climate* 4, 785-818.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1992. Effect of changes in interannual climatic variability of CERES-Wheat yields: Sensitivity and 2×CO_2 general circulation model studies. *Agricultural and Forest Meteorology* 62, 159-189.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1996. The effect of changes in daily and interannual climatic variability on CERES-Wheat: A sensitivity study. *Climatic Change* 32, 257-292.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1997. Mean and variance change in climate scenarios: Methods, agricultural applications, and measures of uncertainty. *Climatic Change* 35, 367-396.

Mendelsohn, R. and J. Neumann (eds). (in press). *The Impacts of Climate Change on the U.S. Economy*. Cambridge University Press, Cambridge, United Kingdom.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The impact of global warming on agriculture: A Ricardian analysis." *American Economic Review* 84(4):753-771.

Mitchell, J.F.B. and T.C. Johns. 1997. On the modification of global warming by sulphate aerosols. *Journal of Climate* 10:245-267.

Mitchell, J.F.B. and D.A. Warrilow. 1987. Summer dryness in northern mid-latitude due to increased CO_2. *Nature* 330, 238-240.

Mitchell, J.F.B., T.C. Johns, and R.A. Davis. (in press). Towards the construction of climate change scenarios. *Climatic Change*.

Mitchell, J.F.B., C.A. Senior, and W.J. Ingram. 1989. CO_2 and climate: A missing feedback? *Nature* 330, 238-240.

Mitchell, J.F.B., T.C. Johns, J.M. Gregory, and S.F.B. Tett. 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376, 501-504.

Noda, A. and T. Ttokioka. 1989. The effect of doubling CO_2 concentration on convective and non-convective precipitation in a general circulation model coupled with a simple mixed layer ocean. *Journal of the Meteorological Society of Japan* 67, 95-110.

Parry, M.L., T. R. Carter, and N. T. Konijn (eds). 1988. *The Impact of Climate Variations on Agriculture.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Poiani, K. A. and W.C. Johnson. 1993. Potential effects of climate change on a semi-permanent prairie wetland. *Climatic Change* 24, 213-232.

Reader, M.C. and G.J. Boer. 1998. The modification of greenhouse gas warming by the direct effect of sulphate aerosols. *Climate Dynamics* 14, 593-607.

Richardson, C.W. and D.A. Wright. 1984. WGEN: A Model for Generating Daily Weather Variables. Agricultural Research Service, ARS-8. U.S. Department of Agriculture, Washington, D.C.

Robock, A., R.P. Turco, M.A. Harwell, T.P. Ackerman, R. Andressen, H.S. Chang, and M.V.K. Sivakumar. 1993. Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Climatic Change* 23, 293-335.

Rosenberg, N.J. (ed). 1993. Towards an integrated impact assessment of climate change: The MINK study. *Climatic Change* (Special Issue) 24, 1-173.

Rosenthal, D.H., H.K. Gruenspecht, and E.A. Moran. 1995. Effects of global warming on energy use for space heating and cooling in the United States. *Energy Journal* 16(1), 41-54.

Rosenzweig, C. and M.L. Parry. 1994. Potential impact of climate change on world food supply. *Nature* 367, 133-138.

Rotmans, J., M. Hulme, and T.E. Downing. 1994. Climate change implications for Europe: An application of the ESCAPE model. *Global Environmental Change* 4, 97-124.

Santer, B.D., K.E. Taylor, T.M.L. Wigley, T.C. Johns, P.D. Jones, D.J. Karoly, J.F.B. Mitchell, A.H. Oort, J.E. Penner, V. Ramaswamy, M.D. Schwarzkopf, R.J. Stouffer, and S. Tett. 1996. A search for human influences on the thermal structure of the atmosphere. *Nature* 382, 39-46.

SCENGEN. http://www.cru.uea.ac.uk/~mikeh/SOFTWARE/scengen.html.

Schimel, D., et al. 1996, Radiative forcing of climate change. In *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second*

Assessment Report of the Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). Cambridge University Press, Cambridge, United Kingdom.

Schlesinger, M.E. and Z-C. Zhao. 1989. Seasonal climatic changes induced by double CO_2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model. *Journal of Climate* 2, 459-495.

Schlesinger, M.E., N. Andronova, A. Ghanem, S. Malyshev, T. Reichler, E. Rozanov, W. Wang, and F. Wang. 1997. Geographical Scenarios of Greenhouse-Gas and Anthropogenic-Sulfate-Aerosol Induced Climate Changes. Climate Research Group, Department of Atmospheric Sciences, University of Illinois, Urbana-Champaign, USA. http://crga.atmos.uiuic.edu/public/CRG_Publications/Geographical.pdf

Semenov, M.A. and E.M. Barrow. 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* 35, 397-414.

Shabalova, M.V. and G.P. Können. 1995. Climate change scenarios: comparisons of paleo-reconstructions with recent temperature changes. *Climatic Change* 29, 409-428.

Smith, J.B. and G.J. Pitts. 1997. Regional climate change scenarios for vulnerability and adaptation assessments. *Climatic Change* 36, 3-21.

Smith, J.B. and D. Tirpak (eds). 1989. *The Potential Effects of Global Climate Change on the United States*. EPA-230-05-89-050. US Environmental Protection Agency, Washington, DC.

Smith, T.M., R. Leemans, and H.H. Shugart. 1992. Sensitivity of terrestrial carbon storage to CO_2-induced climate change: Comparisons of four scenarios based on general circulation models. *Climatic Change* 21, 367-84.

Stouffer, R.J., S. Manabe, and K. Bryan. 1989. Interhemispheric asymmetry in climate response to a gradual increase in CO_2. *Nature* 342, 660-662.

Strzepek, K.M. and J.B. Smith (eds). 1995. *As Climate Changes: International Impacts and Implications.* Cambridge University Press, Cambridge, United Kingdom.

Sulzman, E.W., K.A. Poiani, and T.G.F. Kittel. 1995. Modeling human-induced climatic change: A summary for environmental managers. *Environmental Management* 19, 197-224.

Taylor, K.E. and J.E. Penner. 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature* 369, 734-737.

Trenberth, K.E. and T.J. Hoar. 1996. The 1990-1995 El Niño-Southern Oscillation event: Longest on record. *Geophysical Research Letters* 23(1), 57-60.

Viner, D. and M. Hulme. 1992. *Climate Change Scenarios For Impact Studies in the UK. Climatic Research Unit.* University of East Anglia, Norwich, United Kingdom.

Von Storch, H., E. Zorita, and U. Cubasch. 1993. Downscaling of global climate change estimates to regional scales: An application to Iberian rainfall in wintertime. *Journal of Climate* 6, 1161-1171.

Walsh, K. and J. McGregor, 1997. An assessment of simulations of climate variability over Australia with a limited area model. *International Journal of Climatology* 17, 201-224.

Warrick, R.A., C. Le Provost, M.F. Meier, J. Oerlemans, and P.L. Woodworth. 1996. Changes in sea level. In *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). Cambridge University Press, Cambridge, United Kingdom.

Washington, W.M. and G.A. Meehl. 1989. Climate sensitivity due to increased CO_2: Experiments with a coupled atmosphere and ocean general circulation model. *Climate Dynamics* 4, 1-38.

Watterson, I.G. 1997. The diurnal cycle of surface air temperature in simulated present and doubled CO_2 climates. *Climate Dynamics* 12, 533-545.

Wetherald, R.T. and S. Manabe. 1988. Cloud feedback processes in a general circulation model. *Journal of Atmospheric Sciences* 45, 1397-1415.

Whetton, P.H., A.M. Fowler, M.R. Haylock, and A.B. Pittock. 1993. Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. *Climatic Change* 25, 289-317.

Wigley, T.M.L., R. Richels, and J.A. Edmonds. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* 379, 240-243.

Wigley, T.M.L., P.D. Jones, K.R. Briffa, and G. Smith. 1990. Obtaining sub-grid-scale information from coarse-resolution general circulation model output. *Journal of Geophysical Research* 95, 1943-1954.

Wilks, D.S. 1992. Adapting stochastic weather generation algorithms for climate change studies. *Climatic Change* 22, 67-84.

Williams, L.J., Shaw, D., and Mendelsohn, R.. Evaluating GCM output with impact models. *Climatic Change* (In press).

Wilson, C.A. and J.F.B. Mitchell. 1987. A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean. *Journal of Geophysical Research* 92, 13,315-13,343.

4 Integration

Lead Authors
Stewart J. Cohen [1]
Richard S.J. Tol [2]

Contributing Author
Antonio Magalhães, Brazil

4.1 What is integrated assessment of climate change impacts?

Existing studies of the impact of climate change typically look at a certain system in a certain place in isolation from other systems and other places. This handbook addresses a different approach. It tries to include the interactions between the diversity of impacts of climate change, and to place these impacts in the context of other changes. This approach is known as integrated assessment (IA), and the associated models are known as integrated assessment models (IAMs). This chapter provides guidance on conducting an integrated assessment of the impacts of climate change and adaptation to climate change.

Unlinked parallel studies may generate important information on the impacts of climate change. However, such studies may well lead to inconsistencies. For example, water is used by nature, agriculture, industry, and households. A study of the impact of climate change on agriculture alone, keeping the water usage of other sectors constant, may thus overestimate the supply of irrigation water. Land is another resource shared by

[1] Sustainable Development Research Institute, University of British Columbia, Vancouver, Canada.

[2] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands.

many sectors and systems. Further interactions can take place through national and international markets for commodities and capital. Changes in crop yields can be mitigated or exacerbated, depending on changes in market prices determined by yields elsewhere and yields of competing crops. An integrated impact study analyses the key interactions within and between sectors of a particular exposure unit, and between this unit and the outside world. One aim of an integrated impact study is to generate a comprehensive assessment of the totality of impacts, which is greater than the sum of the separate sectoral impacts.

A second purpose of integrated impact research is to enable researchers to place climate change impacts in a broader context such as natural resource management, sustainability of ecosystems, or economic development, and to consider the associated broader questions. Chapter 2, on socio-economic scenarios, provides a broad palette of examples of how changes in population, economy, technology, et cetera, would affect vulnerability to climate change. Similarly, Chapter 5 provides ample cases in which adaptation to climate change interacts with other aims and strategies of decision makers at all levels, from local farmers to national governments.

IA is more ambitious than separate sectoral studies, and consequently is more difficult to achieve. One reason is that additional demands are placed on component studies. Another reason is insufficient knowledge of interactions. A third reason is that IA is at least multi-disciplinary but in most cases interdisciplinary. Furthermore, IA almost always requires co-operation, and often between types of people who are not used to co-operating with one another. These difficulties grow faster than the ambitions of the IA. Whilst ensuring consistency in water use between agricultural and industrial impact studies is relatively easy (although seldom done in practice), a study of the impact of climate change on an entire river basin in the context of overall development is a major task.

The next section briefly reviews current practices in integrated assessment, highlighting crucial elements of IA. Possible approaches to IA for climate change impact and adaptation research are presented, and past applications of IA to climate change impact research are discussed.

4.2 Current practice in integrated assessment

Many researchers practice forms of integrated assessment of climate change, using various modelling and non-modelling approaches (see Weyant et al., 1996; Rotmans and Dowlatabadi, 1998; Tol and Vellinga, forthcoming). Some researchers study the practice of IA (Parson, 1995, 1996, 1997; Shackley and Wynne, 1995; Toth, 1995). So far, no single best method has been found, if there is any. Pragmatic approaches based on common sense dominate the field. This chapter is therefore not a cookbook with proven recipes, but a guide with ingredients and considerations to conduct an integrated assessment of the impacts of climate change and the possibilities of adaptation.

Linkages between climate-sensitive issues (e.g., water management, agriculture, forestry, fish and wildlife, infrastructure planning, and economic development) are complex, so there is a need for multi-disciplinary collaboration in a holistic and pragmatic manner that focuses on issues, not analytical tools. It is not an easy task, however, because of scientific uncertainties and the inherent difficulty of accurately describing the various complexities behind any decision made by governments and other actors. There is an opportunity, however, to develop and communicate a broader appreciation of how climate change could affect a place or a sector.

Most of what is known as integrated assessment (modelling) is about trying to find a proper trade-off between the impacts of climate change and the impacts of greenhouse gas emission abatement. This is a different subject than what this chapter and this handbook are about.

Some integrated assessments pay considerable attention to the impacts of climate change (Edmonds et al., 1993, 1994; Alcamo, 1994; Jacoby and Zang, 1994; Rotmans et al., 1994; Downing et al., 1995, 1996; Tol, 1996, 1997; Jacoby et al., 1997; Morita et al., 1997; see Tol and Fankhauser, forthcoming, for an overview). These studies are typically global. They often lack detail at regional and country levels. Models are not validated against national data.[3] For application to country studies, results of these models should therefore be interpreted with great care. Methodologies are not readily applied either. Each of the above studies required a continuous effort measured in years, with funding that is a multiple of a typical budget for an entire country study.

More use for national studies can be found in the results of existing sectoral IAMs -- again, trying to "replicate" this for other sectors would require a major investment in time and money. In sectoral IAMs, all interactions within a particular sector are represented in a model. This method has been applied to agriculture (Kane et al., 1992; Reilly et al., 1994; Rosenzweig and Parry, 1994; Darwin et al., 1995) and timber (Perez-Garcia et al., 1995), while an effort at the University of Kassel, Germany, is under way for water resources (J. Alcamo, Center for Environmental Systems Research, University of Kassel, personal communication, 1997). For agriculture and timber, models of agricultural productivity were coupled to models of national and international trade, together driven by scenarios for climate, population, technology, and economy. These studies provide some insights into national impacts. However, the outcomes of these models can be used to provide an international context to a national study. For instance, results of the Basic Linked System (BLS), the model used by Rosenzweig and Parry (1994), can be used as "boundary conditions" to a model of the national food market (e.g., world market prices, demand and supply on import and export markets). This was done for England and Wales by Parry et al. (1996), for Egypt by Strzepek et al. (1994, 1995, 1996; Yates and Strzepek, 1996), and for India by Kumar and Parikh (1997).

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[3] The one exception is the Asian-Pacific Integrated Model, or AIM (Morita et al., 1997), which is described in Section 4.4.5.

IAMs can also be developed for a particular region. An example is the work by Parry et al. (1996). It looks at changes in land use patterns in England and Wales. Alternative applications compete for land. Each is differently affected by climatic change. Parry et al. use simple rules to determine the trade-offs. Changing land use patterns emerge. Another example is the work by Strzepek et al. (1994, 1996; Yates and Strzepek, 1996). The flow of the Nile is used as the all-important integrator of natural and human systems in Egypt (see Section 4.4.2).

Integrated approaches are not restricted to building and applying integrated models. IA represents an attempt to evaluate impacts, costs, benefits, and response options for a sector or place. The latter context should be of particular importance for country studies. An IA of a place (e.g., a country) could consistently bring together information on all climate sensitive activities, enabling the analysts to examine possible indirect effects of climate change. This would indicate the total effect of a scenario on the country.

For example, the MINK study (Crosson and Rosenberg, 1993; Rosenberg, 1993) looks at the implications of the drought in the 1930s in the US Corn Belt as a historical analogue to climate change. This study combines models with historical reviews, adding ambiguities and depth to a model-only study (see Section 4.4.1). The Mackenzie Basin Impact Study (MBIS) from Northwest Canada (Cohen, 1997a,b,c) similarly combines common analogue and GCM-based scenarios with sectoral and integrated models, interviews, and workshops, the latter to capture in particular human adaptation and characteristics of subsistence hunting and gathering (see Section 4.4.3).

4.3 Possible approaches to integrated impact assessment

Integrated assessment can be done at different levels of ambition. At the very least, IA should be based on consistent data bases and scenarios (Section 4.3.2). A slightly more ambitious IA would seek to avoid overlap and would try to establish consistency between the analyses of the various sectors, systems, and regions affected by climate change (Section 4.3.3). At the third level of ambition, models are linked so that important feedbacks are taken into consideration (Section 4.3.4). Before starting an IA at whichever level of ambition, a considerable amount of preparatory work needs to be done (Section 4.3.1). Integrated assessment is more than consistency between impact studies, at whichever level of ambition. It also involves outreach to and inputs from people affected by climate change. The role stakeholders can and need to play is discussed in Section 4.3.5. Figure 4.1 illustrates the various elements of and options for an integrated assessment of the impacts of climate change.

4.3.1 Preparatory stages

A number of preparatory steps need to be taken before the actual integrated study can commence: define the study area, issues, and aims; establish the integration core team and the integrators; and find out what has been done to date. The steps need not be taken in this order. The best way perhaps is to iterate two or three times, letting the literature review refine the issues and aims.

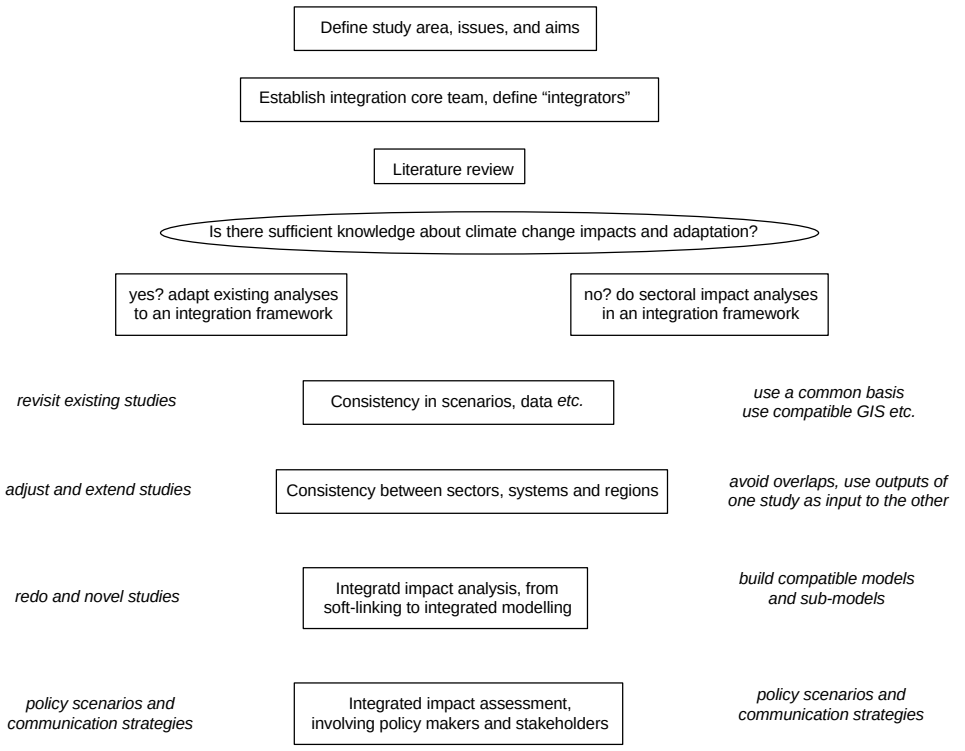

Figure 4.1 A framework for integration.

4.3.1.1 Literature review

Integration exercises require information from the sectoral assessments, and are intended to address the indirect implications of climate change. These data requirements are best articulated early in the research design phase of the country study. Therefore, it is important to find out what has been done so far in climate impact research in the country. An integrated assessment would best try to build on the findings of earlier impact research, and attempt to draw on the acquired expertise. If little impact research has been conducted, it would be advisable to conduct sectoral studies, and place these in an integrative framework right from the start.

4.3.1.2 Issue focus

In a climate impact assessment, the problems of interest are climate-sensitive aspects of ecosystems, resource management, resource extraction operations, or infrastructure maintenance. It is helpful to make the issues clear to the IA's participants, so that they know what questions they are trying to address. One aim of an IA may be to ensure that climate change is taken into consideration in areas in which policy is normally made or has been made for some time without considering climate change as a factor. These could include the implications of climate change for interjurisdictional water management; sustainability of lifestyles; sustainability of ecosystems; economic development (primarily resource-based sectors such as energy, agriculture, forestry, tourism, fisheries); land use allocation/zoning; and maintenance of transportation facilities and networks. If specific regional or national targets are identified for the IA, then it is better done as early as possible, so that more time is available to tailor the study to this aim. An IA may also more modestly aim at acquiring a coherent understanding of the impact of climate change, including the interactions between the various sectors and systems.

4.3.1.3 Study area

The choice of boundaries may depend on the choice of policy targets. For a country study, the choice of boundary is already defined (although, say, international commodity markets or internationally shared water resources may also be of interest). Defining units within the country (e.g., grids, cells) is another matter, and there are several options. It is usually easier to divide a country by administrative units or collections of units because of availability of economic data (e.g., counties, states/provinces, planning regions), and because decision making power is vested in such units. There are also advantages to selecting ecological zones (e.g., forest, grassland, coastal zone) or watersheds. The latter are particularly well suited as integrators of various environmental and resource issues (e.g., navigation, water supply, hydroelectric power production, freshwater habitat, tourism), and often include interjurisdictional concerns which may be a source of conflict between neighbouring jurisdictions. It may be more appropriate to select watersheds rather than administrative units if water management is identified as a policy target for the IA. Of course, the roles of different administrative units in the watershed should then be part of the study. The design of the study would have to be adapted to these non-administrative boundaries (e.g., using data for census divisions instead of states/provinces to construct an economic model).

4.3.1.4 Integration targets

Three levels of ambition are mentioned above: consistent scenarios and data bases, consistent sectoral studies, and integration, including feedbacks. In addition, an IA may want to place the impacts of climate change in a broader context, for instance, by involving the relevant stakeholders in the analysis. Obviously, the goal determines the

approach and the resources required for success, although available resources may constrain both goal and approach.

It is advisable to work from the more modest goals to the more ambitious ones. First, this allows for experience and capacity to be built up before addressing the more difficult task of integrated assessment. Second, should things develop less well than planned (e.g., available funds are less than anticipated, or difficulties arise in the conduct of the analysis), at least some goals will have been achieved. However, when starting modestly, the ambitious end-goal should always be borne in mind, so that pragmatic choices in the short term do not preclude the achievement of larger, long-term goals.

4.3.1.5 Integration core team

A project leader should be able to maintain a sufficiently long-term commitment to the IA. The project leader will be able to manage better if he or she has experience in climate impacts or environmental impacts research, or is familiar with regional issues which may be sensitive to climate. Alternatively, a team of leaders can be established.

Leadership is important, because co-ordination is needed between people who are not used to working together, and do not necessarily want to work together. The integration core team will need to do more than just keeping people together. Much common groundwork is needed, with regard to data, scenarios, software, and so on.

4.3.1.6 Integrators

It is often useful to define one or more integrators. An integrator is a system or resource that acts as an organising or binding principle in an integrated analysis. Good integrators connect to a substantial number of other sectors and systems, and are of prominent interest in their own right. Examples are the tourist sector on a tropical island, or a river in a watershed. The tourist sector is often a major income earner, and changes in sea level, hurricane incidence or intensity, water resources, and local agriculture would each affect the profitability of the sector. A river connects natural and managed ecosystems, industry, and households in their use of water and their use of the river as a discharge channel of various substances. The idea is to establish a “family” of integrators in which various approaches become research targets (Section 4.3.1.4) for the sectoral activities within the program. It should be possible, for example, to set up a regional or country study in which a cost-benefit model, settlement development survey, and land assessment framework are all used, since each addresses different questions and can actually complement one another. Regional or national development plans can also serve as integrators, since they are expressions of the various trade-offs made by governments and other stakeholders, accounting for the domestic natural resource base and external economic forces.

An alternative type of integrator is a common unit of measuring impacts. Advantages of common units are that impacts across sectors and systems can be aggregated, and perhaps compared to other issues (e.g., air pollution, greenhouse gas mitigation). Disadvantages are that crucial information may get lost, and that sometimes crude and debatable assumptions need to made to express impacts in the chosen unit. The most usual metric for common units is money. Money is used to express trade-offs between valuable goods and services that are traded on markets. There are techniques to estimate the monetary values of goods that are not traded, or are implicitly traded. These have been applied to climate change impacts (Pearce et al., 1996). Because of the great uncertainties and many assumptions, the results of such exercises should be interpreted with great care, particularly in economies which are not full commercialised.

4.3.2 Consistency in scenarios and data

It is important to try to establish coherence and consistency between sectoral impact studies. Comparability of results will be greater if studies investigate the same scenarios (for climate, population, economics, and so on) and use the same reference year, the same units, and consistent data bases.

A set of climate and socio-economic scenarios should be identified as early as possible. The climate scenarios can be derived from climate model simulations, analogues, or hypothetical cases (see Chapter 3). The socio-economic scenarios should include population growth, technological changes, and potential economic and political changes that would be important to the region or country of interest over the time period of the climate scenario (see Chapter 2). Scenario characteristics will be regionally unique (due to landscape, history, cultural factors, etc.), providing the context that enables the IA to determine whether or not the impacts of climate change could be significant.

Scenario data are usually needed in a quantitative form, particularly if they are used as inputs to models employed within sectoral and integration activities. In some study components, scenario data will not be needed as direct input because the investigators will be interested in the estimated sectoral impact from a qualitative perspective (e.g., community responses, legal dimensions). Qualitative scenarios would also suffice for impact studies based on expert judgement.

Recall that consistent scenarios and data bases are the minimum requirements for integration. In most country studies, this type of coherence was part of the overall study design. When starting a new study, it is readily enforced because this type of integration also saves work.

4.3.3 Consistency between sectors, systems, and regions

Sectoral impact studies would be somewhat consistent if the same resource is not assumed to be used by two sectors at the same time, and if climate-induced changes in one sector are included in the study of another sector. For example, water consumed or land

occupied by a forest cannot also be consumed or occupied by agriculture. Climate-induced changes in vegetation upstream of a river would affect run-off downstream. Establishing such consistency requires that sector studies be conducted in a co-ordinated fashion. It is may be possible that a qualitative, expert amendment to less strictly co-ordinated results would suffice. It is advisable that this be accompanied by in-depth discussions between the sectoral experts. The reasons are that all the subtleties of the interactions between the sectors should be brought to the fore, and that mutual understanding and appreciation need to be developed to make further steps a success.

Severe overlaps and inconsistencies between sector studies need to be prevented. Stand-alone sector studies would do too much or too little, or would deviate too much from each other. Examples of overlaps are agricultural/ecological and hydrological models both calculating run-off; models of managed and unmanaged ecosystems including the same biomes (e.g., semi-managed forests, extensively grazed grasslands); or studies focusing on different aspects of the same thing (e.g., wildlife versus game for sport hunting/tourism). Examples of possible inconsistencies between sector studies are variables incorrectly held constant (e.g., quality of irrigation water, health status of labour force) and resources that are an inherent part of the sectors (other than mere input or outputs; examples are, again, land and water but also prices). As stated, overcoming such overlaps and inconsistencies requires co-ordination. The nature of such co-ordination is that agricultural scientists and hydrologists do their analysis together. Interdisciplinary co-operation implies that a mutual understanding is developed, including long discussions about semantics and paradigms. It also implies that adjustments, perhaps even concessions, need to be made. Therefore, integration requires good leadership.

Integration also implies considerable learning about other disciplines and novel challenges for the own discipline. The latter arise from the fact that certain elements can no longer be taken for granted, such as exogeneity of agricultural land use in water management, or the seniority of agriculture's water rights. In practice, avoiding overlap means that one sector needs to yield part of the analysis to another sector. In return, boundary conditions on that part are delivered by the other sector. For instance, when coupling an ecosystem model with a hydrological model, only one of the two can calculate run-off. Preference should be given to the sector that best represents the overlapping part. "Best" could be interpreted as in closest accordance with observations, the disciplinary state of the art, or the targets set for the IA. If, for instance, there is a strong interest in floods, and only one of the two models addresses floods, then the choice should be for that model. If, on the other hand, the two alternative models have similar output variables, but one has known deficiencies, then the choice should be for the other model. Avoiding inconsistencies may also require that part of the sectoral analysis be left to other disciplines, using other methods, models, or data. Ensuring consistency may also require that part of the original analyses be extended to include typically overlooked issues. Returning to the run-off example, a hydrological model may well have a better representation of water flows, but an ecosystem model may well have a better representation of water use by plants and how that reacts to changing ambient concentrations of carbon dioxide. The extended hydrological model

would then have the water supply and demand of a responsive ecosystem, in contrast to the static representation in standard hydrological models.

4.3.4 Integrated impact assessment

The difference between integration of sectors and consistency between sectors is that, in the former case, sectoral analyses are purportedly designed to feed into the integration, rather than adjusted. The aim is to establish a consistent and comprehensive overview of the impact of climate change on a particular region (e.g., an island, the coastal zone, a watershed, or the whole country) or a particular system or sector (e.g., land use or tourism), inclusive of the most important feedbacks between sectors. This is a major exercise. It can fail if a clear need or a firm commitment is lacking. It is best to start with an analysis of the system. What are the components? What are the links? What are the issues? With such ambitious goals, it is essential to have clearly and firmly established a family of integrators. The purpose of integrators is to provide structure to the analysis. A clear structure is important because, to most of those involved, integrated analysis is something new.

After the structure of the integrated analysis has been determined, a description is needed of the components, of the interactions between the components, particularly the inputs and outputs of each components, and of the type of analysis or model that would get one from the given inputs to the required outputs. Such analyses or models may be available. If so, these can be applied. Otherwise, these will have to be developed as part of the integration. Note that only at this stage does the full scope of the integrated analysis and the required resources become clear, so that only at this stage can the final work programme and budget be made.

Physical, biological, and socio-economic studies, focusing on one sector or discipline, provide important information in their own right. In an IA, however, these activities also provide input to a new set of “clients”—the integrators. The information needs of the resource accounting model, land assessment framework, community development component, or legal dimensions component are quite different from those of a colleague within a discipline related to that of the investigator.

The integrated analysis can be done in several ways, ranging between two extremes. At the one extreme is soft-linking. At the other extreme is integrated modelling. Soft-linking means that all component analyses are stand-alone, linked through input and output variables, joint scenarios, and combined results. Note that soft-linking does not imply lack of structure or co-ordination. Rather, each component analysis performs its task (whether modelling or stakeholder analysis) within strictly described (and enforced) boundary conditions. At the other extreme, integrated modelling combines all components into a single computer code, describing the entire system. Hard-linking of models lies between soft-linking and integration. Hard-linked models are part of a single computer code, but are recognisable as separate models and could in principle run in a stand-alone version. Integrated models, on the other hand, are no longer recognisable as separate entities and cannot run without the whole model. Note that soft-linking is the

only way to include methods other than computer models. Soft-linking may, for instance, be done by linking expert judgements in an expert panel.

4.3.5 The role of stakeholders

The crucial difference between an integrated analysis and an integrated assessment is that an assessment has a clear policy dimension. This difference comes to the fore in the design of the assessment, which should be done in a collaborative effort of scientists, policy-makers, and stakeholders. It also comes to the fore in the presentation of the result, which should be to a scientific audience, a lay audience, and a policy audience. It may also come to the fore in the construction of scenarios, particularly those elements which involve decisions. An essential element of an integrated assessment is that light is shed on real-life questions (rather than academic problems) in a way that is comprehensible and acceptable to those that have a stake in the issue to be addressed.

A key element to IA in its role to provide a broader context and perspective is that scientists and stakeholders work together on a common set of issues. Complexities increase as more questions are answered. A first goal of IA is to study the potential impacts of climate change on resources and resource uses, the “what-if” question: e.g., How does climate change affect agriculture? This is primarily an activity of researchers, although lay people may also hold considerable knowledge about particular parts, e.g., water and land use management practices. A second goal of IA is to study the policy implications of the estimated impacts, the “so-what” question: e.g., How do changes in agriculture affect food security? This means evaluation; that is, the projected outcomes are compared with the aspirations of citizens, government, etc. Here, stakeholders (government agencies, non-government organisations, businesses) may play a dominant role: researchers should act only as informants and citizens. Alternatively, a specialist may try to measure human preferences, which are implicitly revealed in everyday decisions, and evaluate the implications based on that. A third goal of IA is to study policy responses, the “what should be done” question. Again, this can be done through discussion among stakeholders or through an optimisation model. In the latter case, it is important to select the proper objective function, reflecting the real aims of the decision makers the model seeks to advise.

4.4 Case studies

IAs have followed different paths, but all have attempted to combine information from various sources to address both direct and indirect implications of scenarios of climate change for places, rather than just individual sectors.

4.4.1 The MINK study

This study focused on the states of Missouri, Iowa, Nebraska, and Kansas (MINK) within the US Corn Belt region. The main objective was to assess the regional economic

implications of climate change impacts on agriculture, water resources, forestry, and energy use for both current and projected population and adaptation technologies. The integration tool was a regional input-output model, IMPLAN.

This project was initiated in 1988 by the US Department of Energy to develop a methodology for regional-scale climate impact assessment. Participants included scientists from national laboratories (co-sponsored by government and the private sector), a non-government research organisation (Resources for the Future, RFF), and a scientific research society (Sigma Xi). The research program was done primarily by a team of scientists from RFF over a three-year period.

The research team began by choosing a study area, and describing its climate-sensitive attributes and vulnerabilities. It then selected the integration tool, IMPLAN, which had just been developed by the US Forest Service for other purposes. A climate change scenario was constructed from the 1930s Dust Bowl. A series of sectoral studies were performed using this historical analogue, along with estimates of CO_2 enrichment.

The results of the sectoral studies were used as input to the IMPLAN model. Economic impacts were projected to be negative. Adaptation would offset much of these losses, but some locations within the study area would still experience harsh impacts. The key here is the assumption of proactive adaptation by agricultural producers combined with assumed CO_2 enrichment effects.

This case study was the first attempt at integrated regional assessment of a climate change scenario. It did not include extensive stakeholder consultation but it did point the way toward a process that would enable parallel assessments of key sectors to be used as input to an integrating tool. The result of this process was an estimate, in economic terms, of direct and indirect impacts of climate change on an agricultural region of a developed country. There was acknowledgement, however, of the need to consider some synergism among the various sectoral impacts, and to extend the water resources assessment so that it would include the entire watershed rather than just the MINK portion. It was also suggested that environmental implications should have been included (Crosson and Rosenberg, 1993; Rosenberg, 1993).

4.4.2 Egypt

In 1989-1990, the US Environmental Protection Agency (USEPA) initiated a series of studies to assess the potential global implications of climate change. These were generally sectoral assessments of 18 developing countries. Particular attention was directed to Egypt because of the potential for serious implications for agricultural production resulting from a combination of several climate related stresses: reduced streamflow in the Nile River, sea level rise along the coast of the Nile Delta, and changes in availability of arable land.

The integrated assessment of impacts on Egypt was able to use outputs from sectoral assessments that were already completed. Within the USEPA programme, there had

been assessments of crop yield, Nile River Basin water resources, sea level rise, human health, and forests. All but the last were relevant to the case study of Egypt. These sectoral studies had been under way for three years before the integrated assessment exercise was initiated. The model chosen for the integrated assessment was adapted to accept available inputs. This particular exercise took place over a two-year period that partially overlapped the initial activities.

Participants in the sectoral assessments included academics from the United States and Egypt, government scientists from Egypt, and researchers at the International Institute for Applied Systems Analysis (IIASA) in Austria. These same individuals were brought into the integrated assessment team. After the analysis was completed, a meeting was held in Cairo with stakeholders to review and discuss the results.

The study area and impacts issues were identified near the end of the sectoral assessments. The choice of integration tool was a model of Egyptian agriculture, the Egyptian Agricultural Sector Model (EASM). It was modified to accept as inputs the results from the sectoral studies. This approach is different from MINK in that the sectoral studies were essentially completed before the integrated assessment began.

In this case, there were four climate change scenarios, all based on outputs from climate models. The studies of Nile flow and crop yields were based on these same scenarios. The sea level rise projection was based on an arbitrary selection using information from the IPCC.

Proactive adaptations in water resources, irrigation and agricultural technology, and coastal defences were assessed. The findings were that these would only partially offset the negative impacts of climate change, and at a very high cost. This analysis demonstrated that the interactions of these various sectoral impacts led to a different picture of agricultural losses than the analysis of direct impacts on crop yields alone. Climate-induced changes on the world market for agricultural products proved particularly important (Strzepek et al., 1994, 1995, 1996; Yates and Strzepek, 1996).

4.4.3 Mackenzie Basin Impact Study

MBIS was a case study that assessed several climate change scenarios for north-west Canada. This was a six-year effort (one year for organisation, five years for research) supported by Environment Canada and other sponsors. This was probably the most ambitious attempt to date to perform an IA using a scientist-stakeholder collaborative approach. In addition, several integration exercises were attempted, rather than relying on one integration model.

Two integration workshops were held. The first focused on the “vertical” dimensions. What were the important policy issues that might be relevant to a climate change impact study of this region? The second concerned “horizontal” integration, or the challenge of linking scientists from different disciplines in a common framework.

The vertical integration workshop identified policy concerns related to global warming, in effect establishing targets for study participants. The workshop resulted in the identification of six main policy issues: inter-jurisdictional water management, sustainability of ecosystems, economic development, maintenance of infrastructure, limitation (mitigation) strategies, and sustainability of aboriginal lifestyles. MBIS participants felt that assessing limitation strategies would be beyond the scope of the study, so it was agreed to place the various MBIS activities only within the context of the five remaining policy issues, which represented concerns about adaptation. It is important to note, however, that more than half the MBIS projects had been selected before this workshop took place.

The second integration workshop identified data requirements of study participants and linkages between the various study activities. Each investigator was asked to indicate his or her information needs, and this was displayed in a large matrix. MBIS participants could also use this matrix to identify potential “clients” for their work.

Despite the workshops and other activities held during this exercise, several obstacles to interdisciplinary research became significant challenges. This affected both the transfer of data between investigators and the integration process. The problems related to mismatches in software, and availability and compatibility of data. The latter problem was made worse because data assembling started well before data requirements were established.

Communicating with stakeholders was a complex challenge. There were successes with provincial and territorial government agencies and some aboriginal organisations, but some potential partners did not join in. Climate change is an issue embraced by some and avoided by others, depending on their mandate, jurisdiction, and perception of the importance (or lack of importance) of the climate change issue to their concerns.

Results of the IA showed that impacts would generally be negative, particularly for ecosystems, forestry, and activities dependent on stable conditions for ice and permafrost. However, agriculture could expand. This raised new questions regarding potential land use and economic development conflicts, and the future of aboriginal communities as they attempt to maintain traditional non-wage lifestyles while increasing their participation in the wage economy (Cohen, 1997a,b,c).

4.4.4 Aridas

The Aridas study was conducted by an alliance between the Brazilian federal government, the state governments of Northeast Brazil, universities and non-governmental organisations, and the World Bank. The area of the project was the semi-arid Northeast Brazil (NEB), in particular, the country-side.

Two features were emphasised: first, how to organise an integrated process of planning for the sustainable development of a marginal region like the NEB; and second, how to

deal with the issues of climate variability and climate change from within the planning process.

The NEB is a large, underdeveloped region. The high vulnerability of the population results from their poverty and from the recurrent droughts that cause dramatic crop losses and unemployment crises. In regions like the NEB, decision makers are constantly facing pressing problems such as the need for poverty alleviation, economic growth, employment creation, and drought relief actions. It is difficult to call their attention to possible future problems of climate change.

Therefore, Aridas placed climate change impacts in the context of overall development and present climate variability—the problem of droughts and their social, economic, and environmental impacts.

The general methodological framework was then devised in seven steps:

1. An assessment of the present state of sustainability of the region, in its social, economic, environmental, and political dimensions.

2. An assessment of present vulnerability of the region to climate variability, through an integrated assessment of climate impact and possible societal responses.

3. A business-as-usual scenario of the sustainability of the region in the future; if the development process continues as is, the NEB will be more unsustainable in the future, though per capita incomes will be higher.

4. A scenario of regional climate change; the NEB will probably get more frequent and more severe droughts.

5. An assessment of vulnerability to climate variation in the future.

6. A desired scenario of sustainability in the future, based on comprehensive participation processes; the Northeasterners are looking for the establishment of a future society that will be more just, equitable, and sustainable.

7. A strategy for the sustainable development of the region, including adaptation and mitigation strategies to address climate variability and change, to serve as a guideline to future regional plans.

The Aridas recommendations have been used by several state governments in the NEB, and now in the Amazon region, to orient the preparation of sustainable development plans (Magalhães and Neto, 1989; Magalhães, 1992; Magalhães et al., 1994; Nobre, 1994; Projeto Aridas, 1995).

4.4.5 The Asian-Pacific Integrated Model

The Asian-Pacific Integrated Model (AIM) has been developed in a collaborative effort of nine institutes in five countries in east Asia (China, India, Indonesia, Japan, South Korea), and the leading institute is the National Institute for Environmental Studies of Japan. The Japanese government is the main financier in the form of research contracts and visiting fellowships to the non-Japanese institutes. The seven institutes outside Japan have been responsible for national data collection, and jointly responsible for national model development. In addition, all developed models and data bases have been transferred to these institutes.

AIM integrates population, economy, emissions, concentrations, climate, and impacts. On the impact side, GCM-based climate scenarios serve as inputs to models of water resources (Southeast Asia and Australia only), unmanaged ecosystems (whole world), malaria (whole world), and agriculture (Southeast Asia and Australia only). AIM focuses on water supply and vegetation, malaria transmission, and crop yield potentials. The impact models are process-oriented and geographically explicit, often with great detail.

For example, model results for Indonesia indicate an increase from 75 to 108 million people at high risk of malaria, a decrease in rice yields of 2%, and a worsening of drought conditions in 75% of the country. As another example, Thailand's population at risk of malaria is projected to remain unchanged, but rice and cassava yields could fall by 2% and 24%, respectively, and 83% of the country may face more severe droughts (Morita et al., 1997).

The development of the AIM model has been a major research effort. It cannot be repeated with the limited funds available in a typical country study. Nevertheless, Asian institutes in particular should draw on the knowledge accumulated in the AIM project.

4.5 Advantages and constraints of integrated assessment

Organising and developing an integrated assessment of climate change impacts for a region or country is a new process which has not been widely tested.

Integrated impact and adaptation assessments of long-term climate change involve multi-sectoral, multi-disciplinary, multi-cultural, and multi-jurisdictional collaboration and partnerships. A successful IA could lead to the establishment of new data bases and a broader network of informed scientists and stakeholders. These will have value long after the completion of the regional or country studies. If the vertical (science-policy) and horizontal (science-science) integration components develop successfully, all parties should feel a sense of ownership in the results of this exercise. This would hopefully lead to a well-informed, regional- or country-scale research and policy response.

Integrated assessments, with stakeholder collaboration, can be difficult to pursue, particularly given the complex and uncertain nature of the climate change issue, the large size of most study areas, and the lack of immediacy of climate change compared with other regional issues (e.g., deficient health care, poverty, soil degradation). It is also important to recognise that each region is unique because of its history and geography. Specific experience with that region is an important asset, and the success of this and other regional and country studies will be quite limited without collaboration outside of international and federal government agencies.

Given the time and budgetary constraints which are often imposed on impacts research, researchers rarely have sufficient time to collect new data or develop new models. Research will depend on existing data bases and models for much of its work, and it will be difficult to overcome gaps in basic information (e.g., climate, soils, vegetation, population, economic transactions). A second limitation is the difficulty in maintaining internal consistency in a large, multi-disciplinary group (scales, assumptions, units of measure) and in ensuring the compatibility of various sub-components. It may be difficult to reach consensus on the choices of integrators, but there is no reason why a country study should restrict itself to one particular integration exercise. Each one would provide its own unique insights.

The following is a list of “lessons” which may be useful for those who are planning a regional or country IA of climate change impacts:

- The effort required to attract stakeholders and maintain scientist-stakeholder collaboration cannot be underestimated. Time and resources will need to be allocated specifically for this purpose, but the IA will be richer for it. This will also increase the probability of stakeholders becoming shareholders in the climate change impacts issue.

- The choice of study area will be influenced by political boundaries, but it is advantageous to consider watersheds and other ecological boundaries as well.

- It is essential that all scenarios and assumptions are consistent across the sectoral analyses, or integration will be hampered.

- A common data platform (e.g., for geographic information systems) should be identified as early as possible. This may not be easy, because of previous investments by participating agencies, institutions, etc., but incompatibility of data formats may become an important obstacle to integration. A home page on World Wide Web could be set up, but this would require additional resources, and there would be questions of access, confidentiality, and security.

- There is no substitute for personal contact. Communication through newsletters and reports, etc., is not enough. Electronic mail will be an important asset in co-ordination and communication between personal meetings and visits, but direct contact is important, especially with stakeholders.

- The choice of impact indicators (economic, environmental, social) should not be made in isolation from the particular situation faced in the study region or country. The specific conditions of the study area should be taken into account when choosing such measures.

- There is no single best way to integrate knowledge from different disciplines. Modelling exercises should be complemented by non-model approaches, including direct interaction between scientists and stakeholders during all phases of the assessment. This interaction enables the study to draw on local knowledge as well as on scientific research projects. A process that is determined by goals, not analytical tools, will result in a more successful integrated assessment.

References

Alcamo, J. (ed). 1994. *IMAGE 2.0: Integrated Modelling of Global Climate Change.* Kluwer, Dordrecht, The Netherlands.

Cohen, S.J. (ed).1997a. *Mackenzie Basin Impact Study Final Report*. Environment Canada, Downsview, Ontario, Canada.

Cohen, S.J. 1997b. Scientist-stakeholder collaboration in integrated assessment of climate change: Lessons from a case study of Northwest Canada. *Environmental Modeling and Assessment* 2, 281-293.

Cohen, S.J. 1997c. What-if and so-what in Northwest Canada: Could climate change make a difference to the future of the Mackenzie Basin? *Arctic* 50 (4), 293-307.

Crosson, P.R. and N.J. Rosenberg. 1993. An overview of the MINK study. *Climatic Change* 24, 159-173.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses. 1995. *World Agriculture and Climate Change - Economic Adaptations*. Agricultural Economic Report 703. US Department of Agriculture, Washington, DC.

Downing, T.E., R.A. Greener, and N. Eyre. 1995. *The Economic Impacts of Climate Change: Assessment of Fossil Fuel Cycles for the ExternE Project*. Environmental Change Unit and Eyre Energy Environment, Oxford and Lonsdale, United Kingdom.

Downing, T.E., N. Eyre, R. Greener, and D. Blackwell. 1996. *Projected Costs of Climate Change for Two Reference Scenarios and Fossil Fuel Cycles*. Environmental Change Unit, Oxford, United Kingdom.

Edmonds, J.A., H.M. Pitcher, N.J. Rosenberg, and T.M.L. Wigley. 1993. Design of the global change assessment model GCAM. In *Costs, Impacts, and Benefits of CO_2 Mitigation*, Y. Kaya, N. Nakicenovic, W.D. Nordhaus, and F.L. Toth (eds). IIASA, Laxenburg, Austria.

Edmonds, J.A., M. Wise, and C. MacCracken. 1994. Advanced energy technologies and climate change: An analysis using the global change assessment model (GCAM). In *Global Climate Change -- Science, Policy, and Mitigation Strategies*, C.V. Mathai and G. Stensland (eds). Air & Waste Management Association, Boston, Massachusetts, USA, 627-644.

Jacoby, H.D., R.S. Eckaus, A.D. Ellerman, R.G. Prinn, D.M. Reiner, and Z. Yang. 1997. CO_2 emission limits: Economic adjustments and the distribution of burdens. *Energy Journal* 18 (3), 31-58.

Jacoby, H.D. and Z. Yang. 1994. Integrating scientific, economic, and ecological aspects of global change. In *Global Climate Change—Science, Policy, and Mitigation Strategies*, C.V. Mathai, and G. Stensland (eds). Air & Waste Management Association, Boston, Massachusetts, USA, 645-653.

Kane, S., J.M. Reilly, and J. Tobey. 1992. An empirical study on the economic effects of climate change on world agriculture. *Climatic Change* 21, 17-35.

Kumar, K.S.K. and J. Parikh. 1997. *Potential Impacts of Global Climate Change on Indian Agriculture* (draft).

Magalhães, A.R. 1992. Understanding the implications of global warming in developing regions: The case of Northeast Brazil. In *Regions and Global Warming*, J. Schmandt and J. Clarkson (eds). Oxford University Press, New York, pp. 237-256.

Magalhães, A.R., and E.B. Neto. 1989. *Impactos sociais e econômicos variacões climáticas e repostas governamentais no Brasil*. Programa das Nações Unidas para O Meio-Ambiente. Secretaria de Planejamento e Coordenação do Ceará, Fortaleza, Brazil.

Magalhães, A.R., E.B. Neto, and S.S. Panegides. 1994. *Projecto Aridas: Uma Estrategia de Desenvolvimento Sustentavel para o Nordeste – Documento Basico*, Secretaria de Planejamento, Orcamento e Coordenacao da Presidencia da Republica (SEPLAN), Brasilia, Brazil.

Morita, T., M. Kainuma, K. Masuda, H. Harasawa, K. Takahashi, Y. Matsuoka, J. Sun, Z. Li, F. Zhou, X. Hu, K. Jiang, P.R. Shukla, V.K. Sharma, T.Y. Jung, D.K. Lee, D. Hilman, M.F. Helmy, M. Yoshida, G. Hibino, and H. Ishii. 1997. *Asian-Pacific Integrated Model (AIM)*. National Institute for Environmental Studies, Tsukuba, Japan.

Nobre, P. 1994. *Climate and Climate Change in the Northeast*. Aridas Project. Ministry of Planning and Budget, Brasilia, Brazil (unpublished paper).

Parry, M.L., J.E. Hossell, P.J. Jones, T. Rehman, R.B. Tranter, J.S. Marsh, C. Rosenzweig, G. Fischer, I.G. Carson, and R.G.H. Bunce. 1996. Integrating global and regional analyses of the effects of climate change: A case study of land use in England and Wales. *Climatic Change* 32, 185-198.

Parson, E.A. 1995. Integrated assessment and environmental policy making. *Energy Policy* 23 (4/5), 463-475.

Parson, E.A. 1996. Three dilemmas in the integrated assessment of climate change — An editorial comment. *Climatic Change* 34, 315-326.

Parson, E.A. 1997. Informing global environmental policy-making: A plea for new methods of assessment and synthesis. *Environmental Modeling and Assessment* 2, 267-279.

Pearce, D.W., W.R. Cline, A.N. Achanta, S. Fankhauser, R.K. Pachauri, R.S.J. Tol and P. Vellinga. 1996. The social costs of climate change: Greenhouse damage and the benefits of control. In *Climate Change 1995: Economic and Social Dimensions -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel*

on Climate Change, J.P. Bruce, H. Lee and E.F. Haites (eds). Cambridge University Press, Cambridge, United Kingdom, pp. 179-224.

Peres-Garcia, J., L.A. Joyce, C.S. Binkley, and A.D. McGuire. 1995. Economic impacts of climatic change on the global forest sector: An integrated ecological/economic assessment. In *Proceedings of a Meeting on Economics of Carbon Sequestration in Forestry*, Bergendal, The Netherlands.

Projeto Aridas. 1995. *A Strategy for Sustainable Development in Brazil's Northeast*. Ministry of Planning and Budget, Brasilia, Brazil.

Reilly, J.M., N. Hohmann, and S. Kane. 1994. Climate change and agricultural trade: Who benefits, who loses? *Global Environmental Change* 4 (1), 24-36.

Rosenberg, N.J. 1993. Towards an integrated impact assessment of climate change: The MINK study. *Climatic Change* 24 (1-2).

Rosenzweig, C. and M.L. Parry. 1994. Potential impact of climate change on world food supply. *Nature* 367, 133-138.

Rotmans, J., and H. Dowlatabadi.1998. Integrated assessment of climate change: Evaluation of methods and strategies. In *Human Choices and Climate Change: A State of the Art Report*, S. Rayner and E.L. Malone (eds). Batelle Pacific Northwest Laboratories, Washington, D.C.

Rotmans, J., M. Hulme, and T.E. Downing. 1994. Climate change implications for Europe: An application of the ESCAPE model. *Global Environmental Change* 4 (2), 97-124.

Shackley, S. and B. Wynne. 1995. Integrating knowledge for climate change: Pyramids, nets and uncertainties. *Global Environmental Change* 5, 113-126.

Strzepek, K.M., S.C. Onyeji, M. Saleh, and D.N. Yates. 1994. *An Assessment of Integrated Climate Change Impacts on Egypt*. WP-94-48. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Strzepek, K.M., S.C. Onyeji, M. Saleh, and D.N. Yates. 1995. An assessment of integrated climate change impacts on Egypt. In *As Climate Changes: International Impacts and Implications,* K.M. Strzepek and J.B. Smith (eds). Cambridge University Press, New York, pp. 180-200.

Strzepek, K.M., D.N. Yates, and D.E.D. El Quosy. 1996.Vulnerability assessment of water resources in Egypt to climatic change in the Nile Basin. *Climate Research* 6 (2), 89-95.

Tol, R.S.J. 1996.The damage costs of climate change: Towards a dynamic representation. *Ecological Economics* 19, 67-90.

Tol, R.S.J. 1997.On the optimal control of carbon dioxide emissions: An application of FUND. *Environmental Modeling and Assessment* 2, 151-163.

Tol, R.S.J. and S. Fankhauser (forthcoming). On the representation of climate change impacts in integrated assessment models. *Environmental Modeling and Assessment.*

Tol, R.S.J. and P. Vellinga (forthcoming). The European forum on integrated environmental assessment. *Environmental Modeling and Assessment*.

Toth, F.L. 1995. Practice and progress in integrated assessments of climate change: A workshop overview. *Energy Policy* 23 (4/5), 253-268.

Weyant, J., O. Davidson, H. Dowlatabadi, J.A. Edmonds, M. Grubb, E.A. Parson, R. Richels, J. Rotmans, P.R. Shukla, R.S.J. Tol, W.R. Cline, and S. Fankhauser. 1996. Integrated assessment of climate change: An overview and comparison of approaches and results. In *Climate Change 1995: Economic and Social Dimensions—Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, J.P. Bruce, H. Lee, and E.F. Haites (eds). Cambridge University Press, Cambridge, United Kingdom, pp. 371-396.

Yates, D.N. and K.M. Strzepek. 1996. Modeling economy-wide climate change impacts on Egypt: A case for an integrated approach. *Environmental Modeling and Assessment* 1 (3), 119-135.

5 Adaptation to Climate Change: Theory and Assessment

Lead Authors
Ian Burton [1]
Joel B. Smith [2]
Stephanie Lenhart [2]

5.1 Introduction

Adaptation refers to all those responses to climate change that may be used to reduce vulnerability. (Vulnerability is susceptibility to harm or damage potential. It considers such factors as the ability of a system to cope or absorb stress or impacts and to "bounce back" or recover.) Adaptation can also refer to actions designed to take advantage of new opportunities that may arise as a result of climate change.

In assessing climate change impacts, it is imperative to take adaptation into account. Plants, animals, and humans will not simply continue on as they have without climate change but are quite likely to modify their behaviour. Plants, animals, and ecosystems may migrate to new locations. Humans may change their behaviour to cope with a different climate (e.g., more heating/cooling, switch crops) or if necessary may migrate. To fully account for vulnerability to climate change, an assessment of impacts needs to account for those adaptations that are likely or even reasonable to assume to happen. Without assessment of such adaptations, the impacts researchers could well overstate the potential negative effects of climate change. An additional reason for assessing adaptation is to inform policy makers about what they can do to reduce the risks of climate change.

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[1] Atmospheric Environment Science, Environment Canada, Downsview, Ontario, Canada.

[2] Stratus Consulting Inc., Boulder CO, USA.

Adaptation is treated in three ways in this handbook. Section 5.2 of this chapter is a theoretical section, in which the concept of adaptation is explained in relation to both "normal" climate variability and climate change. A typology of adaptations is developed at a broad generic level as an aid to the identification of adaptation measures, and the idea of maladaptation is also introduced.

Section 5.3 provides some suggestions for the generic design of adaptation studies. This includes reference to some specific techniques that have been developed and indication where further information may be obtained. This is not comprehensive and will undoubtedly benefit from the practical experiences of those who seek to put these methods to the test, in country studies and elsewhere.

Specific adaptation measures relevant to particular economic sectors or areas of impact are discussed in each of the sectoral chapters in Part II. An attempt has been made to keep the terminology of adaptation consistent between sectors, but the field of adaptation to climate change is relatively new and there is at the moment no generally accepted consensus about the definition of terms. No doubt this will emerge as the research and policy debates continue.

5.2 Theoretical aspects of adaptation

The first part of this section describes the importance of adaptation as part of the United Nations Framework Convention on Climate Change (UNFCCC) and suggests some definitions of key concepts regarding adaptation . The remaining theoretical discussion of adaptation to climate change is organised around a set of simple questions designed to show what it is that is being adapted to; who or what is doing the adapting; and in what way, when, and how the adapting is being done. The section concludes with a discussion of the capacity to adapt.

5.2.1 Adaptation and maladaptation to climate change and variability

The UNFCCC includes five clauses that specifically address adaptation as follows:

> All Parties . . . shall . . . formulate, implement, publish and regularly update national and . . . regional programmes containing measures to mitigate climate change . . . and measures to facilitate adequate adaptation to climate change (Article 4, Section 1 (b)).
>
> The Parties should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate its adverse effects . . . To achieve this, such policies and measures should take into account different socio-economic contexts, to be comprehensive, cover all relevant sources, sinks, and reservoirs of greenhouse gases, and adaptation (Article 4, Section 3).

> All Parties . . . shall co-operate in preparing for adaptation to the impacts of climate change (Article 4, Section (e)).
>
> All Parties . . . shall . . . take climate change considerations into account, to the extent feasible, their relevant social, economic and environmental policies and actions, and employ appropriate methods, for example impact assessment, formulated and determined nationally, with a view to minimising adverse effects on the economy on public health, and on quality of the environment, of projects or measures undertaken by them to mitigate or adapt to climate change (Article 4, Section 1 (f)).
>
> The developed country Parties and other developed Parties…shall also assist the developing country Parties that are particularly vulnerable to the adverse effects of climate change in meeting the costs of those adverse effects (Article 4, Section 4)

These references to adaptation constitute only a small part of the Framework Convention, which is primarily devoted to "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Article 2). It is now clear that the climate is already changing and that the world is committed to more change before stabilisation can be reached. Adaptation is therefore of growing importance, and is likely to receive more attention both in the research community and in the ongoing negotiations under the Convention.

Under the Kyoto Protocol to the Framework Convention (negotiated at Kyoto, December 1997) a "clean development mechanism" is defined in Article 12 of the Protocol. The clean development mechanism is mainly concerned with international co-operation in the reduction of greenhouse gas emissions, the so-called "certified project activities", but the Article also provides in Clause 8 that:

> The Conference of the Parties serving as the meeting of the Parties to this Protocol shall ensure that a share of the proceeds from certified project activities is used to . . . assist developing country Parties that are particularly vulnerable to the adverse effects of climate change to meet the costs of adaptation.

Thus the financing of adaptation in some countries has been specifically linked to the measures for reducing emissions.

Adaptation is a very broad concept, and as applied to climate change it can be used in a variety of ways. An impression of this variety can be sensed by reference to three definitions found in the recent literature. The following definitions are taken from the recent literature:

> Adaptation to climate is the process through which people reduce the adverse effects of climate on their health and well-being, and take advantage of the opportunities that their climatic environment provides (Burton, 1992).

> . . . the term adaptation means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change (Stakhiv, 1993).
>
> Adaptability refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions (IPCC, 1996).

These three definitions give a flavour of the range of ideas included under the term adaptation. It is also helpful sometimes to view complex concepts like adaptation through their opposites. For adaptation, this can mean its absence or something that is contrary to it. The absence of adaptation means doing nothing to offset adverse impacts. It can mean, for example, that a particular threat has been considered together with the costs of potential adaptive response, and that it has been considered better to do nothing and take the risk, rather than bear the costs of adaptation (cost-benefit analyses).

The notion of maladaptation refers to those actions which tend to increase vulnerability to climate change. It is possible to make development or investment decisions while neglecting the actual or potential impacts of climate or climate change. Such decisions are termed maladaptive. The concept of maladaptation applies not only to climate change, but also to present or "normal" climate. Hence a first step in adapting to climate change can be to stop or alter existing maladaptive processes or practices. For example, increased vulnerability to future climate change is being created where properties are being built in hazard zones such as flood plains or coastal areas that are now subject to floods and storms.

5.2.2 What are adaptation measures?

There are potentially many adaptation measures that may be adopted in response to climate change. The Second Assessment Report of IPCC Working Group II mentioned or described 228 different adaptation measures (IPCC, 1995).

It is useful therefore to classify adaptation measures using an overall framework. A commonly used classification groups adaptation measures into eight categories (Burton et al., 1993):

1. *Bear losses.* All other adaptation measures may be compared with the baseline response of "doing nothing" except bearing or accepting the losses. In theory, bearing loss occurs when those affected have no capacity to respond in any other ways (for example, in extremely poor communities) or where the costs of adaptation measures are considered to be high in relation to the risk or the expected damages.

2. *Share losses.* This type of adaptation response involves sharing the losses among a wider community. Such actions take place in traditional societies and in the most

complex, high-tech societies. In traditional societies, many mechanisms exist to share losses among a wider community, such as extended families and village-level or similar small-scale communities. At the other end of the spectrum, large-scale societies share losses through public relief, rehabilitation, and reconstruction paid for from public funds. Sharing losses can also be achieved through private insurance.

3. *Modify the threat.* For some risks, it is possible to exercise a degree of control over the environmental threat itself. When this is a "natural" event such as a flood or a drought, possible measures include flood control works (dams, dikes, levees). For climate change, the major modification possibility is to slow the rate of climate change by reducing greenhouse gas emissions and eventually stabilising greenhouse concentrations in the atmosphere. In the language of the UNFCCC, such measures are referred to as mitigation of climate change and are considered to be in a different category of response from adaptation measures.

4. *Prevent effects.* A frequently used set of adaptation measures involves steps to prevent the effects of climate change and variability. An example would be for agriculture: changes in crop management practices such as increased irrigation water, additional fertiliser, and pest and disease control.

5. *Change use.* Where the threat of climate change makes the continuation of an economic activity impossible or extremely risky, consideration can be given to changing the use. For example, a farmer may choose to substitute a more drought-tolerant crop or switch to varieties with lower moisture. Similarly, crop land may be returned to pasture or forest, or other uses may be found such as recreation, wildlife refuges, or national parks.

6. *Change location.* A more extreme response is to change the location of economic activities. There is considerable speculation, for example, about relocating major crops and farming regions away from areas of increased aridity and heat to areas that are currently cooler and which may become more attractive for some crops in the future (Rosenzweig and Parry, 1994).

7. *Research*. The process of adaptation can also be advanced by research into new technologies and new methods of adaptation.

8. *Educate, inform, and encourage behavioural change.* Another type of adaptation is the dissemination of knowledge through education and public information campaigns, leading to behavioural change. Such activities have been little recognised and given little priority in the past, but are likely to assume increased importance as the need to involve more communities, sectors, and regions in adaptation becomes apparent.

The IPCC Technical Guidelines (Carter et al., 1994) include another category of adaptation called restoration. This is described as follows: "Restoration, which aims to restore a system to its original condition following damage or modification due to climate". From the perspective of adaptation as a continuous process, and as a learning process, the notion of restoration might even be considered as maladaptive, if by

restoration is meant a return to a pre-existing state. Successful adaptation is more likely to involve making changes after an event to reduce future vulnerability.

5.2.3 Adapt to what?

Knowledge of present and future climate is not by itself sufficient basis for the development of an adaptive response. Further information is needed on the likely or possible impacts of these changes. This in turn requires an understanding of the relationship between climate (including many specific climate parameters) and socio-economic activities, as described in Chapter 1, Getting Started.

The understanding of adaptation to climate change can be increased by investigating adaptation to present climate as well as future climate. Adapting to present climate is not the same as adapting to future climate change, but provided that allowances are made for the differences, much can be learned about adaptation options and the process of their adoption. Studies of adaptation to current climate also make it clear that human activities are not now always as well adapted to climate as they might be. The mounting losses from great natural disasters for example (Figure 5.1 and Table 5.1) are in substantial part associated with extreme atmospheric events. It has been shown (Burton et al., 1993) that these losses cannot be ascribed to the events alone but are also due to lack of appropriate human adaptation (also called human adjustment) and that losses are in some cases being increased by maladaptation.

In the development context, therefore, a prudent adaptive response to the threat of climate change may be to improve adaptation to existing climate and its variability, including extreme events. Improving adaptation to current climate variability is not an alternative to preparing for adaptation to longer term changes in climate. It is an adjunct, a useful first and preparatory step that strengthens capacity now to deal with future circumstances.

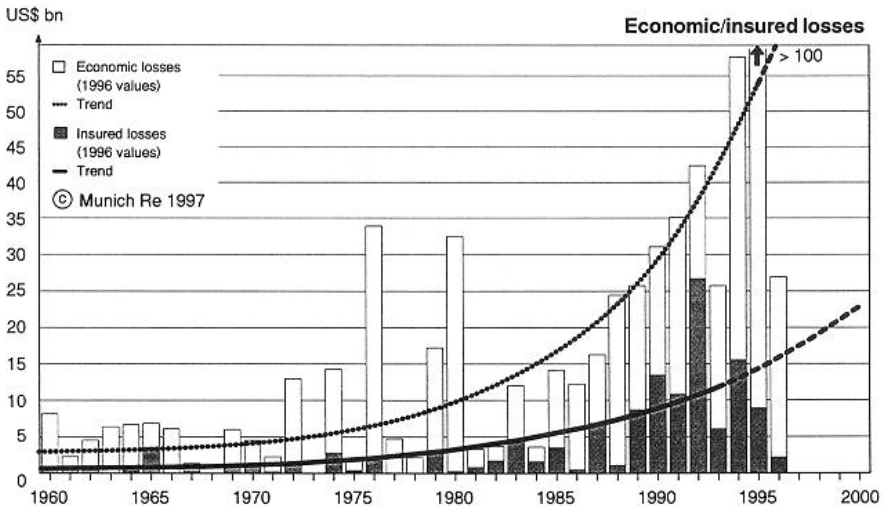


Figure 5.1 Economic and insured losses due to great natural disasters, 1960-1993, with trends extrapolated to 2000 (Source: Munich Reinsurance, 1994, as cited in McCulloch and Etkin, 1995).

Table 5.1. Decadal totals of economic and insured losses (billions of 1993 US$) (Source: Munich Reinsurance (1994); cited in McCulloch and Etkin (1995).

Losses	1960-1969	1970-1979	1980-1989	1984-1993	Last 10 years[1]
Economic	42.7	82.2	130.5	204.4	4.8
Insured	5.7	9.6	26.3	69.5	12.2

[1] The losses of the last 10 years, i.e., 1984-1993 divided by the losses of the 1960s. Therefore economic losses are 4.8 times greater and insured losses 12.2 times greater.

Source: Munich Reinsurance, 1994, as cited in McCulloch and Etkin, 1995.

5.2.4 Who and what is it that adapts?

Adaptation occurs in both natural and socio-economic systems. All species of plant and animal life are adapted and adapting to climate, and may be expected to respond adaptively to future climate change to the extent that time allows. The more mobile species may be able to migrate fast enough, whereas the less mobile may be in danger of severe impact, up to and including extinction. In some instances migration may be impossible, as in island ecosystems or high mountain ecosystems, where the limits of migration are set by the height of the mountains. The adaptation of natural unmanaged ecosystems does not have to be left entirely to chance. It is possible to adopt policies and practices which assist species in adapting, for example, by designating and protecting migration corridors.

By analogy, similar relationships exist in socio-economic systems. All socio-economic sectors (e.g., agriculture, forestry, water resources) are now adapted to some extent to climate, and these adaptations have to be changed to fit the new conditions of a changing climate. This includes, for example, adaptation by farmers, by farm suppliers, by consumers of farm products, by agricultural policy makers, in short, by all the stakeholders in the agricultural system. Much the same can be said for all other socio-economic sectors. Each adapts as a whole and in its component or constituent parts. Each of these socio-economic sectors also adapt in association with other sectors.

Adaptation in socio-economic sectors is generally considered to be easier to implement when the investment of activity has a shorter product cycle. For example, a different grain crop can be planted every year, whereas tree crops require longer to replace, and forests have a life-cycle of decades to hundreds of years. Large-scale and long-term indivisible investments (such as dams, irrigation projects, coastal defences, bridges, and storm drainage systems) can be costly to retrofit to meet new climate conditions, and so adaptation measures need to be considered in such investment decisions at an earlier stage. Long-term adaptation is therefore an ongoing process that involves ecosystems

and socio-economic systems in their entirety. Adaptation is in effect the process of successful change or evolution. Studies of adaptation to future climate therefore need to consider other changes as well. This is why scenarios of future climate should be complemented with socio-economic scenarios, even though it is recognised that this significantly increases the uncertainty of projections (see Chapters 2 and 3).

Everything and everyone can in theory adapt. There are two purposes for impact and adaptation research. One is to provide possibilities, options, information, and understanding that will facilitate successful adaptation; the other is to gain a better understanding of vulnerability, i.e. the residual impacts after adaptation has been considered and adopted where appropriate.

5.2.5 How does adaptation occur?

An important distinction is made between adaptation that may be expected to occur by itself — often called autonomous or spontaneous adaptation — and adaptation which requires conscious intervention or preparation, which is referred to as planned adaptation, or adaptation strategy or policy. This distinction may be applied at different levels of decision making. For example, from the perspective of a Ministry of Agriculture, autonomous adaptation may refer to those actions that farmers undertake themselves without government intervention, such as a decision to plant a different crop or variety or to change the time of planting. From a farmer's perspective, however, such an action is not spontaneous but is likely to have involved some serious consideration and advance planning. Although considerable analysis can go into farm-level decisions, the main concern of this handbook is the identification and assessment of adaptation options at the governmental or sectoral level.

5.2.6 When does adaptation take place?

Adaptation can occur before, during, or after any external stimulus or threat. Thus it is quite possible to take adaptive measures in anticipation of climate change. Such adaptation measures are called anticipatory or preventive adaptation (Smith, 1997).

Climate change may actually be experienced as a change in frequency or intensity of extreme events. For example, a severe drought, flood, or windstorm may be associated with climate change. Measures can be taken in advance to reduce impacts or damage, including provision of additional water supplies or more economical use of remaining supplies (in the case of drought), and steps to protect or remove vulnerable property from floods or windstorms. Hence disaster preparedness is an important component of climate change action plans.

Adaptation measures taken in anticipation of climate change can and usually should be harmonised with responses to current extreme events. Adaptation to extreme climatic events in the present may or may not take account of future climate change. However, since such extreme events will be a feature of climate change in the future, it makes sense to improve responses to similar events now occurring. In effect, improving response to extreme climatic events in the present (reduce vulnerability, increase

resilience, and strengthen adaptation capacity) provides a sort of training opportunity for learning how to improve response to future climate change. The fact that many regions now report increasing damage from climate events (extreme and not so extreme) demonstrates that current adaptation is not always as effective as it might be, and that maladaptive choices are being made.

Adaptation during climate change has been described as gradual, step-wise, and short-term.

Adaptation also takes place after the event. Provision of relief to the victims and measures to rehabilitate and reconstruct damaged property and communities are part of the adaptation process, not least because actions after one event may serve also as preparation for the next occurrence. In bringing relief and rehabilitation to affected people and settlements, it is important to take advantage of the opportunity to make them less vulnerable, and to take care not to increase future vulnerability. A sound policy of reconstruction after extreme climatic events can thus be part of a progressive adaptation strategy. Where the reverse occurs and greater vulnerability is created over time, it is again appropriate to speak of maladaptation.

Adaptation after climate change impacts can be describe as reactive or corrective. All these terms are used at some point in the following chapters. The terminology is still evolving and has not reached a steady state. As research proceeds and as the policy debates continue, it is possible that a more standardised terminology will emerge.

5.2.7 What capacity to adapt?

Adaptation capacity remains a large question in all discussions about the impact of climate change. At one end of the scale are confident assertions that human adaptive capacity is very large and that a great deal can and will be done to reduce the impact of climate change by the adoption of adaptation measures (NAS, 1992; Goklany, 1995). In different climatic regions of the world, people have adapted to much greater extremes of climate, it is argued, than the scale of changes now anticipated. Since human beings have managed to survive and prosper in such a wide range of climatic environments, it is sometimes claimed that coping with climate change will not present a difficult problem, although it is recognised that adaptation could be costly and that the costs remain in large part unknown and unestimated.

At the other end of the scale it is argued that adaptation in socio-economic systems takes time and might be extremely costly. Considerable expenditure could be involved in making the necessary changes to reduce vulnerability to climate change, although these costs have not been the subject of much research to date. Further, the fact that human communities are adapted to life across a wide range of climate conditions does not mean that such adaptations and the measures they involve can readily be transferred from region to region rapidly. The harmony of agriculture, forestry, water management, and so forth with climate conditions has been developed over decades, even centuries, in a slow, evolutionary process often involving much trial and error. Unless the projected

pace of climate change can be slowed, there may not be enough time for many of the proposed adaptation measures to be implemented.

5.2.8 Increasing adaptive capacity

If adaptation of various kinds is to be used as an effective way of responding to climate change, measures to increase adaptive capacity will be needed. What determines adaptive capacity? Probably the strongest explanatory variable for adaptive capacity is wealth. The wealthier nations, as well as wealthier communities and individuals within nations, have the resources at their disposal to seek out and pay for adaptation options to reduce vulnerability and to recover from adverse impacts.

Wealth by itself is not sufficient. Indeed there are circumstances when wealth can encourage decisions which are maladaptive in the long run, but can be profitable at the short term. For example, the development of recreational amenities in high hazard zones such as exposed coastal areas or on sites subject to the risk of avalanche may increase exposure, vulnerability, and damages. The added adaptive capacity that is theoretically possible with greater wealth must also be blended with scientific understanding and public knowledge and awareness. Scientific understanding is needed especially of the potential impacts of climate change. Thus the answers to the question “adapt to what?” are important.

Other factors that can enhance adaptive capacity include access to information and especially to technology and technological skills. The strengths of the institutions of government and of the private sector are also important. Another factor is the relative distribution of health, education, and wealth. Where a society or community includes a larger number of poor, handicapped, elderly, very young, poorly educated, and diseased or otherwise unhealthy people, then the more vulnerable it is likely to be to climate change and the lower the adaptive capacity. Countries also differ widely in the extent to which their economy is reliant upon climate-susceptible activities such as agriculture, forestry, or fisheries, or is poorly endowed with water resources. In general, the greater the degree of reliance on climate sensitive activities the greater the vulnerability to climate change; conversely, the greater the portion of the economy in manufacturing and the service sector the lower the vulnerability.

A final, somewhat intangible, factor is the degree of flexibility in a society. Adaptation to climate change requires changes in how and where natural resources are managed. The ease with which changes can be made in management of natural resources is an important factor in the ability of a society to adapt to climate change.

5.3 Assessment of adaptation measures

Assessment of adaptation options requires an understanding of what is meant by adaptation; what we mean by the term adaptation is described above. Assessment of adaptation also requires evaluating how well different practices and technologies will avoid adverse climate change impacts by preventing or minimising them, by enabling a

speedy and efficient recovery from their effects, or by taking advantage of positive impacts. This section addresses the evaluation of adaptation measures.

The methods described here provide a range of options that have been applied to the evaluation of climate change adaptation measures. Some options rely heavily on expert judgement and have limited data needs, whereas others involve quantitative analysis and require more resources.

In general, an approach to estimate (in either qualitative or quantitative terms) both the costs of implementing a measure and the potential benefits from doing so is needed. Benefits can be thought of as climate change impacts (or damages) avoided or positive effects taken advantage of. Thus, such an assessment relies heavily on the techniques described in the sectoral chapters of this handbook for assessing the impacts of climate change. The impact assessment methods need to be applied in an iterative manner in which total potential impacts are estimated first and then, as adaptation options are identified, the potential impacts under adaptation are estimated. This information can then be used to estimate the damages avoided because of adaptation. For example, climate-crop models are commonly used to identify changes in crop yields under different conditions of temperature, moisture availability, and so forth. Where significant declines in yield are suggested by the models, it is possible to run the same climate scenario with different management options or substitute crops. It has been found in many such studies that farm-level adaptation (changing cultivars or varieties of crop) can significantly reduce the impact of projected climate change on crop yields, and in some cases can lead to an increase in yields over present values (e.g., Rosenzweig and Iglesias, 1994). Such modelling exercises are useful in identifying the technical possibilities for adaptation and the potential damages avoided. They do not by themselves give any information on the likelihood of such adaptation options being used or adopted or on the relative benefits of various adaptation options. Nor do they tell what obstacles to their adoption may exist. Thus, for most purposes, these results need to be further evaluated using the techniques described in this section.

The costs of implementing adaptation measures and attempts to rank or monetise benefits involve a number of important considerations, but the applicable tools are generally those that are used to evaluate other projects or policy questions. In addition, many sources provide guidance for conducting benefit-cost analysis in the context of project analysis (see, e.g., Ward and Derren, 1991; Winpenny, 1991; Pearce et al., 1994; Squire and van der Tak, 1995). Other sources provide detailed guidance on how to assess environmental impacts and incorporate them in benefit-cost analysis (World Bank, 1991; Hassan and Hutchinson, 1992; Lutz, 1993; Munasinghe, 1993; Dixon et al., 1994; Weiss, 1994; ADB, 1996). To select the appropriate assessment methods, a country needs to consider the following criteria:

1. How well the method addresses the goals and objectives of the assessment (e.g., the level of precision needed for decision making, the usefulness of the tool for building consensus).

2. The ability of the method to address uncertainties (e.g., related to the magnitude of impacts, the timing and spatial pattern of impacts, the effectiveness of adaptation measures, and future socio-economic conditions).

3. The availability of inputs (e.g., data from impact assessments, socio-economic data, cost estimates).

4. The availability of resources (e.g., time, expertise, money).

This section reviews a range of qualitative and quantitative approaches for weighing the trade-offs among adaptation measures. Many of these options can be used in combination. Each method is described and evaluated here against the four criteria listed above, and the results of this evaluation are summarised in a matrix at the end of this section.

5.3.1 Forecasting by analogy

Empirical investigations of adaptation to present-day climate variability or to climate events in the past provide insights into the process of adaptation and the conditions needed for its successful promotion. Forecasting by analogy looks at events that have had a similar effect in the recent past to the likely impact of future events associated with climate change. The assumption is that lessons can be learned from such past experience and applied to future situations (Glantz, 1988).The following is a broad outline for the design of studies of current adaptation to climate variability or of past analogues for future climate changes.

- Identify from climate scenarios the climate changes which are likely to have a significant impact on the country or region. For example, this may be sea level rise (associated with coastal flooding, strong winds, and salt-water intrusion), or a change in the temperature/ precipitation regime (associated with an increase in the frequency and intensity of droughts or storms).

- Review recent experience in managing responses to climatic/hydrometeorological events that correspond to the changes under climate change scenarios. Where there is no local experience of response to such changes or events, examples may be sought in other, similar places.

- For the chosen events, examine the instrumental record to obtain an up-to-date picture of the trends in occurrence, including any changes in magnitude, frequency, duration, or location. It is important to evaluate how the selected events compare to expected events under climate change.

- For the chosen events, conduct a survey and analysis of the actions taken, drawing as appropriate upon the discussion of types of adaptation in this chapter. The objective of assembling information on adaptation actions is to permit an analysis of their effectiveness in reducing impacts. Such an analysis could be directed to actual adaptation responses that have been tried, and also to other possible action which

have been proposed but not used. The detailed design of any such study depends upon local circumstances.

Level of Precision. This approach does not provide a method to weigh the trade-offs among different adaptation options, rather it provides insights into how the adaptation process may work. The advantage of this approach is that it relies on actual human responses to past events. However, there are many uncertainties related to how economic and social events may differ in the future, thus leading to potentially different outcomes.

Ability to Address Uncertainties. This approach requires the use of expert judgement to carefully select analogue scenarios, assess how uncertainties may affect the findings, and interpret the results in a manner that will be useful to decision makers.

Input Needed. To apply this approach, the experts will need to access a wide range of data and expertise related to past events. Preparing this type of study usually involves the relevant research community of climatologists, meteorologists, hydrologists, entomologists, epidemiologists, and the like. The organisation of such a study often requires the co-operation of an interdisciplinary and multi-agency group or task force. Steps may be needed to bring such a group together and to involve them in the design of the study.

Resource Requirements. The resources needed to apply this approach will vary depending on the effort devoted to developing a sufficiently detailed understanding of past events to guide future planning and decision making. This effort is likely to be more resource intensive than some of the other available methods, and usually would be conducted in conjunction with one or more of the methods that allow for a direct comparison of potential adaptation options.

5.3.2 Screening to identify anticipatory adaptation measures

A formal approach for applying expert judgement to screen adaptation measures is included in the US Country Studies Program's Steps in Preparing Climate Change Action Plans: A Handbook (Benioff and Warren, 1996). The approach focuses on anticipatory adaptation measures (i.e., options that can be implemented now to address climate change). In this approach, each measure is evaluated against six suggested criteria; however, other criteria may be used.

This approach relies heavily on expert judgement. Expert judgement can be used to develop a preliminary evaluation of various adaptation measures or to identify measures for further research. In addition, approaches that rely on expert judgement are often useful for involving decision makers and key stakeholders and can be used to build consensus. However, it is important to recognise that in applying these approaches it is possible to tailor a case to make a certain strategy appear to be better than others. Therefore, justification of each decision that relies on expert judgement should be provided.

Level of Precision. Given an adequate understanding of potential vulnerability, planning and policy objectives, and the relative level of effort associated with various adaptation options, experts can conduct a screening that will be useful for general planning or for establishing research priorities. However, it is likely that in many cases this approach will not provide the level of detail needed to support the implementation of adaptation measures that involve investments in resources or political capital.

Ability to Address Uncertainties. This method does not include any formal provisions to explicitly consider uncertainties in the assessment. It is left to the experts to weigh uncertainties.

Input Needed. The experts will need to be familiar with the results of the impact assessment, potential changes in socio-economic conditions in the absence of climate change, current planning or investment initiatives, relative costs and benefits of measures, implementation barriers, and other adaptation or mitigation policies.

Resource Requirements. The resources need for this method are relatively modest. This is the simplest approach, the least time consuming, and the least costly. Depending on the level of expertise available and the effort made to build consensus, this approach could require an investment of as little as a few hours to a few days for one to several individuals.

5.3.3 Tool for environmental assessment and management

The Tool for Environmental Assessment and Management (TEAM) was developed by Decision Focus, Inc. (DFI, 1996) for the US Environmental Protection Agency (USEPA) as a user-friendly software package to assist decision makers in evaluating strategies for adapting to climate change. TEAM uses a multi-criteria approach to help planners recognise a wide range of decision criteria and set priorities among objectives. This approach does not necessarily identify an “optimal” adaptation option, but rather requires the analyst to draw a conclusion by looking at the “whole picture”. The advantage of TEAM is that it provides an interactive format to help structure and define the decisions under consideration.

The TEAM software includes components on coastal resources, water resources, and agriculture, as well as a generic assessment component. The software asks the user to enter information through a guided question-and-answer sequence and then uses a menu-driven graphic presentation of results for the evaluation of adaptation options. The user selects specific “strategies” or adaptation options and criteria and then assigns a relative score (excellent, good, fair, and poor) for how each strategy meets each criterion. In addition to qualitative rankings, the user has the option to enter absolute data for each strategy (e.g., dollar amounts).

The TEAM software requires an IBM-compatible 386 PC with a 3.5" disk drive and a mouse. To run TEAM, the user also needs Microsoft Windows (Version 3.1 or higher) and Microsoft Excel (Version 5.0c).

Level of Precision. The results provided by this method are relative and do not necessarily identify a single preferred option, but allow the user to consider multiple criteria. This method is very flexible in the level of effort required and, consequently, the level of precision provided by results. For example, this method can be used to quickly generate results based on expert judgement or can be used in conjunction with detailed benefit-cost analyses to incorporate multiple criteria. In presenting results, it is important to highlight the subjective nature of relative rankings to ensure that quantitative scoring does not imply a level of precision that is unwarranted.

Ability to Address Uncertainties. This method allows the analyst to quickly and easily adjust relative scoring or to weight various criteria to test the sensitivity of the analysis to uncertainties, and thus to develop a range of potential results.

Input Needed. The experts will need to be able to develop relative rankings of how selected measures compare to selected criteria. This will require familiarity with the results of the impact assessment, potential changes in socio-economic conditions in the absence of climate change, current planning or investment initiatives, and relative costs and benefits of measures, implementation barriers, and other adaptation or mitigation policies.

Resource Requirements. The resources needed for this method can be relatively modest, but depend on the level of effort that goes into developing the relative rankings of different measures. The more effort that goes into evaluating how the options perform against specific criteria the more precise the results will be. It may only take a few hours to complete an initial analysis using the TEAM software. However, the effort to provide necessary information to the experts involved, build consensus among stakeholders, and develop a format for presenting the results of this analysis could require an investment of a few days to several months.

5.3.4 Adaptation decision matrix

The Adaptation Decision Matrix (ADM) is presented in the US Country Studies Program's *Steps in Preparing Climate Change Action Plans: A Handbook* (Benioff and Warren, 1996). This approach uses a decision matrix to analyse the cost-effectiveness of adaptation options by comparing costs measured in dollars with benefits measured in a common metric, but not necessarily monetary units.[3] This approach is useful when many important aspects of a decision cannot be easily monetised.

Level of Precision. The advantage of this approach is that it provides a way to identify the most preferred measure for reaching a goal and incorporates multiple criteria or objectives. However, it does not obviate the need for detailed research and analysis to

[3] This approach differs somewhat from the description of cost-effectiveness analysis in Section 5.3.6 because in the ADM method the estimate of benefits is usually subjective and combines several different types of benefit attributes, whereas in cost-effectiveness analysis either the benefits or the costs are fixed and a measure of effectiveness is developed (such as monetary units per lives saved).

provide a basis for evaluating the adaptation measures against the criteria of interest. Without such detailed analysis, the scoring may be mainly subjective and thus not necessarily reliable for policy making.

Ability to Address Uncertainties. Similar to the TEAM software, this method allows the analyst to quickly and easily adjust relative scoring or to weight various criteria to conduct sensitivity tests and develop a range of potential results.

Input Needed. The experts will need to be able to (1) develop either qualitative or quantitative estimates of how measures compare to selected criteria and (2) estimate the cost of implementing such measures. It is important to note that to evaluate relative cost-effectiveness the metric used to estimate benefits must be the same across all criteria. Developing such estimates will require familiarity with the results of the impact assessment, potential changes in socio-economic conditions in the absence of climate change, current planning or investment initiatives, and relative costs and benefits of measures, implementation barriers, and other adaptation or mitigation policies.

Resource Requirements. Similar to the TEAM software, the resources needed for this method depend on the level of effort that goes into developing the benefit and cost estimates for different measures. Depending on the level of expertise, information available, and desire to build consensus, this approach could require an investment of only a few days to several months.

5.3.5 Benefit-cost analysis

Unlike cost-effectiveness analysis and multi-criteria assessment, benefit-cost analysis can be used to determine whether an individual adaptation response is economically justified (i.e., are its benefits greater than its costs?) The other evaluations can be used to rank responses but not to determine whether they should be undertaken at all.

A benefit-cost analysis involves essentially two steps: identifying and screening benefits and costs to be included in the analysis, and converting them to monetary units when possible. No economic analysis is able to account for every benefit and cost, but including all important benefits and costs is key to a valid analysis. The following description of benefit-cost analysis is adapted from Smith et al. (1997).

A methodical identification and screening analysis is useful for ensuring that all potentially important types of benefits and costs have been considered. Using lists of potential climate change impacts and possible adaptation measures, applicable benefit or cost categories can be identified. The identification and screening process provides the foundation for an economic evaluation of adaptation measures. Economic evaluation consists of quantifying and valuing the benefits and costs. Quantification entails measuring the benefits and costs in terms of their physical effects on market systems and non-market systems. Valuation entails converting the magnitude of each benefit or cost from physical units to monetary units.

Level of Precision. This method can be used to develop detailed and robust analyses of adaptation measures. However, this approach can be highly resource intensive,

particularly when primary research is undertaken. As an alternative, expedited evaluation methods when carefully applied are very useful, particularly within the context of project evaluation. However, expedited methods are not generally as precise or technically defensible as primary research. In some cases, expedited evaluations will not be of sufficient technical quality or comprehensiveness to provide an accurate perspective of a measure's overall merits and faults.

Ability to Address Uncertainties. This method is amenable to a variety of techniques to address uncertainties (see Section 5.3.7).

Input Needed. The analysts will need to be able to develop qualitative and quantitative estimates of the costs and benefits associated with an adaptation measure. Developing such estimates involves having the right types of data, technical expertise, and professional judgement about the use of prices or the development of more appropriate measures of welfare. It also will require familiarity with impact assessments, future socio-economic baselines, and similar measures that have already been implemented either in the current areas of interest or in a comparable geographic region. Limitations in available data can prevent the useful application of this method.

Resource Requirements. This method is relatively resource intensive and depends on the availability of sufficient time, budget, and expertise to undertake a detailed analysis. Expedited evaluation methods include a range of techniques and practices that require fewer resources; however, even these expedited techniques are generally more resource intensive than methods that rely on expert judgement. Depending on the level of expertise and information available, this approach could require an investment of several months to several years.

5.3.6 Cost-effectiveness analysis

Cost-effectiveness analysis is a variation of cost-benefit analysis in which either benefits or costs are fixed. This method is applicable when it is difficult to quantify and monetise benefits. In such cases, it may be possible to compare adaptation measures by determining their cost differences for achieving a fixed level of effectiveness.

Level of Precision. If the goals of the assessment are amenable to this type of analysis, this method can be used to develop results with sufficient precision for decision making. However, because benefits and costs are measured in different units, cost-effectiveness analysis provides no direct guidance when it is unclear whether the total benefit from an adaptation measure justifies the total cost, or when the optimal budget level for an adaptation measure is unclear.

Ability to Address Uncertainties. The sensitivity of results generated using this method can be tested by varying the fixed value (benefits or costs). In addition, a variety of techniques may be used to address uncertainties (see Section 5.3.7).

Input Needed. Because benefits will need to be quantified only in a common metric (rather than monetised), the input needs for this method are somewhat less burdensome than those for benefit-cost analysis. However, as in benefit-cost analysis, developing

quantitative estimates of benefits will require familiarity with impact assessments, future socio-economic baselines, and similar measures that have already been completed either in the current area of interest or in a comparable geographic region.

Resource Requirements. Although this method is somewhat less resource intensive than benefit-cost analysis, it still requires a considerable commitment of time and resources. Depending on the level of expertise and information available, this approach could require an investment of several months to several years.

5.3.7 Approaches for addressing uncertainty and risk

Analysis of climate change adaptation measures involves a number of analytical challenges, including scientific uncertainties, economic uncertainties, data limitations, and the need to evaluate issues that may not readily be conceived of in monetary terms. The following approaches can be used, in conjunction with quantitative analyses of adaptation measures, to address uncertainty and risk (adapted from Hurd et al., 1997, and Hobbs et al., 1997).

1. *Sensitivity analysis.* This is the process of determining whether varying input values significantly alters the output value (net benefits). In other words, determining whether the decision has characteristics that suggest that climate change (or other sources of uncertainty) could be relevant.

2. *Use of scenarios.* This approach is generally used for climate parameters, but it can also be used for other areas of uncertainty. It involves generating a limited set of plausible input values and their associated outcomes (net benefits). Evaluating a measure under both “worst case” and “best case” scenarios can illustrate whether uncertainty is important to the final decision.

3. *Switch-point analysis.* This approach is used to identify the conditions that would be necessary to alter a decision regarding whether or not to implement an adaptation measure. For example, how much would climate need to change to make an adaptation measure the preferred alternative? Or, if a decision were made assuming no climate change, but global warming occurred anyway, would the potential loss of net benefits be significant enough to alter a choice of adaptation measures? A decision maker can then evaluate this information against subjective probabilities (e.g., how likely is it that such a climate change will occur?).

4. *Decision analysis under uncertainty.* This approach applies decision criteria such as maximising the payoff by selecting the adaptation with the largest potential gain (“maximax”) or minimising the maximum regret (“minimax”) by avoiding the most damaging outcome to evaluate alternative measures when the probabilities associated with various inputs or outcomes are unknown.

5. *Decision analysis under risk*. This approach use a decision criterion (e.g., maximise the expected payoff) in conjunction with subjective probabilities or probability distributions for the inputs of the analysis (e.g., risks, values, costs) to evaluate the payoffs from alternative measures. This approach can be presented in a payoff

matrix or a decision tree. If delaying implementation of adaptation measures is feasible, the benefits of waiting a decade or longer for better information could be evaluated using Bayesian analysis (for example, see Hobbs et al., 1997).

Each of these approaches provides insight into the relevance of uncertainty in a decision about whether or not to implement a specific adaptation measure. The analyst can begin with the least resource-intensive approaches (e.g., meta-analysis, sensitivity analysis) and can use the results of these analyses to determine whether more sophisticated approaches (e.g., probabilistic approaches) are warranted. Examples of these approaches can be found in the literature on quantitative analysis (e.g., Stokey and Zeckhauser, 1978; McKenna, 1980; Clemen, 1990; Finkle, 1990; Morgan and Henrion, 1990; Perrings, 1991; Ready, 1995; Dakins et al., 1996; Schimmelpfennig, 1996; Hobbs et al., 1997).

5.3.8 Implementation analysis

Another method that relies on expert judgement and allows for consideration of multiple criteria is implementation analysis. Rather than evaluating the relative benefits from different adaptation measures, this method focuses on identifying the least costly measure (in terms of money, time, political capital, etc.). This approach is useful when it can be assumed that the benefits of different adaptation measures will be comparable. In applying this method, the analyst identifies any implementation barriers and evaluates how difficult or easy it will be to overcome these barriers. A matrix can be used to identify barriers, actions to overcome the barriers, what time and financial resources are required, and the degree of difficulty (i.e., a summary of the other criteria) in overcoming the barriers. A three-point rating system can be used in which one X represents the barrier easiest to overcome and three Xs represent those most difficult to overcome. The results from the analysis of barriers can be used to adjust rankings of measures developed from a benefit-cost analysis, an ADM analysis, or a TEAM multi-attribute analysis. However, if the barriers are only a matter of cost, the estimated costs of overcoming the barriers can be entered directly into the evaluation of adaptation options. The IPCC's (1990) *Report of the Coastal Zone Management Subgroup: Strategies for Adaptation to Sea Level Rise* provides a description of potential environmental, economic, social, legal, and institutional barriers to adapting to sea level rise (this report also groups sea level rise adaptation options in three categories, retreat, accommodate, and protect, and describes how the potential barriers differ between these groups).

Level of Precision. This approach is useful when benefits can be assumed to be positive and comparable among a set of adaptation measures. The level of precision provided depends on the effort spent in estimating the requirements for overcoming barriers, and this approach will not necessarily identify a single preferred measure.

Ability to Address Uncertainties. This method does not include any formal provisions to explicitly consider uncertainties in the assessment. It is left to the experts to weigh potential uncertainties.

Input Needed. The experts will need to be able to develop qualitative or quantitative estimates of what it would take to overcome identified barriers to implementation. Developing such estimates will require familiarity with similar implementation efforts that have already been completed either in the area of interest or in a comparable geographic region.

Resource Requirements. The resources needed for this method depend on the level of effort that goes into developing the estimates for overcoming implementation barriers associated with different measures. Depending on the level of expertise, information available, and desire to build consensus, this approach could require an investment of only a few days to several months.

5.3.9 Summary of selected methods

A summary of selected methods, selection criteria, and references is provided in Table 5.2.

Table 5.2 Summary of selected methods

Method	Level of Precision	Ability to Address Uncertainties	Inputs Needed	Resource Require-ments	Sources
Forecasting by Analogy	Low	No formal provisions.	Detailed historical or contemporary account	Moderate	Glantz, 1991
Screening	Low	No formal provisions	Expertise to make a yes/no evaluation against selected criteria	Low	Benioff and Warren, 1996
Tool for Environmental Assessment and Management	Moderate	Assumptions can easily be modified to test sensitivity	Expertise to establish a relative ranking against selected criteria; computer and software	Moderate	DFI, 1996
Adaptation Decision Matrix	Moderate	Assumptions can easily be modified to test sensitivity	Expertise to establish a relative ranking against selected criteria, ability to estimate costs of measures	Moderate	Benioff and Warren, 1996
Benefit-Cost Analysis	High	Variety of approaches	Data intensive	High	Smith et al., 1997
Cost-Effectiveness Analysis	Useful when either benefits or costs are fixed	Variety of approaches	Moderately data intensive	High	McKenna, 1980
Implementation Analysis	Useful when benefits can be assumed to be positive and comparable among measures	No formal provisions	Expertise to estimate requirements for overcoming barriers	Low	ADB, 1996; IPCC, 1990

References

ADB. 1996. *Economic Evaluation of Environmental Impacts*. Vol. 1 and II. Asian Development Bank, Manila, Philippines.

Benioff, R. and J. Warren. 1996. *Steps in Preparing Climate Change Action Plans: A Handbook.* US Country Studies Program, Washington, DC.

Benioff, R., S. Guill, and J. Lee (eds). 1996. *Vulnerability and Adaptation Assessments: An International Guidebook.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Burton, I., R.W. Kates and G.F. White. 1993. *The Environment as Hazard*. Second Edition. Guilford Press, New York.

Burton, I. 1992. *Adapt and Thrive*. Canadian Climate Centre, Downsview, Ontario. Unpublished manuscript.

Carter T.R., M.L. Parry, H. Harasawa, and S. Nishioka (eds). 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Department of Geography, University College, London. U.K. and Centre for Global Environment Research, National Institute for Environmental Studies, Japan.

Clemen, R. 1990. *Making Hard Decisions.* Duxbury Press Belmont, California, USA.

Dakins, M.E., J.E. Toll, and M.J. Small. 1996. Risk-based environmental remediation: Bayesian Monte Carlo analysis and the expected value of sample information. *Risk Analysis* 16(1), 67-79.

DFI. 1996. *Tool for Environmental Assessment and Management: Quick Reference Pamphlet*. Prepared by Decision Focus Incorporated in cooperation with V. Narayanan of Technical Resources International and Office of Policy, Planning and Evaluation, US Environmental Protection Agency, Washington, DC.

Dixon, J.A., L. Scura, R.A. Carpenter, and P.B. Sherman. 1994. *Economic Analysis of Environmental Impacts (2nd Edition).* Published in association with ADB and the World Bank. Earthscan, London.

Finkle, A.M. 1990. *Confronting Uncertainty in Risk Management: A Guide for Decision-Makers*. Resources for the Future, Washington, DC.

Glantz, M.H. 1991. The use of analogies in forecasting ecological and societal responses to global warming. *Environment* 33 (5), 10-15 and 27-33.

Glantz, M.H. (ed). 1988. *Societal Responses to Regional Climate Change: Forecasting by Analogy*. Westview Press, Boulder, Colorado, USA.

Goklany, I.M. 1995. Strategies to enhance adaptability: Technological change, sustainable growth and free trade. *Climatic Change* 30, 427-449.

Hassan, H.M. and C. Hutchinson. (eds). 1992. *Natural Resource and Environmental Information for Decisionmaking.* The World Bank, Washington, DC.

Hobbs, B.J., P.T. Chao, and B.N. Venkatesh. 1997. Using decision analysis to include climate change in water resources decision making. *Climatic Change* 37, 177-202.

Hurd, B., R.S. Raucher, G. Pitts, T. Ottem, R. Bishop, M. Hanemann, and D. Burmaster. 1997. *White Paper: Analysis of Uncertain Regulatory Benefits and Costs: Assessing the Conceptual and Empirical Issues*. Prepared for the U.S. Environmental Protection Agency, Office of Economy and Environment, Washington, DC.

IPCC. 1990. *Report of the Coastal Zone Management Subgroup: Strategies for Adaptation to Sea Level Rise*. Prepared by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change, Geneva.

IPPC. 1995. *Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds). Cambridge University Press, Cambridge, United Kingdom.

IPCC. 1966. *Climate Change 1995. The Science of Climate Change. Contribution of the WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. J.T. Houghton et al. (eds.) Cambridge University Press, Cambridge, United Kingdom.

Lutz, E. (ed). 1993. *Toward Improved Accounting for the Environment.* The World Bank, Washington, DC.

McCulloch, J. and D. Etkin (eds). 1995. *Proceedings of a Workshop on Improving Responses to Atmospheric Extremes: The Role of Insurance and Compensation.* Held October 3-4, 1944. Environment Canada, The Climate Institute, and the Insurers Advisory Organization, Toronto.

McKenna C. K. 1980. *Quantitative Methods for Public Decision Making*. Quantitative Methods for Management Series. McGraw-Hill, New York.

Morgan, W.G. and M. Henrion. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, United Kingdom.

Munasinghe, M. 1993. *Environmental Economics and Natural Resource Management in Developing Countries.* The World Bank/CIDIE (Committee of International Development Institutions on the Environment), Washington, DC.

NAS, 1992. *Policy Implications of Greenhouse Warming*. National Academy of Sciences. National Academy Press, Washington, DC.

Pearce, D.W. et al. 1994. *Project and Policy Appraisal: Integrating Economics and the Environment.* OECD, Paris.

Perrings, C. 1991. Reserved rationality and the precautionary principle: Technological change, time, and uncertainty in environmental decision making. In *Ecological Economics*, R. Costanza (ed.), Columbia University Press, New York.

Ready, R.C. 1995. Environmental valuation under uncertainty. In *Handbook of Environmental Economics*, D.W. Bromley (ed), Blackwell, Cambridge, Massachusetts, USA.

Rosenzweig, C. and Iglesias, A. (eds.) 1994. *Implications of Climate Change for International Agriculture: Crop Modeling Study*. EPA 230-B-94-003. US Environmental Protection Agency, Washington, DC.

Rosenzweig, C. and M.L. Parry, 1994. Potential impact of climate change on world food supply. *Nature* 367, 133-138.

Schimmelpfennig, D. 1996. Uncertainty in economic models of climate change impacts. *Climatic Change* 33, 213-234.

Smit, B. 1993. *Adaptation to Climate Variability and Change. Report of the Task Force on Climate Adaptation*. Canadian Climate Program Board Department of Geography, University of Guelph, Occasional Paper No. 19. Environment Canada, Downsview, Ontario.

Smith, J.B. 1997. Setting priorities for adapting to climate change. *Global Environmental Change* 7, 251-264.

Smith, J.B, S.E. Ragland, R.S. Raucher, and I. Burton. 1997. An Overview of Methods for Assessing Benefits and Costs of Adaptation Measures. Report to the Global Environment Facility. Hagler Bailly Services, Inc., Boulder, Colorado, USA.

Squire, L. and H.G. van der Tak. 1995. *Economic Analysis of Projects.* The World Bank, Washington, DC.

Stakhiv, E. 1993. Evaluation of IPCC Adaptation Strategies. Draft Report. Institute for Water Resources, U.S. Army Corps of Engineers. Fort Belvoir VA, USA.

Stokey E. and R. Zeckhauser. 1978. *A Primer for Policy Analysis*. W.W. Norton & Company, New York.

Ward, W.A. and B.J. Deren. 1991. *The Economics of Project Analysis: A Practitioner's Guide.* Prepared for the Economic Development Institute of the World Bank, Washington, DC.

Weiss, J. 1994. *The Economics of Project Appraisal and the Environment.* Edward Elgar Publishing Company, Brookfield, Vermont, USA.

Winpenny, J.T. 1991. *Values for the Environment: A Guide to Economic Appraisal*. Overseas Development Institute, London.

World Bank. 1991. *Environmental Assessment Sourcebook: Volumes I-III.* World Bank Technical Papers 139, 140, and 154. The World Bank, Washington, DC.

6 Water Resources

Principal Lead Author
Kenneth M. Strzepek [1]

Lead Authors
Max Campos, Costa Rica
Zdzislaw Kaczmarek, Poland
Arturo Sanchez, Costa Rica
David N. Yates, USA

Contributing Authors
J. Carmichael, USA
G.M.S. Chavula, Malawi
A.B. Chirwa, Malawi
M. Mirza, Bangledesh
B. Minarik, Slovakia
R. Warrick, New Zealand

6.1 Nature of the problem

In the water resources sector, technology, economics, and institutions interact to make water supply meet water demand. In managing water resource systems, water managers ask, “Can we modify the management of current systems to adapt to climate change?”, “How might climate change impact the design of new water resource infrastructure?”, and “Should climate change be included in our current planning?”.

The water resources sector by its nature is very adaptive, on various time and spatial scales. Also, water managers have a wealth of knowledge and experience managing under changing hydrologic and socio-economic conditions. This experience places them in a good situation to be able to adapt the operation of their systems to a change in climate, if that change is not too great or too rapid.

This chapter takes a comprehensive view of climate change impacts on water resources; it includes water demand and water resources management as well as water supply. Water resources management (i.e., the water supply infrastructure and operating procedures) is an important aspect of a climate change assessment because it is used to redistribute water supply both spatially and temporally to meet water demand. Insights can be gained and conclusions drawn from analysing only the physical impacts on water supply and water demand, but the focus of the approach presented here is to provide

[1] Civil, Environmental and Arch Engineering, University of Colorado, Boulder, CO, USA.

insights for decision and policy makers as to the potential impacts of climate change on the water resources sector and the options for adaptation.

This chapter familiarises the user with the range of methods that are appropriate for (1) estimating the biophysical impacts of climate change on hydrologic resources in terms of water quantity (annual and seasonal distribution) and quality, and aquatic ecosystem effects; and (2) estimating the socio-economic impacts of climate change on both water demand (including direct impacts on hydrologic resources and indirect impacts via other biophysical impacts) and water resources management parameters (including, but not limited to, river runoff, reservoir yields, supply reliability, hydropower production, water use, supply/demand balances, effects and costs of adaptation, and economic impacts with and without adaptations). The potential climate change impacts to various components of the water resources sector are summarised below.

Biophysical impacts

Hydrologic resources. The main components of the hydrologic cycle are precipitation, evaporation, and transpiration. Changes in the climate parameters – solar radiation, wind, temperature, humidity, and cloudiness – will affect evaporation and transpiration. Changes in evapotranspiration and precipitation will affect the amount and the distribution, spatially and temporally, of surface runoff. Changes in runoff in combination with sea level rise will affect streamflow and groundwater flow. Streamflow and groundwater are considered natural water or hydrologic resources.

Water quality. All offstream water withdrawals change the chemical, biological, or thermal quality of the water during use, and when that water is released back to the stream, it can affect the water quality of the receiving water body. For water quality and environmental protection needs, the water management system can be designed to provide either dilution flows or wastewater treatment. Climate change can affect the water quality aspect of the water management system in three ways. First, reduced hydrologic resources may leave less dilution flow in the stream, leading to degraded water quality or increased investments in wastewater treatment. Second, higher temperatures reduce the dissolved oxygen content in water bodies. Third, in response to climate change, water uses, especially those for agriculture, may increase the concentration of pollution being released to the streams. Together, these pose a threat to the water quality and the integrity of the aquatic ecosystem.

Aquatic ecosystem. **{**tc "***Aquatic ecosystem (natural water demands)*** " \l 2.**}** There are many complex interactions among the elements of the aquatic ecosystem, which comprises natural water demands. Climate is a direct input to the energy source and chemical variables of the system, and an indirect input to the flow regime, habitat structure, and biotic factors. These elements are in a sensitive balance. Even a slight change to just a few of the key elements can greatly affect the integrity of the ecosystem.

Socio-economic impacts

Water demand. Water use is generally divided into non-market and market uses. Non-market water uses are aesthetic uses, certain recreational uses, and aquatic ecosystem integrity.

Market water uses can be aggregated into five major water use sectors:

- Agriculture: Irrigation and livestock;
- Industry: Industrial, mining, navigation, recreation;
- Energy: Thermoelectric cooling and hydroelectric power;
- Municipal: Public supply, domestic, and commercial;
- Reservoir.

An additional market use is dilution water for pollution abatement. It is typically considered a market use because it can be valued at the cost savings of additional waste treatment to meet water quality standards.

Water management system. The water management system (i.e., water supply system) is made of two parts: surface water and groundwater. Although they are linked at the river basin water balance level, they are distinct in the water supply infrastructure. Climate change can affect the surface water supply via reduced flows into the storage reservoir or increased variability in inflow, which will affect firm yields from existing storage facilities. An additional impact in arid and semi-arid regions could be increased reservoir evaporative losses. The groundwater supply will be affected by increased or decreased percolation of water due to changes in the amount and distribution of precipitation and streamflow. This can lead to increased pumping costs if percolation decreases because of decreased precipitation or losses of soil moisture from increased evapotranspiration.

6.1.1 Components of a water resources assessment

With great uncertainties about the local and regional impacts of climate change on hydrologic resources and uncertain future water demands driven by socio-economic change, an assessment of climate change impacts on water resources is a complex process. In addressing the sensitivity of water resources to changes in climate, the biophysical and socio-economic conditions must be considered.

To help policy and decision makers focus on the issues of climate change and water resources, it is recommended to divide the assessment process into five main components:

- Assessment of biophysical impacts on:
  - hydrologic resources,

  - water quality, and
  - aquatic ecosystem integrity.

- Assessment of socio-economic impacts on:
  - demand from market water use sectors, and
  - water resources management systems.

The assessment of climate change impacts on the hydrologic resources of a country is the first and most important assessment to be carried out because a wide range of modelling tools allows for a quantitative analysis of climate change impacts, and hydrologic resources are the key component of the entire water resources sector (i.e., aquatic ecosystems, water quality, water use, and water management are all based on the hydrologic resources of a country).

For national assessments with limited budgets, it may be possible to analyse only a single component of the water resources sector. If so, it is recommended that the impacts on the hydrologic resources be assessed. Expert judgement could then be used to assess impacts on the other sector components. For example, under increased temperatures, wetlands will experience increased potential evapotranspiration, as well as reduced streamflows to the wetlands. Thus, the wetlands would experience both increased demand for water and reduced supply of water, which would decrease wetland area. This type of analysis can be attempted at a quantitative or qualitative level, depending on data and expertise.

If there are sufficient resources to perform a quantitative assessment of additional components, priority should be based on the relative social, ecological, and economic importance of each component to the country. For example, a country highly dependent upon irrigated agriculture should assess impacts on water use and the water management system. A country dependent upon wildlife, sport fishing, or eco-tourism should analyse the impacts on aquatic ecosystems.

There are no formal guidelines for determining priorities. Local experts in consultation with international impact assessment experts should be able to develop a country study plan that fits within the given budget constraints. Alternatively, a reasonable budget should be developed which allows for a comprehensive analysis of impacts at the country level.

6.1.2 Key considerations in defining the scope

The steps below highlight key considerations in defining the scope of a water resources assessment.

Select the exposure unit

The river basin would generally be the most appropriate primary exposure unit for assessing impacts on hydrologic resources. The relationship between a river basin impact assessment and a country level assessment can take four different forms:

1. The river basin assessed covers only a portion of the total watershed and the country's hydroclimatic characteristics are homogeneous (e.g., the Nitra River in Slovakia is part of the Danube Basin, but representative of most of Slovakia).

2. The river basin assessed covers only a portion of the total watershed and the country has two or more distinct hydroclimatic zones (e.g., Kazakhstan's eastern river, the Ulba Ula).

3. The watershed is encompassed in a large regional or international river basin and is in an upper basin location (e.g., Uganda and Sudan are completely within the upper portion of the Nile Basin).

4. The watershed is encompassed in a large regional or international river basin and is in a lower basin location (e.g., Bangladesh is in the lower part of the Ganges and Brahmaputra systems; Vietnam is in the lower part of the Mekong Basin).

Define the study area

The study area should be selected according to the hydrology and the specific goals of the assessment. Two general types of study areas, representative basin or sub-area, can be used.

If the river basin assessed covers only a portion of the total watershed, then the river basin can be used as a representative basin. A country located in a single hydroclimatic zone can be represented by a single basin. A country made up of two or more distinct hydroclimatic zones can be represented by a river basin from each zone.

If the watershed lies completely within a large regional or international river basin, then two sub-area approaches can be used. Countries located in the headwaters of the basin (upper basin location) can use a single upstream sub-area basin. Countries located in the middle or downstream of the basin (lower basin location) should assess both the upstream portion of the basin as well as the country's portion.

Select a time horizon

The temporal and spatial scales of an assessment are linked in hydrologic modelling and depend on the type of impact to be assessed. For floods, a small time step of hours or days is needed, whereas for droughts, months to years are needed. Yates and Strzepek (1994) have shown that, particularly in arid and semi-arid regions, an annual time step does not capture climate change impacts well and a seasonal or monthly model is needed.

For countries with limited streamflow data, an annual time step is recommended for the hydrologic assessment. Only mean annual precipitation and mean annual temperature are used to predict basin runoff. Although not extremely accurate for modelling current runoff, use of an annual time step is adequate to predict the change in the basin runoff

associated with changes in temperature and precipitation. Thus, it provides an adequate indication of a river basin's sensitivity to climate change.

For countries with sufficient streamflow and climate data, a monthly lumped integral model or water balance approach is recommended for the hydrologic assessment. However, monthly models might not capture the true response of the basin to precipitation events distributed throughout the month, so it is important to understand what kind of error is introduced when aggregating temporally. As an example, if data are given daily and aggregated uniformly over the month, information that gives insight into a basin's response to storm events can be lost. The total monthly precipitation could occur during one storm, but when applied uniformly over the month, true soil moisture dynamics might not be captured.

In hydrologic modelling, the temporal scale determines the spatial scale. For example, flash floods that last 1 to 12 hours occur in basins on a scale of 1 to 200 square miles. A larger lumped spatial scale will not capture the dynamics of this event. Thus, the spatial scale should be sufficiently small so that the flood wave can travel one spatial step in less than a single time step. Although the primary exposure unit for assessing hydrologic climate impacts suggested in this chapter is a river basin, in some cases, river basins will need to be divided into sub-basins to ensure that the spatial scale matches the selected temporal scale.

The other components of a water resources assessment require longer time steps and larger spatial scales. For these components, it is better to aggregate the hydrologic assessment over time and space than to increase the temporal and spatial scales of the hydrologic analyses to match the socio-economic and water management systems analyses.

Identify a preliminary range of adaptations

Identifying preliminary adaptation measures allows the user to ensure that the selected methods will be useful for evaluating adaptation and that assessments of related sectors that may affect adaptation possibilities will be undertaken (e.g., if one of the adaptation measures considered is implementation of more efficient irrigation practices, an agriculture assessment should also be performed).

The first step in identifying preliminary adaptation options is to determine whether the country (or river basin of interest) has a dominant water use such as thermoelectric cooling or irrigation. If a dominant water use is identified, then this activity should be examined for adaptation opportunities. For example, where irrigation is important, crop water use and yield could be modelled as a function of temperature and precipitation. Alternatively, areas of large municipal demand could be examined using a tool to model possible water saving via various demand management schemes. Thus, identifying preliminary adaptation options can help direct and focus the assessment process.

Determine general data availability

The data required for a water resources assessment are a mixture of hydrometeorological and socio-economic data. In general, a water resources assessment requires substantial amounts of reliable data to lend credence to the results being generated. The key is to find a study site (i.e., a river basin) that has a sufficiently long runoff record, no less than 10 years of data. Ideally, this basin will also have a corresponding climate record of the same or longer period.

Much of the needed data can be found in published sources, whereas estimates such as changes in technology and future water use require educated guesses of experts. Listed in the tables in Section 6.2 are the data needs for each of the assessment components. Section 6.3 provides sources for these data. The issues of providing spatially averaged values and generating mean monthly values are discussed in detail in the references and suggested readings are provided at the end of this chapter.

Determine the need for integration across sectors

The water resources sector does not function in isolation. Water resources are a common link to several sectors. The human health, fisheries, coastal zone, and agriculture sectors typically will need specific information about water resources impacts for their impact assessments. Water resources researchers should have strong linkages to other sectors being assessed so that selected methods and approaches satisfy the needs of other sectors and data are shared across sectors. Water resources needs to be conceptualised as an integrated sector and not as an independent one.

6.2 An array of methods

The user should critically review the methods available to assess the biophysical and socio-economic impacts of climate change before selecting and testing one or more that will be used. This section provides an overview of available methods for the biophysical components of a water resources assessment: hydrologic resources, water quality, and aquatic ecosystem integrity; and the socio-economic components: demand from water use sectors and the water management system. Each subsection presents a brief theoretical background of techniques and methods and discusses the application of the techniques in assessing climate change impacts. To assist the user, the strengths and weaknesses of each method are also described. Countries with extensive hydrologic modelling experience and existing distributed integral and distributed differential models should continue to use these models.

As a general caution, when choosing a method for analysing climate change impacts on water resources, it is important to keep in mind the difference between precision and accuracy in analysis, particularly in quantitative modelling. Models with very detailed spatial and temporal representations of biophysical processes require much data but can predict, precisely, the impact of climate change on the state of the system at a particular location and time. However, models that describe the potential change in the driving climate variables provide very coarse and uncertain outputs both in space and time.

These models are not very precise. If the results from the climate models are used to drive precise process models, the results may be precise but will not be accurate, because the exact changes in climate parameters at the level of detail of the process model are not known.

An example would be trying to assess the impact of climate change on flash floods using standard general circulation models (GCM) estimates of monthly precipitation. Flash floods usually occur on catchments of less than 500 square kilometres with rainfall events of less than 6 hours. Hydrologic methods to model this process are very detailed and precise. Standard GCM precipitation output is often on a spatial scale of 50,000 square kilometres and a time scale of one month. The GCM results typically provide very little information about the small-scale weather systems responsible for flash floods. Using imprecise GCM output with a precise hydrologic model will provide precise streamflows that are not very accurate. Three approaches that can be used to address this problem are estimates of climate change that account for spatial variability, techniques to account for uncertainty in estimates, and careful presentation of the results to appropriately reflect their true accuracy.

6.2.1 Criteria for selecting methods to assess biophysical impacts

The methodologies and modelling approaches presented here span a wide range of spatial and temporal scales. The choices to be made in method selection depend on the hydroclimatic conditions, water resource modelling expertise, data availability, and the resources (time and funding) dedicated to the water resources assessment. If resources are limited, the scope of the analysis can be limited and a detailed analysis can be conducted on a few study sites or sector components, rather than a simple analysis with a comprehensive scope. The relative performance of recommended models against these criteria is shown in Tables 6.1, 6.2, 6.3, and 6.4, which summarise available models.

6.2.1.1 Assessment of hydrologic resources impacts

Techniques to assess impacts on hydrologic resources are available for all spatial and temporal scales of analysis and for all levels of local data availability. Four methods for assessing impacts on hydrologic resources are described: expert judgement, analogue methods, predictive models, and process-based models.

Expert judgement

In terms of assessing climate change impacts on hydrologic resources, expert judgement has a very limited role. Given the data availability and expertise in water resources, it is likely that for all but the smallest budgets some quantitative modelling of hydrologic resources could be performed. However, if additional modelling is infeasible, expert judgement is a valuable tool in assessing impacts on water quality, aquatic ecosystems, water demand, and water management systems. In applying expert judgement, the user

should be aware that experts may have difficulty estimating the consequences of events that have not been experienced and may not be able to provide estimates with sufficient accuracy for decision making.

Table 6.1 Lumped integral models and requirements.

Models	Time Scale	Spatial Scale	Processes Modelled	Data Needs	Cost	Time	Expertise	Advantages/ Disadvantages
CLIRUN	Day, month	Catchment to large basin	Drought, annual yields, large-scale flooding	PET, precipitation, runoff	Low	Low	Medium	Limited data needs; runoff data needed
HBV	Hour, day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data, runoff	Medium	Medium	Medium	Wide range of temporal and spatial scales modelled; large data requirements
NAM	Hour, day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data, runoff	Medium	Medium	Medium	Wide range of temporal and spatial scales modelled; large data requirements
SHE	Day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data, runoff	Medium	High	Medium	Wide range of temporal and spatial scales modelled; large data requirements
TANK	Day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, runoff	Medium	Medium	Medium	Wide range of temporal and spatial scales modelled; limited data requirements
WATBAL	Day, month	Catchment to large basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, runoff	Low	Low	Medium	Limited data needs; PET and snowmelt modelled; runoff data needed

Table 6.2 Distributed integral models and requirements.

Models	Time Scale	Spatial Scale	Processes Modelled	Data Needs	Cost	Time	Expertise	Advantages/ Disadvantages
HEC-1	Rainfall event	Catchment	Flooding	Rainfall, land cover, soil data	Medium	Medium	Medium	Flash flood modelling, ungauged catchments; event model not continuous simulation
HSPF	Hour, day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data, runoff	High	High	High	Wide range of temporal and spatial scales modelled; large data requirements
PRMS	Day	Catchment to river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data, runoff	High	High	High	Wide range of temporal and spatial scales modelled; detailed and large data requirements
IDRO-1	Rainfall event	Catchment	Flooding	Rainfall, land cover, soil data	Medium	Medium	Medium	Flash flood modelling, ungauged catchments; event model not continuous simulation
SWRRB	Day	Small to large river basin	Drought, annual yields, large-scale flooding	Temperature, precipitation, land cover, soil data	High	High	Medium	Ungauged basins, large scale, water quality and erosion; detailed and large data requirements

Analogue methods

Examination of past extreme events is useful for showing how systems actually were affected by climate variation and how they responded. For example, Campos and Sanchez (1995), used past El Niño events as an analogue climate change scenario for Costa Rica and Panama. This study found important decreases in reservoir storage, reduction of firm power generation, and an increase in fossil fuel burning for electricity generation. The problem with analogue scenarios is that greenhouse gas induced climate change is likely to differ from past events, and care should be taken in finding and using appropriate analogues. Nonetheless, analogues can be useful for analysing the vulnerability of the water resources sector to extreme events.

Predictive models

Predictive models which are based on empirical and statistical relationships can be used for quick and low cost assessments. However, because these models do not account for physical thresholds, the process-based models described below generally are most appropriate for water resources impact assessments. Many of the predictive models are based on a fundamental theorem in hydrologic theory that was first developed by Dooge (1992). This theorem suggests that when looking at the long-term water balance of a large catchment or region, an appropriate assumption is that the change in storage is zero. Dooge (1992) points out that any estimate of the impact of climate change on water resources depends on the ability to relate change in actual evapotranspiration to estimated changes in precipitation and potential evapotranspiration. Thus, annual average statistical values of a watershed have been used to develop models that can estimate impacts to water resources. Two annual models are a model developed by Turc (1954), which relates precipitation and temperature to runoff, and a model developed by Ol□dekop (as cited in Yates, 1996), which relates precipitation, evapotranspiration, and potential evapotranspiration to runoff.

Process-based models

Process-based hydrologic models are a class of numerical models used to describe the response of watersheds to climatic inputs. Although the available models vary in precision, they all fall within the acceptable level of accuracy for estimating climate change impacts. Yates et al. (1997) compared hydrologic assessment techniques ranging from simple to complex and found that they estimate the same magnitude and direction of impacts.

Four classifications or methodologies for modelling hydrologic processes were identified by Todini (1988). In increasing order of data needs, these classifications are stochastic, lumped integral, distributed integral, and distributed differential models.

The stochastic modelling approach centers on developing relationships that describe an output variable like runoff in terms of input variables such as precipitation and temperature, without prescribing the physical processes that occur.

Lumped integral models are physically based models that normally use the fewest number of parameters that can describe a basin's response to climatological events. These models are designed to look at medium-to-large watershed areas (100 to 30,000 square kilometres; Z. Kaczmarek, Polish Institute of Geophysics, personal communication, 1997) and are often referred to as water balance models. These models are not usually applicable to event-scale processes (daily or hourly precipitation events), but are used after uniformly lumping a sequence of events (precipitation and runoff) to monthly mean values. The catchment or sub-catchment is modelled as a single, homogenous unit subject to uniform events and parameters. Parameters for this model type usually are not meant to represent physical catchment characteristics. These models can incorporate interannual variability by accounting for changes in catchment storage. The common link in most water balance approaches is the computation of a mass balance within the soil moisture zone. There are many ways of representing the infiltration, discharge, and storage behaviour of the soil moisture zone (Shaw, 1983; Chow et al., 1988; Rawls et al., 1993). However, it has been shown that some basins are quite sensitive to the estimation of potential evapotranspiration, so an accurate representation of this variable is important (Dooge, 1992; Yates and Strzepek, 1994).

CLIRUN (Kaczmarek, 1991) is a water balance runoff model that has been applied in many climate change assessments. The approach from this model was adapted and integrated into WATBAL, a climate impact assessment tool for studying river basin response to climate change (Yates, 1996) (see Box 6.1).

There are two major sources of water pollution: non-point sources (e.g., agriculture runoff) and point sources (e.g., municipal and industrial discharges). Climate change could have significant impacts on non-point source pollution from agriculture. In addition, cooling water discharges could be affected by changes in temperature and streamflow. However, climate change should have little impact on per capita or per industrial unit pollution from municipal and industrial sources.

A wide variety of water quality models, in terms of both water quality constituents and level of detail, are available. Some of these models include simple conservative dilution models, simple dissolved oxygen models, detailed dissolved oxygen models (with the nitrogen and phosphorus cycles modelled), toxics models, and advective diffusion models for temperature, dissolved oxygen, nutrients (nitrogen and phosphorus), algae/periphyton/macrophytes, and pH.

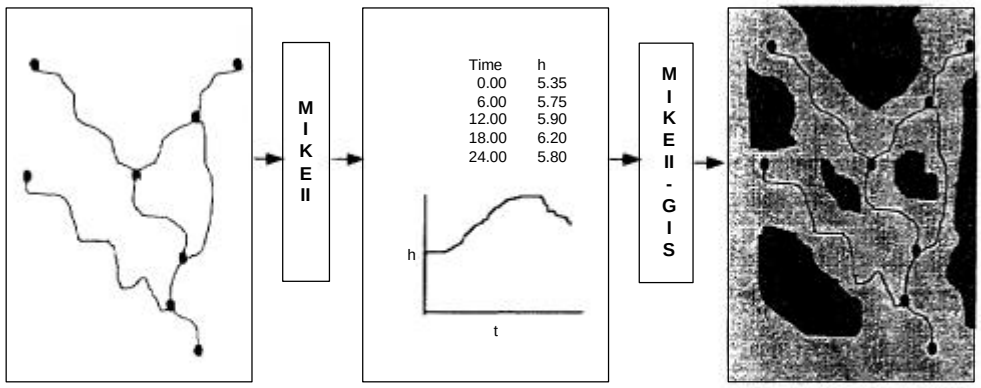
For non-point source pollutants, there are area- and model-based methods for estimating pollutant loadings to receiving waters. Simple area-based loadings can be used as inputs to river and lake/reservoir water quality models. Where data and resources exist, models of non-point source loadings can be used, and adaptations can also be evaluated. Chapra (1996) provides a detailed background of water quality modelling

and simplified tools of analysis. See Box 6.2 for an example of how a water quality model has been used to analyse climate change impacts.

Box 6.1 Example: Modelling the effects of climate change on flooding in Bangladesh (Mirza and Warrick, 1997).

Problem: To estimate climate change impacts on flooding.

Methods: Using an empirical model of precipitation and temperature to the streamflow for the Ganges, Brahmaputra and Meghna River basins. These results are input to the hydraulic model MIKE11 to determine water surface elevation. Then a GIS with DEM data was used to estimate flood inundation.



Box 6.1, Figure 1 Schematic of methodology for water quality assessment.

Testing of methods/sensitivity: MIKE 11 and the empirical runoff models were calibrated and validated for the three basins.

Scenarios: Four GCM scenarios were developed for the catchments. The CISCRO9, GFDL, UKTR, and LLNL GCMs were scaled for three different global mean temperatures using the SYNGEN system.

Impacts:

Area (in million hectares) of Bangladesh inundated under 2, 4 and 6°C temperatures for the precipitation changes from four GCMs

Model	Mean				20-year			
	0°C	2°C	4°C	6°C	O°C	2°C	4°C	6°C
CSIR09	3.77	4.65	4.68	4.71	5.18	5.18	5.20	5.22
UKTR	3.77	4.87	5.08	5.24	5.18	5.35	5.50	5.61
GFDL	3.77	4.84	5.02	5.17	5.18	5.33	5.36	5.48
LLNL	3.77	4.68	4.73	4.78	5.18	5.20	5.25	5.29

The results show that for a 2°C global warming all scenarios estimate approximately a 30% increase in mean flooding, but less than a 5 % increase for the 20-year flood (P>Q =0.05).

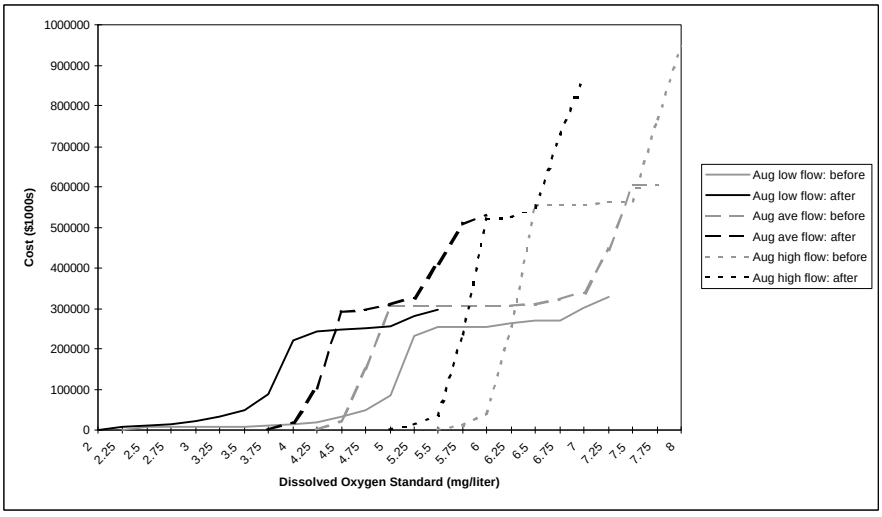
Box 6.2 Example: Impact of climate change on water quality and wastewater treatment costs on the Nitra River Basin, Slovakia (Carmichael et al., 1996).

Background: Climate change is expected to lead to increased river and lake temperatures, due to the interaction of these bodies with air, by mixing and surface interaction. Changes in water temperature affect water quality. For example, the saturation concentration of dissolved oxygen and the reaction rates of BOD, nitrogen and phosphorus with dissolved oxygen and with phytoplankton all will change in response to water temperature changes

Problem: To estimate climate change impacts on water quality and waste water treatment costs on the Nitra River Basin, Slovakia.

Methods The meteorological relationship between air temperature and river temperature is estimated using regression analysis. River water temperature is regressed on air temperature, using a 29-year time series for the region. This yields the necessary coefficients for estimating how great the climate change impact will be on the hydrologic system.

The hydrological system is modelled using Qual2e, which was developed by USEPA and the Environmental Research Laboratory in Athens, Georgia, USA (Brown and Barnwell, 1987). The effects of changes in river water temperature and river flows on river water quality may then be analysed. The economic model incorporates two processes. First, the impacts of pollutant emissions from each polluting site on dissolved oxygen quality levels downstream are included. Second, the economic costs of choosing different treatment options (primary, secondary, tertiary, etc.) at each polluting site are included. The model is then able to choose the least-cost combination of treatment plants, across all polluting sites, that will improve dissolved oxygen concentrations to predetermined levels.



Box 6.2, Figure 1 Impact of Climate Change on Least Cost Water Quality Solution for the Nitra River

Testing of methods/sensitivity: the models are calibrated for existing conditions and observed DO levels are compared.

Scenarios: Two synthetic local scenarios were developed by researchers in the Hydro-Meteorological Service.

***Impacts*:** The results indicate that costs required to reach generally acceptable quality levels rise exponentially, particularly in August and October. Extremely expensive wastewater treatment technologies may be partially avoided under the present situation, while significant improvements in water quality are still accomplished. Under the climate change scenario, these expensive technologies are forced into use at a much lower water quality standard. Only small quality improvements may be accomplished before costs rise dramatically.

Table 6.3 presents a summary of available water quality assessment models and describes the general requirements for each model. Data requirements for these models are burdensome, and the choice of model will depend on data availability. The user should choose the surface water quality model (streams and reservoirs) that has appropriate temporal and spatial scales for the chosen scope of analysis and the data available.

Table 6.3 Water quality assessment models and requirements.

Model	Time Scale	Processes Modelled	Management Modelling	Cost	Time	Expertise	Advantages
Qual2E	Multiple	Nitrogen, phosphorus, dissolved oxygen	No	Medium	High	High	Widely used
DESERT	Multiple	Nitrogen, phosphorus, dissolved oxygen	Yes	Medium	High	High	Optimisation
STREAM-PLAN	Multiple	Simple ground-water	Yes	Medium	High	Medium	Economic modelling of treatment options
WEAP	Month	Groundwater and water quality	Yes	Medium	High	Medium	Quality and quantity modelling

6.2.1.2 Assessment of aquatic ecosystem integrity impacts

The aquatic ecosystem is complex, and assessment of this system will most likely depend on the construction of predictive models. Freshwater ecosystems contain flora and fauna such as algae, periphyton, and macrophytes residing directly in the water, and these are affected by water quantity and quality. Models of these systems are sometimes considered water quality models (see above), and many exist.

Assessing impacts on other aspects of the aquatic ecosystem (such as fish, waterfowl, and wildlife that depend on water quality and quantity) requires integration with biological assessment methods that have been developed for other sectors such as biodiversity and fisheries. The results of a hydrologic assessment are often required as inputs for these other sectoral assessments. For example, fish are sensitive to water temperature and dissolved oxygen contents. Thus, modelling the climate change impacts on these parameters provides the necessary information for assessing impacts to fisheries.

6.2.2 Criteria for selecting methods to assess socio-economic impacts

The methodologies and modelling approaches presented here span a wide range of spatial and temporal scales. There is no single model or approach appropriate for all socio-economic assessments of climate change impacts. Different approaches provide different insights. Care must be taken to understand the strengths and weaknesses of the approach being used and to identify the appropriate policy questions that it will be used to answer. The selection of an approach will depend on the particular impact of concern (e.g., job losses, changes in economic growth, relative growth of different sectors over time) and the particular question being addressed (e.g., are there any significant interactions between sectors as climate changes?). The approach should always be selected based on the question of interest.

As with the biophysical methods, the choices to be made in method selection depends on the hydroclimatic conditions, the water resource modelling expertise, data availability, and the resources (time and funding) dedicated to the water resources assessment. The relative performance of recommended models against these criteria is shown in Tables 6.4 and 6.5, which summarise available models.

6.2.2.1 Assessment of water demand impacts

When addressing climate change impacts on water demand, one is faced with two major questions:

- What will the water demand be under future baseline conditions?
- How will climate change affect that baseline scenario?

In many respects, determining the impact of warmer temperatures and changes in precipitation on water demand is more straightforward than "estimating" water demand 50 to 100 years in the future. Water demand is a function of population growth, economic growth, and technological change. Techniques for developing future socio-economic scenarios for these variables are described in Chapter 2. As part of the water resources assessment, the socio-economic scenarios are used to estimate water demand in the future and the expected change in water demand as a result of climate change.

Demand under future conditions

It will be very difficult within the scope of a climate change assessment to do more than a simple "statistical" approach to estimate water use:

$$\text{Water Use}_{RY} = [\text{Activity}_{RY}] \times [\text{Water Use/Activity}]_{RY},$$

where RY is a reference year (year of interest for the assessment).

The $\text{Activity}_{\mathbf{RY}}$ will be developed as part of the future socio-economic baseline scenario. However, the $[\text{Water Use/Activity}]_{RY}$ must also be estimated. The user should be extremely careful when estimating this number and avoid the temptation of simply applying the average water use per activity as obtained from historical data. It may be that there are no data to justify changing this number. However, a reasonable alternative estimate should be developed based on an assessment of the factors that can affect water demand (and on available reference documents).

What is the amount of water use by an industry, a municipality, or irrigated croplands? Water demand is sometime confused with water requirements. Water requirement is the minimum amount of water needed for social or economic activities. A water requirement does not respond to the price of water supply. Although some social or economic activities such as human daily water consumption or low-flow conditions for navigation exhibit minimum needs or requirements, they are usually only a small part of total water use in the activity.

Demand is a function of price as well as other factors, including the price of substitute goods, institutional requirements or opportunities (e.g., environmental legislation), and income. The user should consider all these factors when estimating demand for water under climate change. For example, Kindler and Russell (1984) point out that per capita domestic or municipal water use is positively correlated to per capita income and inversely correlated to household size. Climate impact analyses for economies that are likely to undergo large changes in per capita income and household sizes over the next 25 to 100 years need to address this issue.

In addition to estimating future water use, the user should also ensure that sensitivity analyses are performed on the $[\text{Water Use/Activity}]_{\mathbf{RY}}$ coefficient to examine the effect of different demand levels on water resource vulnerability.

Demand under climate change conditions

Climate change may affect water use in five water use sectors: agricultural, industrial, energy, municipal, and reservoir losses.

- *Agricultural.* Water use for agriculture includes irrigation and livestock water. Changes in irrigation and livestock water use due to changes in temperature and precipitation can be estimated using climate change impact assessment methods for these sectors (see Chapters 6 and 9). Alternatively, irrigation water use can be estimated by using the appropriate reference crop or crops and a potential evapotranspiration model. Irrigation water is used to make up the difference between crop water requirements and precipitation. Thus, irrigation water use will be the difference between actual evapotranspiration and the new precipitation estimates. Livestock water use can best be estimated from the literature for livestock water use versus climate data. If direct statistical relationships do not exist, then a spatial analogue approach is suggested (i.e., find a location with current hydroclimatic

conditions that are analogous to those forecast for the river basin of interest under climate change and use the per head water use values).

- *Industrial.* Temperature and precipitation have little direct impact on the water use of most industries. Reduction of flow in rivers due to climate change may put increased pressure on waste treatment processes, leading to increased water recycling and a decline in industrial water use, as seen in Sweden (Falkenmark, 1997).

- *Energy.* Water use for energy production takes two forms: hydroelectric and thermoelectric. Reduced flow will reduce hydropower reservoir storage and thus reduce potential energy production. Warmer temperatures will increase evaporation from reservoirs, so more streamflow will be required to maintain the same hydropower energy production. Increased temperature has little direct effect on thermal efficiency; however, increased river temperature and reduced flow can cause cooling discharges to violate environmental standards (see Chapter 11).

- *Municipal.* Kindler and Russell (1984) observed that residential water use is inversely correlated with rainfall and positively correlated with average temperature. Little work has been completed on the impact of long-term climate change on domestic water use. Most analyses to date have drawn information from the response of domestic water users to short-term droughts or warm periods. However, the user must be careful when selecting an analogue approach for domestic water use because climate alone is not sufficient to determine an analogue. Similar socio-economic indicators (income and household size) as well as climatic variables must be used in selecting analogues since, as stated above, domestic water use is correlated with these socio-economic indicators. In addition, short-term responses of water use could be much different than responses to the prospect of permanent water restrictions and possible lifestyle changes.

- *Reservoir losses*. Increased temperatures lead to increased evaporation, with all other meteorological variables held constant. The increase in reservoir losses to evaporation can be estimated using standard depth evaporation estimates, which are based on estimates of lake or reservoir surface areas. Surface area is a function of reservoir geometry and volume. The volume is a function of inflow (runoff) and outflow (releases); therefore, demand and supply for reservoir water must be analysed to quantitatively measure the impact of climate change on reservoir losses to evaporation.

Total water demand is the summation over all water use sectors. The estimate of total demand will reflect potential increases or decreases caused by climate change without any adaptation. In assessing impacts, it is important to clearly identify the level of impact associated with three alternatives: no adaptation, an assumed level of autonomous adaptation, and planned adaptations.

6.2.2.2 Assessment of water management system impacts

Water management system impacts can be analysed using two different approaches. First, water resource system modelling can be used to analyse reservoir systems and determine how design and management assumptions might need to be changed. Second, economic analyses can be used to assess how water demand and supply might be shifted among water uses.

Water resource system modelling

Water resource infrastructure has been developed to protect socio-economic systems from climate variability. The most important component in the water resource infrastructure is the reservoir. This technological element is designed to adjust the temporal distribution of water supply to the demands of the socio-economic system. This entails storing water in wet periods of the year for release in dry periods; storing damaging floodwater for slow, non-damaging release; and providing storage of highly variable yearly flows.

Large capital expenses have been incurred to build water systems whose designs were based on hydrologic regimes assumed to be driven by historical climate conditions. However, if climate change reduces or increases river flow, the design assumptions will need to change. The system may be able to adapt, but at what cost? Reduced flow will mean less supply and potential economic damages. Increased flow may mean an under-designed reservoir or spillway with potential flood risk, which may be reduced by additional capital investment.

Two classes of river basin management models can be used to assess climate change impacts: optimisation and simulation models. A monthly simulation approach would be best if limited data are available. Table 6.4 presents a summary of available river basin simulation models and describes the general requirements for each model. As in the hydrologic assessment, any country with capabilities more advanced than those recommended are encourage to use them as well as the recommended methodologies. Box 6.3 provides an example of an assessment of climate change effects in Malawi.

Table 6.4 River basin simulation models and requirements.

Model	Time scale	Additional processes modelled	Demand modelling	Cost	Time	Expertise	Advantages
HEC-5	10 day, month	No groundwater	No	Medium	Medium	Medium	Detailed multiple reservoir operation
IRIS/IRAS	10 day, month	Groundwater and water quality	No	Low	Medium	Medium	Groundwater, natural aquatic systems and water quality
MITSIM	10 day, month	Simple groundwater	Yes	Low	Medium	Medium	Economic modelling
WEAP	10 day, month	Groundwater and water quality	Yes	Medium	Medium	Medium	Detailed demand modelling

Box 6.3 Example: Impact of climate change on water resources of Malawi (Chavula and Chirwa, 1996).

Problem: To estimate climate change impacts on the national water resources of Malawi and to develop a national management strategy in light of the possible changes.

Methods: 1) Selection of the representative basin throughout the hydro-climatic zones of Malawi, 2) hydro-meteorologic data analysis, 3) calibration and validation of the WATBAL hydrologic model for the representative basins, 4) modelling of the climate change impacts on the representative basins.

Testing of methods/sensitivity: The hydrologic model was calibrated and validated for three basins using 10 years of climate and runoff data sets.

Scenarios: Synthetic sensitivity scenarios.

Impacts: Climate change impacts on water resources show an increase in annual runoff for the GISS scenario and a decrease of runoff for the GFDL scenarios.

Sensitivity of river runoff to changes in precipitation and temperature

		P0	P+10	P+20	P-10	P-20
South	T0	0%	32.4%	73.7%	-24.0%	-41.2%
Rukuru	T2	-15.9%	9.4%	42.7%	-34.4%	-47.9%
	T4	-31.1%	-13.4%	10.6%	-44.2%	-54.1%
Bua	T0	0%	25.5%	55.8%	-21.6%	-39.6%
	T2	-21.1%	-1.2%	22.7%	-38.0%	-52.3%
	T4	-42.6%	-28.1%	-11.3%	-54.6%	-64.9%
Linthipe	T0	0%	27.8%	60.3%	-22.7%	-40.1%
	T2	-13.9%	10.0%	38.1%	-32.9%	-48.0%
	T4	-29.0%	-10.3%	12.2%	-44.0%	-55.7%

Adaptive response: Recommended adaptive responses to climate change for Malawi are to 1) implement water conservation measures, 2) reduce the current variability of runoff by means of increased storage capacity, and 3) enhance measurement, monitoring and knowledge of the hydrologic system.

WEAP (Raskin et al., 1998) is a comprehensive river basin tool that is easy to use and has been employed in a number of climate change impact assessments (e.g., Strzepek, 1997). This tool models reservoirs and their operation, hydropower generation, and water demand for agricultural, municipal, industrial, environmental, and recreational uses. A monthly time step is used in this model, and the results of a hydrologic assessment of runoff changes can be used directly as input to the model.

The list of models presented in Table 6.4 is by no means complete, but it include models that have all been used in climate change assessment and are publicly available for assessments. A more detailed list of hydrologic and systems management software tools can be found in the *Handbook of Hydrology* (Maidment, 1993) and *Handbook of Water Resources* (Mays, 1996).

Economic assessment methods

Strzepek et al. (1996) discusses economic tools for use in climate change assessment. The following is a summary of the key elements of this publication. A variety of analytical methods can be used to assess the economic impacts of climate change (see Chapter 2). Each method has strengths and weaknesses, and each provides different insights useful to decision makers. Any single impact assessment may contain elements of one or more of these methods. Most available models can be categorised as either macroeconomic or sectoral models.

A number of studies have examined the economic consequences of climate impacts as related to water resources (e.g., Vaux and Howitt, 1984; Hurd et al., 1998). Typically, the studies have taken a partial equilibrium sectoral approach, examining the effects in a single market or a group of closely related markets. However, because of complex interdependencies among even seemingly unrelated markets, partial equilibrium analyses can yield potentially misleading results for evaluating broad, economy-wide effects. The potential for error is exacerbated when there are direct impacts on multiple sectors. For example, changes in temperature and precipitation may have a direct impact on the availability of water and on water markets. This direct impact can have indirect effects on markets that rely on the availability of water – and are themselves directly affected by climate change – such as agriculture, forestry, and electricity supply. A partial equilibrium analysis will typically not account for all of the potential indirect effects. An aggregation of results from partial equilibrium analyses of the separate effects will neglect potentially important interdependencies. In contrast, a macroeconomic analysis is internally consistent. The consistency of sectoral forecasts with realistic projections of economic growth is ensured since they are estimated within the context of a single model. However, the ability to model an entire economy is accomplished at the sacrifice of potentially valuable sectoral detail. For many river basin-level analyses of water resources impacts, partial equilibrium approaches are the most appropriate.

Table 6.5 presents a summary of available economic models for water resource assessments and describes the general requirements for each model.

Table 6.5 Summary of water resources economic methods and requirements.

MODEL	Time Scale	Model Scope	Cost	Time	Expertise	Advantages
Sectoral	Monthly	Overall water supply and demand	Medium	Medium	Medium	Transparent; lower costs
Spatial Equilibrium	Monthly	Watershed	High	High	High	Regions of water supply and use
Macroeconomic	Annual	Water and general economy	High	High	High	Captures sectoral interactions

6.2.3 Tools for assessment

In Sections 6.2.1 and 6.2.2, a wide variety of methodologies were presented. Many of these methods and techniques have been coded into computer software. Table 6.6 lists the contacts for obtaining these tools. In addition, one of the main clearinghouses for tested and proven software for water resources analysis is the Hydrological Operational Multipurpose System (HOMS) established by the World Meteorological Organization for the transfer of technology in operational hydrology. General Information on HOMS can be obtained via the internet (http://www.wmo.ch/web/homs/homsp1. html) or by contacting:

HOMS Office
Hydrology and Water Resources Department
World Meteorological Organization
P.O. Box 2300
1211 Geneva 2
Switzerland
Tel: +(41 22) 730 8407
Fax: +(41 22) 734 8250

A large number of world wide web sites with data on water resource software and models are now available. Analysts can search for specific modelling needs via a web search tool. Three sites are very comprehensive:

- *Internet Software Guide for Engineers Software* (http://www.100folhas.pt/software/). This site from Portugal provides freeware, shareware, and demos. Categories of interest include hydraulics and hydrology.

- *USGS Water Resources Applications Software* (http://water.usgs.gov/software/). This software and related material (data and documentation) are made available by the US Geological Survey (USGS) to be used in the public interest and the advancement of science. Includes geochemical, groundwater, surface water, and water quality codes.

- *IRRISOFT* (http://www.wiz.uni-kassel.de/kww/irrisoft/irrisoft_i.html). Database on irrigation and hydrology software, Department of Rural Engineering and Natural Resource Protection, University of Kassel, Germany.

Table 6.6 Software tools for climate change assessment: Contacts for obtaining software[a].

Hydrologic Models (Lumped Integral)	
CURUN	Institute of Geophysics, Polish Academy of Science, Warsaw, Poland
HBV	Swedish Meteorological and Hydrological Institute 601 76 Norrköping, Sweden
NAM	The Danish Hydraulic Institute, Agern Alle 5, DK-2970
SHE	The Danish Hydraulic Institute, Agern Alle 5, DK-2970
TANK	National Research Center for Disaster Prevention, Tokyo, Japan.
WATBAL	Research Application Program, National Center for Atmospheric Research, Boulder, Colorado, USA 80301
Hydrologic Models (Distributed Integral)	
HEC-1	Hydrologic Engineering Center; U.S. Army Corps of Engineers; 609 Second Street; Davis, CA, USA 95616-4687; (916) 756-1104
HSPF	(Stanford Watershed Model) Center for Exposure Assessment Modeling, U.S. EPA Environmental Research Laboratory, Athens, Georgia, 30613 USA
PRMS	Office of Surface Water, U.S. Geological Survey, WRD 415, National Center, Reston, Virginia, USA 22092
IDRO-2	Citta Studi scrl, Piazza Leonardo da Vinci 7, 20133 Milano, Italy
SWRRB	Grassland, Soil, and Water Research Laboratory, ARS, U.S. Dept of Agriculture, 808 East Blackland Rd. Temple, Texas, 76502 USA
Water Quality Assessment Models	
QUAL2E	Center for Exposure Assessment Modeling, U.S. EPA Environmental Research Laboratory, Athens, Georgia, 30613 USA
DESERT	Water Project International Institute for Applied Systems Analysis A-2361-Laxenburg, Austria
STREAM-PLAN	Water Project International Insatiate for Applied Systems Analysis A-2361-Laxenburg, Austria
WEAP	Stockholm Environment Institute, Boston, Massachusetts, USA
River Basin Simulation Models	
HEC-5	Hydrologic Engineering Center, U.S. Army Corp of Engineers Davis, California, USA
IRIS/IRAS	Water Project International Institute for Applied Systems Analysis A-2361-Laxenburg, Austria
MITSIM	Prof. Kenneth M. Strzepek; Campus Box 428; University of Colorado; Boulder, CO 80309-0428 USA
WEAP	Stockholm Environment Institute, Boston, Massachusetts, USA

a. For advise on selecting and obtaining economic models, contact local (e.g., university, research institute) economists.

6.3 Scenarios

Once an assessment method has been selected and tested and the necessary data have been collected, the key inputs and assumptions need to be formulated. Before applying a method it is necessary to develop climatic and socio-economic baseline scenarios, climate change scenarios, and assumptions about the potential for autonomous adaptation.

- Climate baseline conditions. The climate baseline for the natural system and biophysical impacts needs to be developed (e.g., temperature, precipitation, relative humidity, sunshine hours, wind speed, solar radiation, albedo). Ideally these data

are daily, with maximum, minimum, and average temperatures. Monthly is the maximum time scale that is useable. The data should be a time-series with as many years of data as possible, and should be provided for as many stations as possible in each river basin being analysed and surrounding areas. Chapter 3 addresses development of climate scenarios.

- Future socio-economic baseline conditions. The socio-economic baseline is crucial to estimating the magnitude of the impacts of climate change on the water management system and its ability to adapt. Chapter 2 provides a discussion of key considerations in developing these baselines.

- Future climate change conditions. Since the impacts on hydrologic resources are driven by the same climate variables as for many other sectors (e.g., temperature, precipitation, solar radiation), the user is referred to Chapter 3 for this material. For the water resources assessment, incremental scenarios and multiple GCMs are recommended (it is also important that the results from different GCM runs not be averaged for the water resources assessment).

- Autonomous adjustment. The technological, economic, and policy adaptations to climate change that each user may analyse will differ greatly, depending on the hydroclimatic zone, the level of economic development, and the relative sensitivity of the water resources system to potential climate change. An impact assessment should examine potential impacts assuming no autonomous adjustment, but also should examine impacts under one or more scenarios about the level of autonomous adjustments that would occur. River basin simulation models can be used to assess autonomous adaptations (as well as planned adaptations). For example, operational adaptations such as changed allocation priorities and pricing structures can be evaluated. The recommended WEAP model is well suited for this task. This is a very powerful model, focused mainly on the technological aspects of water resources adaptation.

6.4 Assessment of autonomous and planned adaptation

The methods described above can be used to assess how impacts would change as a result of adaptation. For example, river basin simulation models can be used to assess adaptation. Structural adaptations such as new reservoirs, canals linings, and ground-water extraction can be analysed with the simulation model. In addition, operational adaptation, changed allocation priorities, and pricing structures can be evaluated. Methods for assessing the trade-offs associated with implementing planned adaptation are described in Chapter 5 of this handbook.

This section highlights the types of adaptation measures that may be applicable to the water resources sector. When addressing adaptation in the water resources sector, it is

important to recognise that most adaptation will take place at the project or river basin scale. Water resources adaptations can be divided into two major classes:

- Supply adaptation, which can take three forms:
  - modification of existing physical infrastructure;
  - construction of new infrastructure; and
  - alternative management of the existing water supply systems.

- Demand adaptation, which can take three forms:
  - conservation and improved efficiency;
  - technological change; and
  - market/price-driven transfers to other activities.

6.4.1 Water supply adaptations

Since one of the major impacts of climate change is changes in the temporal and spatial distribution of precipitation and temperature, the resulting river flow (or hydrologic resources) may be shifted in time and space. A change in the spatial and temporal distribution of river flow could greatly affect the efficiency of the existing water supply infrastructure.

Modification of existing physical infrastructure

In many countries, extensive capital investment in water supply infrastructure has been made. However, with climate change impacts, the systems may not perform as designed. Adaptation to climate change may be achieved by modifying this existing investment. In some river basins, no suitable projects exist for new development, and thus adaptation utilising existing investment is most economical. Possible adaptations to address decreased flows as a result of climate change include:

- changing location or height of water intakes;

- installing canal linings;

- using closed conduits instead of open channels;

- integrating separate reservoirs into a single system; and

- using artificial recharge to reduce evaporation.

Possible adaptations to address increased flows as a result of climate change include:

- raising dam height;

- adding more turbines;

- increasing canal size; and
- removing sediment from reservoirs for more storage.

Construction of new infrastructure

In river basins where full development has not been realised, new projects could be built to adapt to the changed runoff and water demand conditions. These projects could include the following:

- reservoirs;
- hydroplants;
- delivery systems;
- well fields; and
- inter-basin water transfers.

Alternative management of the existing water supply systems

In some river basins, the nature of the climate change or physical, environmental, or institutional constraints do not warrant or allow new infrastructure projects. Thus, the adaptations to be considered would involve changes to the management of the existing system. Possible adaptations include the following:

- change operating rules;
- use conjunctive surface/groundwater supply;
- change the priority of release;
- physically integrate reservoir operation system;
- co-ordinate supply/demand.

6.4.2 Water demand adaptations

Water demand adaptation can be achieved through conservation and improved efficiency, technological change, or transfers to other activities.

Conservation and improved efficiency

There are a variety of measures that can be taken to promote conservation and improved water use efficiency, including those listed in Table 6.7 by type of water use.

Table 6.7 Adaptation measures to promote conservation and improve water use efficiency.

Type of Water Use[a]	Measure
Domestic	Low-flow toilets Low-flow showers Re-use of cooking water More efficient appliance use Leak repair Commercial car washing where recycling takes place Rainwater collection for non-potable uses
Agricultural	Night time irrigation Lining of canals Introduction of closed conduits Improvement in measurements to find losses and apply water more efficiently Drainage re-use Use of wastewater effluent Better control and management of supply network
Industrial	Re-use of acceptable quality water Recycling
Energy	Keeping reservoirs at lower head to reduce evaporation Changing releases to match other water uses Taking plants off-line in low flow times Co-generation (beneficial use of waste heat)

[a] Reservoir losses is not listed because physical measures to reduce surface evaporation on large-scale reservoirs have not proven successful. The only effective measure is to reduce surface area by changing operating policies and or storing water as groundwater.

Technological change

A variety of changes in the production process can reduce water use, and these are categorised as technology change. Measures that can be taken to promote technology change are listed in Table 6.8 by type of water use.

Market- or price-driven transfers to other activities

Another adaptation approach is to use price to shift water between sectors. An example of this would be water transfers from agriculture to municipal uses. In the western United States, where the value of water in municipal use is as much as 20 times the value for some irrigated crops, water rights have been transferred from agriculture to municipal uses. Sometimes this is undertaken on a partial basis (e.g., just one or two

farmers on a canal); in other cases an entire canal's water rights are sold and the area is no longer farmed or is transformed to dry-land farming.

Table 6.8 Adaptation measures to promote technology change.

Type of Water Use[a]	Measure
Domestic	Water efficient toilets Water efficient appliances Landscape changes Dual supply systems (potable and non-potable) Recycled water for non-potable uses
Agricultural	Low water use crops High value per water use crops Drip, micro-spray, low-energy, precision application irrigation systems Salt-tolerant crops that can use drain water Drainage water mixing stations
Industrial	"Dry" cleaning technologies Closed cycle and/or air-cooling Plant design with reuse and recycling of water imbedded Shift products manufactured
Energy	Additional reservoirs and hydropower stations Low head run of the river hydropower More efficient hydropower turbines Alternative thermal cooling systems Cooling ponds, wet tower, and dry towers

a. Reservoir losses is not listed because physical measures to reduce surface evaporation on large-scale reservoirs have not proven successful. The only effective measure is to reduce surface area by changing operating policies and or storing water as groundwater.

6.5 Summary and implications

The methodologies and modelling approaches presented in this chapter span a wide range of spatial and temporal scales within the scope of assessing climate change impacts on a nation's water resources system. The choices to be made in model selection and the scope of analyses depend on the hydroclimatic conditions, the water resource modelling expertise, data availability, and the time and financial resources dedicated to the national assessment. The exact nature of potential climate change at the spatial scale of a study site is impossible to predict at this time. GCMs provide plausible scenarios of what "could" be. In performing a climate change assessment, the goal should be to gain insights into how vulnerable a country's water resources are to the range of climate changes and what adaptation measures (if any) should be implemented. Therefore, it is more important to analyse more scenarios with simple models than to spend effort collecting detailed data and conducting few model runs. In addition, it is more important to look at multiple assessment components than to conduct many evaluations of few components. The reason for this "simple" approach is that first order impacts on each of the components can be identified with simple approaches; however, some of the more intriguing and non-intuitive impacts come from the integrated impacts of two or more components. Climate change impacts on one

component may either mitigate or exacerbate impacts on another component. The goal in applying the methodologies presented in this chapter is to develop insight and understanding into water resources vulnerability and adaptation, not to develop predictions.

References

Campos, M., A. Sanchez, and D. Espinoza. 1995. Adaptation of hydropower generation in Costa Rica and Panama to climate change. In *Adapting to Climate Change: An International Perspective.* Springer-Verlag, New York, pp. 232-242.

Chapra, S. 1996. *Surface Water Quality Modelling.* McGraw-Hill, New York.

Chow, V.T. et al. 1988. *Applied Hydrology.* McGraw-Hill, New York.

Kaczmarek, Z. 1991. *Sensitivity of Water Balance to Climate Change and Variability*, IIASA Working Paper WP-91-047. IIASA, Laxenburg, Austria.

Kindler, J., and C. Russell (eds). 1984. *Modeling Water Demand.* Academic Press, New York.

Maidment, D. (ed). 1993. *Handbook of Hydrology.* McGraw-Hill, New York.

Mays, L.W. (ed). 1996. *Handbook of Water Resources.* McGraw-Hill, New York.

Shaw, E.M. 1983. *Hydrology in Practice.* Van Nostrand Reinhold, United Kingdom.

Todini, E. 1988. Rainfall-runoff modeling: Past, present, and future. *Journal of Hydrology* 100, 341-352.

Yates, D. and K.M. Strzepek. 1994. Comparison of water balance models for climate change assessment runoff. Working paper. IIASA, Laxenburg, Austria.

Suggested readings

Abbott, M.B. et al. 1986a. An introduction to the European Hydrological System, Systeme Hydrologique Europeen, SHE: 1. History and philosophy of a physically-based, distribution modelling system. *Journal of Hydrology* 87, 45-59.

Abbott, M.B. et al. 1986b. An introduction to the European Hydrological System, Systeme Hydrologique Europeen, SHE: 2. Structure of physically-based distributed modelling system. *Journal of Hydrology* 87, 61-77.

Anderson, E.A. 1971. *FORTRAN-IV Program for the Stanford Watershed Model IV.* U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Office of Hydrology, Silver Spring, Maryland, USA.

Arnell, N. 1996. *Global Warming, River Flows, and Water Resources.* John Wiley, New York..

Berndtsson, R., and J. Niemczynowicz. 1988. Spatial and temporal scales in rainfall analysis: Some aspects and future perspectives. *Journal of Hydrology* 100, 293-313.

Brown, L.C., and T.O. Barnwell. 1987. The Enhanced Stream Water Quality Models QUAL2E-UNCAS: Documentation and User Manual. EPA/600/3-87/007. US Environmental Protection Agency, Athens, Georgia, USA.

Burnach, J.C. et al. 1973. *A Generalized Streamflow Simulation System: Conceptual Modeling for Digital Computers.* Report by the Joint-Federal State River Forecasting Center. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, and State of California Department of Water Resources.

Carmichael, J., and K. Strzepek. 1987. *Industrial Water Use and Treatment Practice.* Published for the United Nations Industrial Development Organisation by Cassell Tycooley, Philadelphia and London.

Carmichael, J.J., K.M. Strzepek, and B. Minarik. 1996. Impacts of climate change and seasonal variability on economic treatment costs: A case study of the Nitra River Basin, Slovakia. *Water Resources Development* 12, 209-227.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Department of Geography, University College, London

Chang, L., C. Hunsaker, and J. Draves, 1992. Recent research on effects of climate change on water resources. *Water Resources Bulletin*, 28(2), 273-286.

Chavula, G.M.S. and A.B. Chirwa. 1996. Effects of climate change on water resources of Malawi: Vulnerability assessment and adaptation strategies. Chapter 4 in *U.S.A. Country Studies Program to Address Climate Change: Support to Malawi for Vulnerability and Adaptation Studies*. Preliminary report. Republic of Malawi Ministry of Research and Environmental Affairs, Lilongwe, Malawi, pp. 38-77.

Crawford, N.H., and R.K. Linsley, Jr. 1966. Digital Simulation in Hydrology: Stanford Watershed Model IV. Technical Report 39. Department of Civil Engineering, Stanford University, Stanford, California, USA.

Dooge, J.C.I. 1992. Hydrologic models and climate change. Journal of Geophysical Research 97(D3), 2677-2688.

Dunne, T., and L.B. Leopold. 1978. *Water in Environmental Planning.* W.H. Freeman and Co., New York.

Falkenmark, M. 1977. Reduced water demand — Results of the Swedish anti-pollution program, *Ambio* 6, 2.

Franchini, M., and M. Pacciani. 1991. Comparative analysis of several conceptual rainfall-runoff models. *Journal of Hydrology* 122, 161-219.

Gates, W.L. 1985. The use of general circulation models in the analysis of ecosystem impacts of climatic change. *Climatic Change* 7, 267-84.

Gleick, P. (ed.). 1993. *Water in Crisis.* Oxford University Press, Oxford, United Kingdom.

Goodman, A. 1984. *Principles of Water Resources Planning.* Prentice-Hall, New York.

Gray, D.M., and T.D. Prowse. 1993. Snow and floating ice. In *Handbook of Hydrology*, D. Maidment (ed). McGraw-Hill, New York, pp. 7.1-7.53.

Grotch, S.L., and M.C. MacCracken. 1990. The use of general circulation models to predict regional climatic change. *Journal of Climate* 4, 286-303.

Hazel, P.B.R., and R.D. Norton. 1986. *Mathematical Programming for Economic Analysis in Agriculture.* Macmillan Publishing, New York.

Hurd, B.H., J.M. Callaway, J.B. Smith, and P. Kirshen. 1998. Economic effects of climate change on U.S. water resources. In *The Economic Impacts of Climate Change on the U.S. Economy*, R. Mendelsohn and J.E. Neumann (eds). Cambridge University Press, Cambridge, United Kingdom.

Jensen, M. et al. 1990. Evapotranspiration and irrigation water requirements. *ASCE Manual* 70, 132.

Kaczmarek, Z. 1990. *On the Sensitivity of Runoff to Climate Change and Variability.* IIASA Working Paper WP-90-058. IIASA, Laxenburg, Austria.

Kaczmarek, Z. 1993. Water balance model for climate impact analysis. *ACTA Geophysica Polonica* 41(4), 1-16.

Kaczmarek, Z, and J. Kindler. 1996. National Assessment: Poland. In *Water Resources Management in the Face of Climatic/Hydrologic Uncertainties*, Z. Kaczmarek, K. Strzepek, Somlyody, and Priazhinskaya (eds). Kluwer, Dordrecht, The Netherlands, pp. 224-248.

Kaczmarek, Z., K. Strzepek, L. Somlyody, and V. Priazhinskaya (eds). 1996. *Water Resources Management in the Face of Climatic/Hydrologic Uncertainties*, Kluwer, Dordrecht, The Netherlands.

Kovalesky, V.S. 1993. The Impact of Predicted Climatic Changes on Groundwater. Unpublished manuscript. Water Problems Institute, Russia Academy of Science, Moscow.

Kulshreshtha, S. 1993. *World Water Resources and Regional Vulnerability: Impact of Future Changes.* IIASA Research Report RR93-10. IIASA, Laxenburg, Austria.

Lettenmaier, D.P., and T.Y. Gan. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. *Water Resources Research* 26, 69-86.

Lettenmaier, D.P., and D.P. Sheer. 1991. Climatic sensitivity of California water resources. *Journal of Water Resources Planning and Management* 117(1), 108-125.

Linsley, R.K., Jr. et al. 1982. *Hydrology for Engineers.* Third edition. McGraw-Hill, New York.

Loucks, D., J. Stedinger, and D. Haith. 1981. *Water Resource System Analysis and Planning.* Prentice-Hall, New York.

Mays, L.W., and Y.-K. Tung. 1992. *Hydrosystems Engineering and Management.* McGraw-Hill, New York.

Mirza, M. and R. Warrick. 1997. Climate Change Impacts on Flooding in Bangladesh. Unpublished manuscript.

Niemann, J.D. et al. 1994. Impacts of spatial and temporal data on a climate change assessment of Blue Nile Runoff. Draft working paper. IIASA, Laxenburg, Austria.

Ozga-Zielinska, M., and J. Brzenzinski. 1993. *Basin Conceptual Model (BCM): The Simulation Model of the Monthly Runoff,* Institute of Environmental Engineering, Warsaw University of Technology.

Raskin, P., J. Sieger, and T. Votta, 1998. WEAP Water Evaluation and Planning System: User Guide for Version 97.0. Stockholm Environment Institute - Boston.

Rawls, W.J., D.L. Brakensiek, and S.D. Logsdon. 1993. Predicting saturated hydraulic conductivity utilizing fractal principles. *Soil Science Society of America Journal* 57, 1193-1197.

Riebsame, W. et al. 1995. Complex river basins. In *As Climate Changes: International Impacts and Implication*, K.M. Strzepek and J.B. Smith (eds). Cambridge University Press, Cambridge, United Kingdom, pp. 57-91.

Samuelson, P., and W. Nordhaus. 1989. *Microeconomics.* McGraw-Hill, New York.

Shuttleworth, W.J. 1993. Evaporation. Chapter 4 of *Handbook of Hydrology*, D. Maidment (ed). McGraw-Hill, New York.

Singh, V.P. (ed). 1995. *Computer Models of Watershed Hydrology.* Water Resources Publications, Englewood, Colorado, USA.

Shiklomanov, I. H. Lins, E. Stakhiv, and K. Mostefa-Kara. 1990. Hydrology and water resources. Chapter 4 in Climate Change: The IPCC Impacts Assessment, W.J.McG. Tegart, G.W. Sheldon, and D.C. Griffith (eds). Australian Government Publishing Service, Canberra, Australia, pp. 4-1 to 4-42.

Starosolszky, O. 1987. *Applied Surface Hydrology.* Water Resources Publications, Littleton, Colorado, USA.

Strzepek, K. 1997. Use of WEAP for climate change analysis. Working paper. University of Colorado, Boulder, USA.

Strzepek, K.M. and J.B. Smith (eds). 1995. *As Climate Changes: International Impacts and Implication*. Cambridge University Press, Cambridge, United Kingdom.

Strzepek, K., L. Sembled, and V. Prishnikya (eds). 1996. *Water Resources Management in the Face of Climatic/Hydrologic Uncertainties.* Kluwer, Dordrecht, The Netherlands.

Sugarwara, M. et al. 1983. *Reference Manual for the TANK Model.* National Research Center for Disaster Prevention, Tokyo, Japan.

Turc, P. 1954. Water balance of soils: Relationship between precipitation, evapotranspiration, and runoff (in French). *Annales Agronomique* 5, 49-595 and 6, 5-131.

US Army Corps of Engineers. 1972. *Program Description and User Manual for SSARR Model Streamflow Synthesis and Reservoir Regulation: Program 724-K5-G0010*. US Army Corp of Engineers, Washington, DC.

Vaux, H.J. and R.E. Howitt. 1984. Managing water scarcity: An evaluation of interregional transfers. *Water Resources Research* 20, 785-792.

Viessman, W., Jr. et al. 1977. *Introduction to Hydrology.* Harper and Row, New York.

Von Storch, H. et al. 1993. Downscaling of global climate change estimates of regional scales: An application to Iberian rainfall in wintertime. *Journal of Climate* 6, 1161-1171.

Waggoner, P. (ed). 1990. *Climate Change & U.S. Water Resources.* John Wiley & Sons, New York.

Wolock, D.M., and G.M. Hornberger. 1991. Hydrological effects of changes in levels of atmospheric carbon dioxide. *Journal of Forecasting* 10, 105-116.

Yates, D.N. 1996. WatBal: An integrated water balance model. *International Journal of Water Resources Development* 12(2), 121-139.

Yates, D.N., K. Strzepek, and O. Bowling. 1997. Comparison of hydrologic models Unpublished manuscript. University of Colorado, Boulder, USA.

7 Coastal Zones

Lead Authors
Richard J.T. Klein [1]
Robert J. Nicholls [2]

Contributing Authors
Gualbert H.P. Oude Essink, The Netherlands
Nobuo Minura, Japan
Richard A. Warrick, New Zealand

7.1 Nature and scope of the problem

One of the more certain consequences of global climate change is accelerated global sea-level rise, which will intensify the stress on many coastal zones, particularly those where human activities have diminished natural and socio-economic adaptive capacities. As suggested by Bijlsma et al. (1996), sea-level rise can lead to increased hazard potential for coastal populations, infrastructure, and investment. However, owing to the great diversity of both natural and socio-economic coastal systems and their dynamic response to anticipated changes, future impacts are not always easy to predict. Further, appropriate adaptation will vary with site, depending on environmental and socio-economic circumstances. Thus, careful studies are required to assess possible impacts as well as to identify suitable adaptation options.

In 1992, the former Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change (IPCC) published the so-called Common Methodology for assessing the vulnerability of coastal areas to sea-level rise (IPCC CZMS, 1992a). The

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[1] Potsdam Institute for Climate Impacts Research, Potsdam, Germany.

[2] Flood Hazard Research Centre, School of Social Science, Middlesex University, Enfield, UK.

Common Methodology has been widely applied to identify populations and resources at risk, and the costs and feasibility of possible responses to adverse impacts. This chapter provides an elaboration of the IPCC Technical Guidelines (Carter et al., 1994) for the specific situation of assessing the impacts of sea-level rise on coastal zones. It is based on a combination of widespread experience using the Common Methodology and other methods for coastal vulnerability assessment, which have been developed in response or addition to the Common Methodology (e.g., Kay and Hay, 1993; Gornitz et al., 1994; Nicholls et al., 1995; Yamada et al., 1995; Leatherman and Yohe, 1996; Otter et al., 1996).

This chapter should not be regarded as an update or revision of the Common Methodology, but as a new initiative to present a range of methods and techniques applicable to vulnerability assessment rather than a single approach. It is not intended to be prescriptive as to the use of scenarios or methods to be applied for the assessment of impacts and adaptation options. Instead, it encourages users to select those scenarios and methods that — within the objectives of the country study —are most appropriate to their specific situation.

Sea-level rise, which is the focus of this chapter, is expected to interact with changes in other climatic variables such as temperature, wind regime, precipitation, and soil moisture. Consideration of this interaction is encouraged where relevant and possible, as it will allow for more comprehensive appraisal of possible impacts and adaptation for specific socio-economic sectors. Methods to assess sectoral impacts and adaptation options in coastal zones can be found in other chapters in this handbook, including Water Resources (Chapter 6), Agriculture (Chapter 8), Human Health (Chapter 10), and Fisheries (Chapter 14).

The response of coastal zones to sea-level rise can be highly variable and is greatly influenced by the local geomorphic and ecological coastal configuration. Natural coastal processes interact with and dynamically respond to regional and global changes such as sea-level rise, and thus determine the susceptibility, resilience, and resistance of the coastal zone to these changes.

7.1.1 Delineation of the study area

At a minimum, the study area needs to be defined so that it encompasses all areas that could be physically affected by sea-level rise. It is advisable not to delineate the area too narrowly so as to account for the broad range of uncertainty that is involved in impact assessment. The Common Methodology suggests consideration of all the land area below the contour line that corresponds with the height of a once-every-1,000 years storm surge, given projected sea-level rise by 2100. This and other risk contours are presented in Section 7.2.3.1, and first-order global estimates of storm-surge regimes at a national resolution are provided by Hoozemans et al. (1993). In addition, the study area should consider saltwater intrusion and increased river flooding. In deltaic and estuarine areas, sea-level rise could cause these effects to extend tens of kilometres inland.

In the absence of the required data or other clear criteria to delineate the study area, it is recommended to use the contour line 2 metres above extreme high tide as the landward demarcation, unless the physiography or socio-economic structure of the area suggests that this arbitrary boundary will not suffice. This would be the case when impacts may also be expected to occur farther inland (e.g., as a result of saltwater intrusion, extreme storm surges, or increased river flooding) or, conversely, only close to the coast. The seaward extension of the study area should be based on the area that is likely to be subject to biogeophysical effects of sea-level rise, such as coral reefs, intertidal areas, and wetlands, but may also include coastal waters containing valuable living resources.

7.1.2 Absolute and relative sea-level change

Over the last 100 years, the global sea level rose by 1.0-2.5 mm/yr (Warrick et al., 1996; see also Douglas, 1995; Gornitz, 1995). Estimates of future sea-level rise, as presented in the IPCC Second Assessment Report and shown in Figure 7.1, range from 20 to 86 centimetres for 2100 for the IS92a greenhouse-gas emission scenario, with a best estimate of 49 centimetres (including the cooling effect of aerosols; Warrick et al., 1996). This rate of sea-level rise is about 2-5 times the rate experienced over the last century.

It should be noted that in hindcasting exercises, current models under-predict the observed sea-level rise of the past 100 years, for reasons that are not well understood (Titus and Narayanan, 1996). Future rises may therefore be somewhat higher than predicted by Warrick et al. (1996). Moreover, model projections show that sea level will continue to rise beyond 2100, owing to lags in climate response, even if global greenhouse-gas emissions were stabilised now (Wigley, 1995).

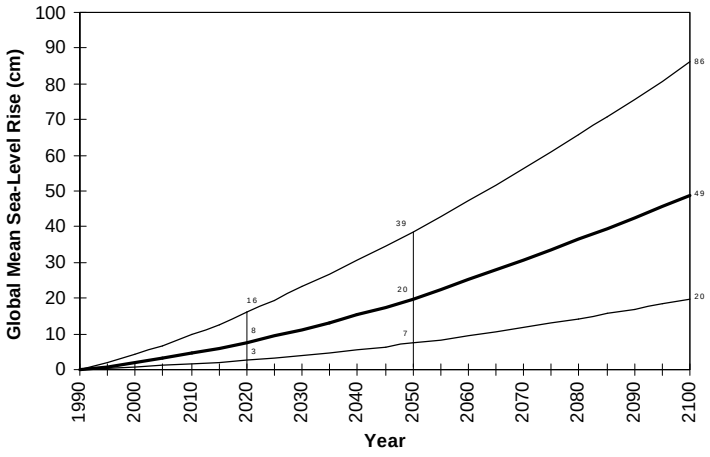

Figure 7.1 Projected global mean sea-level rise for 1990-2100 (low, medium, high estimate), using the IS92a scenario and including the cooling effect of aerosols (Warrick et al., 1996).

In spite of the importance of global sea-level rise scenarios, when assessing impacts it is the local change in relative sea level that matters, not the global average. Relative —or observed —sea level is the level of the sea relative to the land. Subsidence of the land results in a relative sea-level rise that is higher than the global rise, whereas uplift of the land leads to a relative rise that is less than the global average. In extreme cases (e.g., Scandinavia), uplift is causing a relative fall of sea level because the rate of uplift exceeds the present rate of global sea-level rise.

Subsidence and uplift are mostly natural phenomena, associated with long-term geological processes. However, human activities, such as water and hydrocarbon extraction, can also cause subsidence of sedimentary coastal lowlands. Locally, this human-induced subsidence can equal or exceed the projected climate-induced sea-level rise. Examples of cities that have subsided as a result of groundwater exploitation include Venice (Italy), Jakarta (Indonesia), Bangkok (Thailand), Shanghai (China), and Tokyo (Japan). In many deltaic areas, combined natural and human-induced subsidence is made even more apparent by the removal or reduction of sediment supplies, which reduces or stops compensating accretion. In reclaimed coastal lowlands, oxidation of peat can lead to large declines in land level, as can consolidation and loading.

7.1.3 Biogeophysical effects and socio-economic impacts

Irrespective of the primary causes (climate change, natural or human-induced subsidence, dynamic ocean effects), natural coastal systems that experience sea-level rise can be affected in a variety of ways. It is not the aim of this chapter to discuss the details of each type of response and explain how these can be identified. Rather, the six most important (from a societal perspective) biogeophysical effects are dealt with in a more general manner. These six effects are:

- increasing flood-frequency probabilities;
- erosion;
- inundation;
- rising water tables;
- saltwater intrusion; and
- biological effects.

Owing to the great diversity and variation of natural coastal systems and to the local and regional differences in relative sea-level rise, the occurrence and response to these effects will not be uniform around the globe. Therefore, impact studies first need to analyse the extent to which the above effects will occur in the study area before the potential socio-economic impacts can be assessed. The potential socio-economic impacts of sea-level rise can be categorised as follows:

- direct loss of economic, ecological, cultural, and subsistence values through loss of land, infrastructure, and coastal habitats;

- increased flood risk of people, land, and infrastructure and the above-mentioned values; and

- other impacts related to changes in water management, salinity, and biological activity.

The last category of impacts is not considered in this chapter but in the relevant sectoral chapters (Water Resources, Agriculture, Human Health, and Fisheries). However, this chapter does discuss the possibilities and limitations to assess the extent of rising water tables and saltwater intrusion. Clearly, when conducting a comprehensive coastal study, the consequent socio-economic impacts should also be considered, using methods outlined in the appropriate chapters of this Handbook.

Table 7.1 lists the most important socio-economic sectors in coastal zones, and indicates from which biogeophysical effects they are expected to suffer direct socio-economic impacts. Indirect impacts (e.g., human-health impacts resulting from deteriorating water quality) could also be important to many sectors, but these are not shown in the table.

Table 7.1 Qualitative synthesis of direct socio-economic impacts of climate change and sea-level rise on a number of sectors in coastal zones.

Sector	Biogeophysical Effect					
	Flood Frequency	Erosion	Inundation	Change in Water Table	Saltwater Intrusion	Biological Effects
Water Resources			✓	✓	✓	✓
Agriculture	✓		✓	✓	✓	
Human Health	✓		✓			✓
Fisheries	✓	✓	✓		✓	✓
Tourism	✓	✓	✓			✓
Human Settlements	✓	✓	✓	✓		

Note: Methods for vulnerability assessment for the first four sectors are presented in Chapters 6, 8, 10, and 14 of this handbook, respectively. Methods to assess biological effects of climate change in coastal zones are provided in Chapters 10 and 14.

7.2 An array of methods

This section presents and discusses a range of tools and techniques that are available for coastal impact assessment. First, methods for data acquisition and management are discussed, followed by a review of an index-based approach to coastal impact assessment. Indices, which to a greater or lesser extent rely on expert judgement, may be used when data are scarce. When data are available or can be collected, a two-step approach can be followed to assess natural and socio-economic vulnerability to sea-level rise. The two steps involved are the assessment of biogeophysical effects, and the assessment of potential socio-economic impacts.

7.2.1 Acquisition and management of data

The fundamental starting point for any assessment study is the acquisition of basic data on a number of important parameters that characterise the study area. Relevant characteristics of the natural coastal system include the following:

- coastal geomorphology and topography;
- historical relative sea-level changes;
- trends in sediment supply and erosion/accretion patterns;
- hydrological and meteorological characteristics;
- meteorological-oceanographic characteristics; and
- ecosystem characteristics.

Additionally, it is necessary to collect data on the important socio-economic characteristics of the study area, and to develop scenarios of their future development (see Chapter 2). These include:

- demographic developments;
- trends in resource use and economic development;
- land use and ownership;
- infrastructural and other economic assets;
- cultural assets; and
- institutional arrangements.

First and foremost, it is essential to review critically any available material (maps, aerial photographs, satellite images) and previous studies that may have yielded results

or contain background information relevant to impact assessment. Various national and international organisations have developed sites on the World Wide Web that contain coastal bibliographies, databases, and tools as well as numerous links to other relevant information and organisations on the Internet. Examples include the Dutch Coastal Zone Management Centre (http://www.minvenw.nl/projects/netcoast), the Coastal Services Center of the US National Oceanic and Atmospheric Administration (http://www.csc.noaa.gov), and the core-project Land-Ocean Interactions in the Coastal Zone of the International Geosphere-Biosphere Programme (http://www. nioz.nl/loicz).

7.2.1.1 Global sea-level changes

There are a number of databases that may provide useful information on sea-level changes. For example, the Permanent Service for Mean Sea Level (Bidston Observatory, United Kingdom) holds a large number of tide-gauge records showing relative sea-level changes around the world (reviewed by Emery and Aubrey, 1991; Spencer and Woodworth, 1993). A guide to tide-gauge networks and global and regional sea-level data sets can be accessed at http://www.nbi.ac.uk/psmsl/ sea_level.html. Also the World Atlas of Holocene Sea-Level Changes (Pirazzoli, 1991) could provide an indication of long-term, regional, relative sea-level changes. However, the limitations of these data sets need to be appreciated. Hence, it is recommended to use this type of information with caution, especially because the small spatial and temporal scales of the data reduce the reliability of its application at larger scales. For example, see Douglas (1995) for a discussion of sea-level trend analysis.

New data sources are becoming available, including satellite observations of sea-surface elevations using the TOPEX/POSEIDON platform (Fu et al., 1996). Global positioning systems are used to decouple absolute sea-level changes and vertical land movements in some regions (e.g., Zerbini et al., 1996). Some of these data may be useful for impact analysis.

7.2.1.2 Coastal topography and land use

For many countries where information on coastal elevations is lacking, ordinary surveying can be conducted to provide these most basic and essential data for coastal vulnerability assessment. In combination with elevation data derived from satellite measurements (e.g., SPOT) or vertical aerial photography, surveying can yield topographical maps that have utility beyond impact assessment. However, surveying is a laborious and time-intensive process, and therefore relatively expensive. Nonetheless, satellite measurements alone are not yet sufficiently accurate to serve as the only source of contour information.

A rapid and low-cost reconnaissance technique that has been developed to overcome some natural-system data deficiencies is called “aerial videotape-assisted vulnerability analysis” (AVVA) (IPCC CZMS, 1992b; Nicholls et al., 1993; Leatherman et al., 1995). The combination of a video record of the coastline and ground-truth information

can be used to characterise the coastal topography and, with the use of an appropriate model (see Section 7.2.3), allows for estimates of the biogeophysical effects for different sea-level rise scenarios. The video record further provides information on the types of coastal environments, land-use practices, infrastructure, and population indicators.

A major limitation of the AVVA method is that coastal elevations are not estimated quantitatively, but are subjectively interpolated between occasional ground-truth data. Therefore, AVVA does not provide information that is sufficiently accurate to assess whether a particular parcel of land would be inundated as a result of sea-level rise. On the other hand, validation experiments have demonstrated that AVVA is unbiased and reasonably accurate when estimating land loss at a larger scale (Leatherman et al., 1995). Another important limitation is that in extensive low-lying areas such as deltas, AVVA does not provide sufficiently detailed information to allow for an accurate estimate of elevation (Nicholls et al., 1995; Leatherman and Yohe, 1996). Thus, other data sources are essential. Box 7.1 presents results from an impact study of Senegal, which was conducted based on data obtained with AVVA.

Box 7.1 Example: Use of AVVA in coastal impact assessment for Senegal.

Senegal is a West African country with a varied coast that comprises long stretches of sandy coastline, the Senegal Delta, the sheltered shorelines of the Saloum and Casamance estuaries, and a small length of rocky shoreline. An impact study of Senegal was conducted from 1990 to 1993, under sponsorship of the US Environmental Protection Agency. It is one of a number of country studies that have used AVVA as the main source for elevation and land-use data. Other sources of information included published reports, maps, and computer databases .

In following a similar approach to the IPCC Common Methodology, the study aimed to analyse the implications of land loss, including a range of potential human responses and their costs. It did not consider changes other than sea-level rise. The study applied four scenarios of relative sea-level rise: 0.2, 0.5, 1.0 and 2.0 metres by 2100, with most attention being focused on the 1-metre scenario. Socio-economic consequences were assessed using three response scenarios: no protection, important areas protection, and total protection (of areas with a population of more than 10 people per square kilometre).

Erosion from sea-level rise was estimated using the Bruun rule, and the simple inundation concept was used to assess most of the area vulnerable to inundation. For mangroves, the dynamic inundation concept was applied (see Section 7.2.3 for a discussion of these methods). Based on the area of land potentially at loss, an inventory of the market value of buildings was made. The number of buildings also gave an indication of the population at risk. Agricultural land at risk was not evaluated because of a lack of information concerning the total area involved and the market value of agricultural land. For the same reason coastal infrastructure other than buildings was excluded from the analysis. Market and non-market values related to the many functions of coastal wetlands were not considered either, owing again to a lack of suitable information.

The study found that a 1-metre rise in sea level could inundate and erode more than 6,000 square kilometres of land, most of which are wetlands. Erosion on the open coast could threaten buildings valued at more than US$500-700 million (or 12-17 percent of Senegal's 1990 GNP) and displace at least 110,000 to 180,000 people from their homes. Protecting the areas that currently have medium to high development would cost US$255-845 million, mainly for beach nourishment at tourist resorts. Assuming that this investment would be made from 2051 to 2100, it would represent an annual cost of 0.7-2.2 percent of the national gross investment in 1990. Nonetheless, most of the coastline (86 percent) remains undeveloped, even though the population of the Senegalese coastal zone is growing rapidly. Therefore, there is an opportunity to plan for the impacts of sea-level rise as new coastal areas are developed.

Source: Dennis et al. (1995a).

A new technique that does provide detailed absolute coastal-elevation data is called airborne laser scanning (ALS). This operational remote-sensing technique for digital elevation mapping is based on a laser beam scanning the earth's surface from an aircraft. The precise position of the aircraft is determined by a ground-control point operating a global positioning system receiver, allowing the plane to attain high vertical accuracy (10 to 15 cm). ALS is currently used to survey the coastal zone of The Netherlands, providing more than 80,000 measurements per square kilometre.

Remotely-sensed data from satellites (e.g., Landsat, SPOT) can also be used to delineate land use (e.g., IPCC CZMS, 1992b; Frederic R. Harris BV et al., 1992; O'Regan, 1996). This type of information is easily incorporated and analysed within a geographic information system (GIS). As stated above, satellite data cannot yet provide high-accuracy contour information, so this must be obtained from other sources to allow for quantitative analysis. Box 7.2 presents some results that have been obtained using satellite data in an impact study of the Polish coast. Note that subsequent studies (e.g., Zeidler, 1997) have provided revised and updated figures, reflecting the rapidly changing patterns of the Polish economy and inclusion of new boundary conditions.

7.2.1.3 Socio-economic data

Socio-economic data (e.g., population, gross regional product) can often be derived from local or national authorities, and from institutions such as a census bureau and a statistical office. Further, international organisations may possess valuable information. Potential sources include the World Bank (http://www.worldbank.org), World Resources Institute (http://www.wri.org), and the United Nations Development and Environment Programmes and Food and Agricultural Organisation (UNDP, UNEP and FAO; http://www.undp.org, http://www.unep.org, and http://www.fao.org). In view of the often obsolescent nature of socio-economic data, it is always important to verify the reliability of any data with appropriate experts.

7.2.1.4 Management of data

Computerised GIS provides an increasingly powerful means of not only managing but also analysing spatial data. Once created, a GIS database may have further utility in other aspects of coastal zone management.

In principle, most of the analytical methods outlined in this chapter can be incorporated within a GIS, and such an approach is preferred if feasible. As such, the analysis of impacts of sea-level rise can be integrated with the analysis of sectoral impacts, as outlined in other chapters of this Handbook. It is, however, important to realise that any analysis performed using a GIS relies heavily on the accuracy of the data that the GIS contains. The study in Box 7.2 presents some results that have been obtained using a GIS.

Box 7.2 Example: Use of satellite data and GIS in a coastal impact assessment for Poland.

Poland is situated on the Baltic Sea. Eighty percent of its coastline is occupied by dunes, and the remainder is fronted by cliffs. The two main rivers that flow into the Polish part of the Baltic Sea are the Vistula and the Odra. In 1991 and 1992 an impact study was conducted with financial support from The Netherlands' Ministry of Economic Affairs. The study followed the IPCC Common Methodology, which was facilitated by the large amount of well-documented and high-quality data available from various sources in Poland. In addition, satellite imagery was used to identify land use.

The study aimed to establish a vulnerability profile, including ecological and socio-economic values at risk, as well as response costs. Sea-level rise was the only climate change variable considered, using scenarios of 0.3 and 1.0 metre by 2100. Socio-economic development was considered over a time span of 30 years. This included extrapolating historical trends of population and economic growth, and using current capital values from The Netherlands under the assumption that in 30 years Poland would develop to a situation comparable to that of The Netherlands today. Response costs were based on protection; no analysis was made of the costs and consequences of other adaptation options.

In combination with a GIS, the use of satellite images enabled a rapid quantitative assessment of the consequences of sea-level rise in terms of loss of land and property. Also the effects of dike failure could be clearly demonstrated. Under a 1-meter sea-level rise scenario, taking into account socio-economic development and assuming no protection, 1101.2 square kilometres of agricultural land would be lost, as well as 223.0 square kilometres of forests, 140.0 square kilometres of recreational area, 35.7 square kilometres of nature reserve, 23.4 square kilometres of urban area, and 105.4 square kilometres of industrial area.

In terms of the vulnerability profile, the Common Methodology defined four vulnerability classes for different parameters: low, medium, high, and critical (IPCC CZMS, 1992a). These classes are used in the description of the Polish results. It was found that for a projected sea-level rise of 1.0 metre, losses of land and property are expected to be critical (>10 percent of 1992 GNP) if no protective measures are taken. For the same scenario, the number of people who would experience storm-surge flooding in a typical year is about 200,000 (high vulnerability). Most of these people (146,000) would experience flooding more than once a year, suggesting a response would be necessary (i.e., protection or relocation). Full protection can reduce the number of people at risk to about 10,000 (a low to medium vulnerability). The implementation costs are estimated at US$1.5 billion, which is equivalent to 0.02 percent of 1992 GNP, assuming that these costs will occur uniformly over 100 years.

Source: Frederic R. Harris BV et al. (1992)

Examples of the use of GIS in coastal vulnerability assessment include Shennan and Sproxton (1991), IPCC CZMS (1992b), Machida et al. (1993), Nunn et al. (1994a,b), and Sem et al. (1996); Jones (1995) and O'Regan (1996) review the use of GIS in

coastal zone management. More general information can be found in numerous texts, such as Maguire et al. (1991) (See also Chapter 1.)

7.2.2 Index-based approaches

An important constraint that faced many past coastal impact studies was the limited availability of data on both the natural and socio-economic coastal systems. When data are scarce, coastal vulnerability may be assessed using indices that, to a greater or lesser extent, rely on expert judgement. It should be noted, however, that existing studies using index-based methods often lack the level of detail required to draw firm conclusions, and should therefore be seen as a first-order assessment only. Quantitative impact assessment would require at least some of the above data to form the basis of the study. In particular, there needs to be some basic knowledge of coastal elevations and of natural coastal processes and trends to assess the natural coastal response to sea-level rise.

Box 7.3 Example: An index-based approach to coastal impact assessment in Fiji.

Fiji is situated in the Pacific Ocean and comprises two large and 330 small to very small islands. In two phases an impact study was conducted that applied and further developed the method outlined by Kay and Hay (1993). The study was sponsored by the Japanese Environment Agency. In the first phase, the method was tested at four sites on Viti Levu, the largest island, after which it was refined on the peripheral Yasawa islands of Nacula and Viwa during the second phase. Also during the second phase, the vulnerability of the port facilities of the two most important urban centres of Fiji (Suva and Lautoka, both on Viti Levu) was assessed, and a 25-layer GIS database of Viti Levu was constructed so as to allow for island-wide vulnerability analysis. This example summarises the methodology and results of the studies on Nacula and Viwa.

Nacula and Viwa are very small islands with populations of 1200 and 400, respectively. These populations depend strongly on the natural environment for subsistence fishing and agriculture. There are few opportunities for cash employment. As an impact analysis based on monetary valuation was considered to be of little use for subsistence economies, the method that was applied was based on qualitative evaluation of six interacting coastal systems (natural, human, infrastructural, institutional, economic, and cultural). Based primarily on expert judgement, the vulnerability and resilience to sea-level rise of each of these systems were scored on a scale from -3 to 3, for the present and for the future (up to 2100). For the future, two response scenarios were used: no management and optimal management. The overall vulnerability was expressed as an index obtained from aggregating the vulnerability and resilience components.

In the method, areas with higher concentrations of assets were judged to be more vulnerable, whereas areas with diversity and flexibility in the system —whether natural or managerial — were viewed as more resilient. It was found that Nacula can sustain its present population without undue difficulty, although problems could arise after a “direct-hit” cyclone. With sea-level rise inundating some low-lying areas and rendering other areas unsuitable for agriculture, it will become more difficult to sustain the present population. However, the strength of the indigenous culture with its communal support mechanisms is expected to be useful in finding solutions. Viwa is more isolated and more resource-poor than Nacula. Being low-lying, it is more affected by storm surges associated with tropical cyclones than Nacula. The problem of

providing sufficient freshwater supplies is already acute. The island is far less capable of sustaining existing population levels both now and in the future. However, it is anticipated that sea-level rise will not constitute a significant additional stress over the next century.

Source: Nunn et al. (1994a).

One example of an index-based approach has been developed for the Asia-Pacific region by Kay and Hay (1993). It has been applied by Nunn et al. (1994a,b) and Yamada et al. (1995). Box 7.3 summarises the impact study conducted for two islands of Fiji. In the framework used in this approach, the coastal zone is viewed as a set of six interacting systems: the natural, human, and infrastructural systems (the so-called "hard" systems), and the institutional, economic, and cultural systems (the "soft" systems). Kay and Hay (1993) have stressed the importance of determining not only the vulnerability but also the resilience of each of these systems. The qualitative scorings of vulnerability and resilience — largely determined by expert judgement —together determine the coastal Sustainable Capacity Index.

The framework of Kay and Hay (1993), which has been developed to account for the specific situation of subsistence economies in the Asia-Pacific region, does provide some useful guidance for impact assessment, especially in areas with limited data availability or accessibility. However, as stated above, a more comprehensive and quantitative assessment of impacts and adaptation options can only be based on quantitative data.

7.2.3 Methods for assessing biogeophysical effects

This section briefly discusses five of the six coastal biogeophysical effects of sea-level rise that were identified in Section 7.1.3, and outlines which methods are available for their assessment. The application of each method is described in some detail, but it is beyond the scope of this chapter to present all the peculiarities involved in each method. Therefore, the reader is recommended to consult the original references for more detailed descriptions. Biological effects of climate change in coastal zones are discussed in Chapters 10 and 14.

7.2.3.1 Increasing flood-frequency probabilities

One of the first consequences of a rise in sea level on low-lying coastal zones is an increased flood risk associated with storm surges and extreme precipitation and runoff events. In fact, low-lying coastal areas that face permanent inundation under a certain scenario of sea-level rise will first experience increased risk of flooding. In this chapter, only flooding as a result of coastal storm surges is considered, although increases in river flooding could be important locally (see also Chapter 6).

The degree to which coastal land is at risk of flooding from storm surges is determined by a number of morphological and meteorological factors, including coastal slope and

wind and wave characteristics. Together these factors determine a coastal zone's flood-frequency probability curve (also referred to as flood-exceedance curve). The information provided by flood-frequency probability curves can be used to plot design water levels on a topographical map. Design water levels are contour lines that indicate with which probability a particular area could be flooded.

Hoozemans et al. (1993) defined the risk zone as the land area between the coastline and the "maximum" design water level, which is defined as a flood-frequency probability of once per 1,000 years, taking into account global sea-level rise and regional and local aspects such as subsidence, tidal range, and storm characteristics (wind and wave set-up and minimum barometric pressure). Hence, the delineation of the risk zone requires the calculation of the maximum design water level (see Hoozemans et al., 1993).

7.2.3.2 Erosion and inundation

Sea-level rise can activate two important mechanisms that result in the loss of land: erosion and inundation. Erosion represents the physical removal of sediment by wave and current action, and inundation is the permanent submergence of low-lying land. The primary mechanism at any location depends on the geomorphology of the coast. Many other factors than sea-level rise can play a part in determining land loss (e.g., vegetation, sediment supply), yet at the intended level of analysis it is justified not to consider them. More sophisticated analyses would require considerably more data on the coastal sediment budget, and the development of more site-specific models. Such analyses are therefore likely to face severe time and funding constraints in many coastal areas.

Sea-level rise contributes to the erosion of erodible cliffs, coral-reef islands, and gravelly, sandy, and muddy coasts by promoting the offshore transport of sedimentary material. The best known and most widely applied model to estimate erosion has been developed by Bruun (1962) for application on straight sandy shores (see also Dean, 1991; SCOR Working Group 89, 1991; Healy, 1991, 1996; Mimura and Nobuoka, 1995). In other erodible coastal environments alternative erosion models have to be used, which, however, are often based on the Bruun rule.

Low-lying coastal areas such as deltas, coastal wetlands, and coral atolls may face inundation as a result of sea-level rise. Land loss resulting from inundation is simply a function of slope: the lower the slope, the greater the land loss. In addition, the survival of coastal wetlands is dependent upon sediment availability and local biomass production, as well as the potential for these ecosystems to migrate inland. Flood embankments can inhibit this natural adaptation of wetlands to sea-level rise. Healthy, unobstructed wetlands in settings with continuing sedimentation are expected to be able to cope with projected global sea-level rise, although ecosystem characteristics may change.

Healthy coral-reef systems are also believed to be able to keep up with projected sea-level rise (Bijlsma et al., 1996), although some doubt whether maximum accretion rates of 10 mm/yr achieved during the early Holocene can be considered realistic under current ecological and sea-level conditions (Nunn, personal communication, University of the South Pacific, Fiji,1997) Moreover, other climatic and non-climatic stress factors may have diminished the natural resilience and resistance of reefs.

Figure 7.2 summarises the above discussion and indicates how it can be decided what is the appropriate land-loss model for which coastal environment.

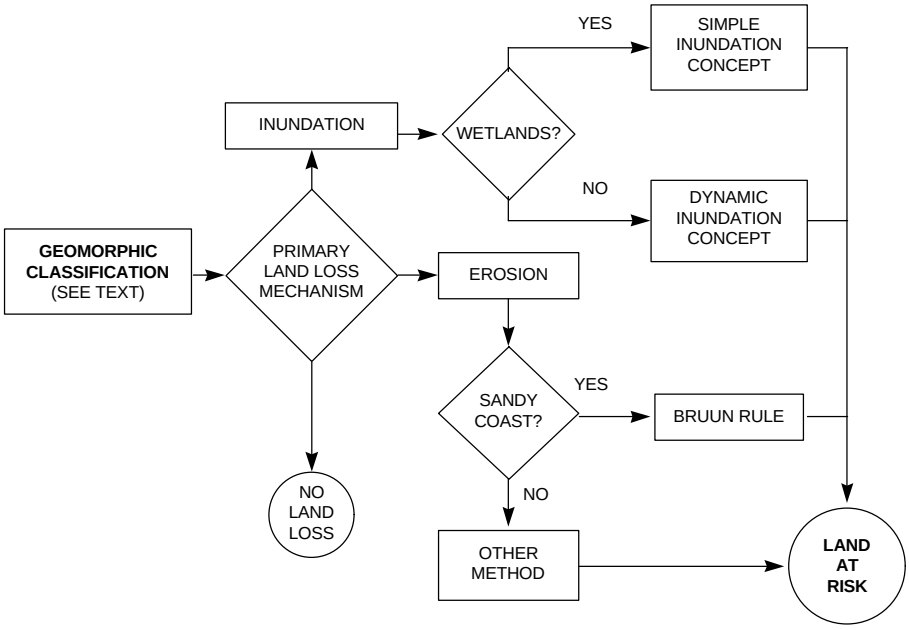

Figure 7.2 Flow-diagram to determine the appropriate method to determine land at risk from erosion or inundation (Nicholls et al., 1995). Wetlands embrace marshes, mangroves, and coral atolls/keys.

7.2.3.3. Rising water tables

Sea-level rise could be associated with a rise in coastal groundwater tables. The distance inland that a water table will be affected by sea-level rise depends on a range of factors, including elevation and subsurface permeability. In some locations, particularly deltas, rising water tables can occur as far as several tens of kilometres inland. The need to assess rising water tables depends on the potential for saltwater intrusion in groundwater (see Section 7.2.3.4) as well as impacts on foundations, drainage systems, and underground services. For semi-confined aquifers, the Mazure equation (Mazure, 1936) can be applied as a first approximation of the water-table rise. Because these impacts occur almost exclusively in urban areas, this is where attention should be focused.

7.2.3.4 Saltwater intrusion

As sea level rises, fresh groundwater and surface water could be displaced by saline water, which could have substantial adverse impacts on drinking-water supply and agriculture. To assess these impacts, knowledge of the spatial and temporal extent of saltwater intrusion is needed. It is important to note that saltwater intrusion is already occurring in many coastal regions, owing to overexploitation of surface water and groundwater (e.g., Han et al., 1995). With growing populations in coastal regions, saltwater intrusion due to this problem is expected to occur more widely, and may enhance the rate of saltwater infiltration. Therefore, it is likely that sea-level rise will exacerbate an already adverse situation.

Assessing the extent of saltwater intrusion in groundwater is difficult because it depends on many factors that are locally variable and often poorly understood. These factors include subsoil characteristics such as porosity and conductivity of the aquifer, hydraulic resistance of the aquitard, and hydraulic variables such as groundwater flow and recharge. Also the geohydrology is important, because this determines whether a freshwater aquifer is confined, semi-confined, or unconfined; sea-level rise will not result in saltwater intrusion in confined aquifers.

Saltwater intrusion in groundwater can be assessed using analytical methods or mathematical modelling. One commonality of the analytical methods is that they are all based on the Badon Ghijben-Herzberg principle, which describes the equilibrium of two stationary immiscible fluids of different density (Badon Ghijben, 1889; Herzberg, 1901). Thus, these methods assume that a sharp interface exists between fresh and saline groundwater. A full discussion of the coastal type-dependent methods that have been derived from the Badon Ghijben-Herzberg principle can be found in Custodio (1987) and Oude Essink (1996).

Owing to the complexity of intrusion processes in groundwater, reliable estimates of the extent of saltwater intrusion in groundwater can in fact be made only by means of mathematical modelling. By using density-dependent solute transport models, spatial and temporal changes in salinity in coastal groundwater can be assessed. A number of such models are available, mostly based on either the finite different method or the finite element method. The US Geological Survey is the leading institute in developing and purchasing public-domain, two-dimensional and three-dimensional groundwater-flow models (http://water.usgs.gov/software/ground_water.html). Important distributors of affordable computer codes are, among others, the International Ground Water Modeling Center (http://magma.mines.edu/igwmc/ software/igwmcsoft/ ground_water.html) and the Scientific Software Group (http://www/scisoftware.com).

Saltwater intrusion in surface water (rivers and estuaries) is a function of the following parameters (Oude Essink, 1996):

- density differences between freshwater and saltwater;
- tidal range;

- river discharge;
- cross-sectional area; and
- vertical mixing of water.

Based on the last parameter, three distinct estuarine conditions can be identified: a mixed estuary, a partially mixed estuary, and a stratified estuary. Stratified estuaries are most susceptible to saltwater intrusion because a saltwater wedge is formed that can reach far upstream.

7.2.3.5 Summary

The above four sections discussed methods to assess the extent and magnitude of five biogeophysical effects of sea-level rise on coastal systems. Table 7.2 lists these methods, indicates for which level of assessment they can be applied, shows the requirements for application —in terms of data, time, skill, and resources —and gives an indication of the reliability and validity of results.

Table 7.2 Summary of the available methods to assess biogeophysical effects of sea-level rise. Scores from 1 to 5 indicate increasing requirements and reliability/validity.

Biogeophysical effect	Assessment method	Requirements				Reliability and Validity
		Data	Time	Skill	Money	
Increasing flood-frequency	Use of current flood-frequency data	3	2	3	2	2
Probabilities	Individual-component method	3	3	3	2	2
Erosion	Bruun rule of thumb	2	1	1	1	1
	Bruun rule	3	3	3	2	2
	Sediment-budget approach	5	5	5	4	3
Inundation	Simple inundation concept	1	1	1	1	1
	Dynamic inundation concept	2	2	3	2	2
	Landscape modelling	5	5	5	5	3
Rising water tables	Mazure equation	3	3	3	3	1
Saltwater intrusion	Analytical methods (sharp-interface approach)	3	2	3	2	1
	Mathematical modelling	5	5	5	5	3

7.2.4 Methods for assessing potential socio-economic impacts

For each area potentially affected by sea-level rise, analysis following the methods outlined in Section 7.2.3 will identify the relevant biogeophysical effects, including the area that will be at increased risk from coastal flooding and the area that is potentially lost as a result of erosion or inundation.

This section presents methods to assess the socio-economic implications of increased flood risk and potential land loss. This is done using a distinction between three fundamental socio-economic impact categories:

- (human) population;
- marketed goods and services; and

- non-marketed goods and services.

For the last two categories, this section outlines techniques that are aimed at expressing these impacts in economic terms, recognising that this may be impossible or undesirable for all values at stake. The first category applies a risk-based approach, using the design water levels described in Section 7.2.3.1.

7.2.4.1 Population

Sea level rise would obviously affect those people living near the coast, because their houses or businesses would be inundated, eroded, or more frequently flooded. A crude way of estimating the number of people affected is to multiply population density by the area affected. The national average population density could be used, but it is preferable to use the population density of coastal counties, provinces, or similar regions. The area affected by sea level rise, and thus the population affected, depends on the extent of protective adaptation. The population density depends on the socio-economic scenarios used.

People are not affected by sea level rise in the same manner. Some would experience a flood of minor inconvenience once in every 15 years instead of once in every 20 years. Others would be forced to migrate. Some would drown. Unfortunately, no classification has been established of the various ways in which people can be affected by sea level rise, let alone methods to estimate their numbers.

Two categories can be estimated, however. Hoozemans et al. (1993) present a method to estimate the number of people affected[3] by coastal floods each year, and how this population-at-risk would change with sea level rise. Their report contains such estimates for all coastal countries. Their databases are, not highly reliable however, and probably include considerable errors of overestimation and underestimation. People living in places that would get permanently inundated or eroded would need to seek a livelihood elsewhere. Thus, an estimate of the people forced to migrate results.

7.2.4.2 Marketed goods and services

Assessment of the increased risk to or potential loss of marketed goods and services is a complicated exercise. First, an inventory is needed of all economic assets and activities in the coastal area affected. Examples of such inventories can be found in Yohe (1990), Mimura et al. (1994), Yohe et al. (1995), Dennis et al. (1995a,b), and Volonté and Nicholls (1995). This inventory needs to be projected into the future, as part of the socio-economic scenarios (see Chapter 2). Further, a quantitative assessment needs to be made of the degree to which these assets and activities will be subject to damage as a result of sea-level rise. Sea-level rise may also lead to costs that are not related directly

[3] Note that ‘affected’ does not distinguish between more and less severe effects of floods.

to the economic assets and activities identified (e.g., evacuation). Further, benefits accruing from new opportunities, if any, should also be taken into account.

A report by Turner and Adger (1996), written for the core project Land-Ocean Interactions in the Coastal Zone (LOICZ) of the International Geosphere-Biosphere Programme (IGBP), provides specific guidance for the application of economic valuation methods in coastal zones, as does a report by Lipton et al. (1995). Even more detailed, and originally written for application in the United Kingdom, is the manual by Penning-Rowsell et al. (1992).

The most important goods and services that could be at risk of sea-level rise, and which are readily quantifiable in monetary terms, include:

- land;
- physical structures (e.g., houses, roads); and
- agricultural and industrial productivity.

These goods and services can either be irreversibly lost as a result of erosion or inundation, or be exposed to a higher risk of flooding, which can cause temporal losses. Also, rising water tables may result in increased likelihood of foundation failure, existing drainage services may be made obsolete (Titus et al., 1987), and underground services in urban areas would be affected (Yim, 1995). In certain low-lying areas, hazards such as liquefaction during earthquakes may be exacerbated.

Potential losses in capital assets such as land, property, and infrastructure cannot be estimated accurately. The problem is that people's anticipation of erosion and inundation will affect the extent, nature, and value of capital assets in the coastal zone, and realistic modelling of people's anticipation has proved exceedingly difficult. However, it is possible to give upper and lower bounds of the potential losses; the methods are associated with Titus (1992) and Yohe (1991), respectively. The upper bound loss assumes that X acres of land will get inundated and eroded, and values this land at its (current or future) market price. The market price supposedly reflects the value of the agricultural and industrial activities the piece of land can support. The properties and infrastructure on this land are assumed to be lost as well. These are valued at their (current or future) market or replacement values. The lower bound loss assumes also that X acres of land will get lost; however, this land is valued not at its market price, but at the market price of similar land farther from the coast. Because of access to the sea and natural beauty, coastal land is often expensive. With sea level rise, the strip of coastal property will not disappear, but move inland. The properties and infrastructure that would be lost with the land are not counted, on the assumption that their owners anticipate sea level rise and depreciate their houses (say) to zero value just before the sea enters the front. Thus, in practice the true loss probably lies somewhere between the upper and lower bounds.

7.2.4.3 Non-marketed goods and services

As the term implies, non-marketed goods and services are not traded on markets. In the absence of a market, these goods and services cannot be readily expressed in monetary terms, because there is no pricing mechanism. This does not suggest, however, that they do not possess economic value. Examples of non-marketed goods and services include recreational values, cultural and subsistence values (e.g., community structures), and natural values (e.g., a wetland's capacity to buffer wave energy and assimilate waste).

Thus, it is important to realise that the total economic value of a coastal system is more than simply the market value of its resources. There are methods to express non-market values in money. These methods are based on revealed and expressed preferences, using implicit markets (people's expenditures on safety or landscape beauty contains information about its value) or hypothetical markets (through interviews and experiments). To date, economic assessment of non-marketed goods and services has been directed primarily at quantifying the value of coastal recreation and indirect-use values such as storm protection and waste assimilation. Empirical studies confirm that these values may be significant in monetary terms (e.g., Dixon, 1989; Costanza et al., 1989; De Groot, 1992; Barbier, 1994; Bateman et al., 1995). More guidance and references on the valuation of non-marketed coastal goods and services can be found in Turner and Adger (1996).

7.3 Scenarios

Scenarios for impact assessment reflect plausible future conditions of all environmental and socio-economic parameters of interest. Some parameters can be considered to be universally important, whereas others are more site-specific. In addition to differentiating between environmental and socio-economic parameters, a distinction can also be made based on whether or not changes in these parameters will be climate-related.

7.3.1 Relative sea-level rise

Since relative sea-level rise is the sum of global sea-level rise, regional oceanic effects, and vertical land movements, it follows that scenarios for relative sea-level rise can be expressed as:

$$S_{r,t} = S_{g,t} + S_{o,t} + V \cdot t \qquad (7.1)$$

where: $S_{r,t}$ = relative sea-level rise in year t (m),

$S_{g,t}$ = global sea-level rise in year t,

$S_{o,t}$ = regional sea-level change induced by oceanic changes in year t (m),

V = vertical land movement (m/yr), and

t = number of years in the future (base year 1990).

The US National Research Council has suggested expressing global sea-level rise scenarios as a quadratic equation (NRC, 1987):

$$S_{g,t} = a \cdot t + b \cdot t^2 \qquad (7.2)$$

where: a = incremental sea-level rise (m/yr), and

b = acceleration factor (m/yr) ^{2}.

The most recent IPCC sea-level rise scenarios shown in Figure 7.1 can be approximated by the values for a and b shown in Table 7.3, using 1990 as the base year. Hence, $S_{g,t}$ can be computed for any year using equation (7.2). The coefficients can be easily adjusted to reflect new scientific knowledge (Nicholls and Leatherman, 1996).

Table 7.3 Values for *a* and *b* in equation (7.2) for three IPCC sea-level rise scenarios (Nicholls and Leatherman, 1996).

IPCC Scenario	Coefficients for equation (7.2)		Sea-level rise	
(Warrick et al., 1996)	*a* (m/yr)	*b* (m/yr) ^{2}	2050 (m)	2100 (m)
Low (no acceleration)	0.0018	0	0.11	0.2
Best	0.0018	0.000025	0.2	0.5
High	0.005	0.000029	0.4	0.9

Alternatively, $S_{g,t}$ can be obtained directly from scenario generators that link simple climate models with sea-level models. Examples of scenario generators include MAGICC and SCENGEN, both developed by the Climatic Research Unit of the University of East Anglia (see Chapter 3).

Given the uncertainties surrounding $S_{g,t}$, it is important that scenarios are selected such that they encompass the likely change (see Figure 7.1). Therefore, a maximum scenario in which $S_{g,t}$ equals 1 metre in 2100 is quite appropriate for such analysis.

As indicated by Warrick et al. (1996), local values for $S_{o,t}$ are highly uncertain and could therefore best be considered zero until more concrete guidance emerges. Values for V can be assessed from a number of different sources, including geological analysis, geodetic surveys, and the analysis of long-term tide-gauge records. Note that equation (7.1) assumes that vertical land movement is responsible for all the deviation of relative sea-level rise from global sea-level rise, and that vertical land movement is linear and will continue unchanged in the future. In areas subject to human-induced subsidence, future vertical land movements may be uncertain as they will depend on human action, necessitating scenarios for subsidence. For instance, Wang et al. (1995) estimate that subsidence in the Shanghai area could vary from 0 to 1 metre by 2100.

7.3.2 Other scenarios

For some coastal areas it could be worthwhile also to consider climatic changes other than sea-level rise (Bijlsma et al., 1996). In mid- to high-latitude regions, a decrease in the return period of extreme rainfall events appears likely. This will be especially relevant for low-lying coastal areas prone to flooding. Cross-referencing with Chapter 6 is desirable to ensure consistency in the analysis. For coral reefs and atolls, increasing seawater temperature could be important because this could adversely affect the growth potential of the coral, which will reduce or remove its ability to keep pace with sea-level rise. Information on both changing rainfall patterns and seawater temperatures may be obtained from general circulation models (see Chapter 3).

Other climatic changes that could have significant consequences for coastal zones, such as changes in wind direction and intensity, remain highly uncertain. The construction of plausible scenarios using the output of general circulation models is not yet possible. However, sensitivity analyses using trend analysis (e.g., Zeidler et al., 1997) or arbitrary scenarios (e.g., Peerbolte et al., 1991) could be helpful in providing insight into the possible consequences.

In addition to climatic scenarios, other types of scenarios may be required for a coastal impacts assessment. Table 7.4 summarises and structures some possible scenarios.

Table 7.4 Examples of the four different types of scenarios that can be used in coastal impact assessment (Klein and Nicholls, 1998).

	Environmental Changes	Socio-Economic Developments
Climate-Induced	• Accelerated sea-level rise • Changes in rainfall patterns • Changes in sea-surface temperature • Changes in wind and wave patterns • El-Niño-related changes • Sediment-budget changes	• Autonomous adaptation • Planned adaptation
Not Climate-Induced	• Vertical land movement • Sediment-budget changes	• Population changes • Land-use changes • Changes in gross domestic product

7.4 Autonomous adaptation

As indicated earlier, natural coastal systems have a capacity to respond autonomously to external pressures such as climate change. This capacity largely determines the system's resilience and resistance to such pressures. Resilient and resistant coastal systems are less vulnerable to sea-level rise because —up to a certain threshold —they can cope with the rise by "growing with the sea". For example, a healthy unobstructed wetland would respond by depositing more sediment, and a coral reef by increasing its

accretion rate. This autonomous adaptation is implicit in the dynamic inundation concept discussed in Section 7.2.3.2 The best way to assess the potential of autonomous adaptation is by looking at historical or geological analogues (e.g., Ellison and Stoddart, 1991; Parkinson et al., 1994; Hopley and Kinsey, 1988).

In many places, however, human activities have reduced the natural coastal system's resilience to sea-level rise such that the potential for autonomous adaptation has decreased. These activities could include infrastructural developments or pollution that prevent natural processes from taking place. Such activities have been termed "maladaptation" by Burton (1996), and it is often beneficial for reasons other than climate change to reverse maladaptive trends. Planned adaptation to sea-level rise (see Section 7.5) should therefore include consideration of options that address maladaptation so as to increase natural coastal resilience and resistance and thus facilitate autonomous adaptation.

Socio-economic systems in coastal zones also have a capacity to respond autonomously to external pressures such as climate change, analogous to natural systems. Land owners could respond to increasing flooding probabilities by building seawalls, farmers may switch to salt-tolerant crops, households may move out of the affected area. Such autonomous adaptation is likely to become more important as sea level rises, but its occurrence will be difficult to assess. It will depend on the timing and effectiveness of planned-adaptation schemes as well as on local culture and traditions. Moreover, protection options that can occur as autonomous adjustments will often be small-scale, and generally sectoral by nature. This could possibly lead to undesirable effects on adjacent coastal areas. For example, protection of eroding cliffs could remove sediment sources of neighbouring beaches.

7.5 Planned adaptation

Given the potential socio-economic impacts they face in spite of autonomous adaptation, countries may wish to plan further measures to prevent, reduce, or cope with these impacts. In addition to doing nothing and reversing maladaptive trends, three distinct response strategies to sea-level rise can be identified (IPCC CZMS, 1990):

- managed retreat;
- accommodation; and
- protection.

The first strategy involves progressively giving up threatened land by strategic retreat from or prevention of future major developments in coastal areas that may be affected by sea-level rise. The second involves continued but altered usage of the land, including adaptive responses such as elevation of buildings above flood levels, modification of drainage systems, and land-use changes. These two strategies are based on the premise that increases in land loss and coastal flooding will be allowed to occur and that some

coastal functions and values will change or be lost. On the other hand, these strategies help to maintain the dynamic nature of coastal ecosystems and thus allow them to adapt naturally. The third strategy involves defensive measures and seeks to maintain shorelines in their present position either by building or strengthening protective structures or by artificially nourishing or maintaining beaches and dunes. This strategy, which has been widely applied to protect human settlements and productive land against existing coastal hazards, often involves the loss of natural functions and values, including resilience and resistance. Therefore, the selection of appropriate adaptation options involves important trade-offs, which need to be evaluated carefully.

7.5.1 Identification of adaptation options

Table 7.5 provides an extensive list of possible adaptation options within the three generic response strategies. The optimal option or mix of options for a given coastal zone strongly depends on the local biogeophysical and socio-economic circumstances, including the anticipated impacts of sea-level rise. For each option it is indicated whether it can occur as an autonomous adjustment or whether it requires strategic action, and whether implementation is effective in a reactive or pro-active manner. Note that Table 7.5 represents a preliminary assessment, to be reviewed and updated as experience grows. See Bijlsma et al. (1996) for more discussion on the different response strategies.

Table 7.5 Response strategies to sea-level rise.

Response strategy	Type of adaptation		Timing of adaptation	
	Autonomous	Planned	Reactive	Pro-active
Managed Retreat				
Emphasis on progressive abandonment of land and structures in highly vulnerable areas and resettlement of inhabitants				
• no development in susceptible areas	✓	✓		✓
• conditional phased-out development		✓	✓	✓
• withdrawal of government subsidies		✓	✓	✓
• presumed mobility		✓		✓
• Accommodation				
Emphasis on the conservation of ecosystems harmonised with the continued occupancy and use of vulnerable areas and adaptive management responses				
• advanced planning to avoid worst impacts	✓	✓		✓
• modification of land use	✓	✓	✓	✓
• modification of building styles and codes	✓	✓		✓
• protect threatened ecosystems		✓		✓
• strict regulation of hazard zones		✓	✓ (?)	✓
• hazard insurance to reinforce regulation		✓	✓ (?)	✓
Protection				
Emphasis on the defence of vulnerable areas, population centres, economic activities, and natural resources				
• hard structural options				
• dikes, levees, and floodwalls	✓	✓	✓	✓
• seawalls, revetments, and bulkheads	✓	✓	✓	✓
• groynes	✓	✓	✓	✓
• detached breakwaters		✓	✓	✓
• floodgates and tidal barriers		✓	✓	✓
• saltwater intrusion barriers		✓	✓	✓
• soft structural options				
• periodic beach nourishment (beach fill)		✓	✓	✓
• dune restoration and creation		✓	✓	✓
• wetland restoration and creation		✓	✓	✓
• afforestation	✓	✓		✓

Table 7.5 does not explicitly consider adaptation options to saltwater intrusion in groundwater. However, a number of options have been suggested by Oude Essink (1996):

- reclaiming land in front of the coast to allow new freshwater lenses to develop;
- extracting saline groundwater to reduce inflow and seepage;
- infiltrating fresh surface water;
- inundating low-lying areas;
- widening existing dune areas where natural groundwater recharge occurs; and
- creating physical barriers.

Most of the adaptation options listed in Table 7.5 appear to require strategic action; few will occur autonomously. However, the precise distinction between autonomous adjustments and strategic action can be difficult to make (Carter et al., 1994). Further, options to protect against sea-level rise can be implemented both pro-actively and reactively, whereas most retreat and accommodation options are best implemented in a pro-active manner. However, when implementing protection options, it is important to realise that large time lags are involved, so timely planning is generally essential to be most effective (Vellinga and Leatherman, 1989). Moreover, a pro-active approach to reducing vulnerability would be beneficial from both an environmental and an economic perspective (Tol et al., 1996).

Until recently, the assessment of possible response strategies focused mainly on protection, or “fossilising” the coast in its present location. For environmental and economic reasons, this may not be prudent in many locations. Therefore, there is a need to identify the full range of possible options within the adaptive response strategies. It is envisaged that the most suitable range of options will vary among and within countries (Bijlsma et al., 1996). To begin this analysis, three simple options might be considered: no protection; protection of the entire coast, unless uninhabited/unused; and an intermediate option of protecting “important areas”, as defined within the study (see Nicholls et al., 1995). It is appreciated that none of these responses is likely to be optimal, yet their assessment can be performed relatively quickly and the results might be used to stimulate more innovative ideas.

Adaptation can and will exploit the fact that coastal infrastructure is not static. There is a turnover of many coastal facilities through major rehabilitation, construction, and technological changes in harbour, industrial, and urbanised areas, averaging roughly 25-30 years. Therefore, there will be recurring opportunities to adapt to sea-level rise, and construction and maintenance plans can take this into account in land-use planning, management, and engineering design criteria (Stakhiv et al., 1991; Yim, 1995, 1996). Moreover, experience with pro-active allowances for accelerated sea-level rise is

growing in terms of protection, accommodation, and retreat, as discussed by Bijlsma et al. (1996).

In view of the uncertainties involved, it is important to identify low-cost, no-regret responses that maintain or enhance the choices available in the future (i.e., maximise flexibility), and sectors where reactive adaptation would have particularly high costs and allowance for future sea-level rise can be considered a worthwhile "insurance policy" (Downing et al., 1996; Nicholls and Leatherman, 1996).

It is important for policy-makers to recognise that although a particular adaptation option may initially appear to be appropriate, there are many constraining factors that determine how successfully that option can be implemented. The applicability of any option must be evaluated against, among other things, a background of a country's technological and human resource capability, financial resources, cultural and social acceptability, and political and legal framework. This does not suggest that these constraints are insurmountable, but that policy-makers must be realistic when considering the range of options available to them (Bijlsma et al., 1996).

7.5.2 Evaluation of adaptation options

It has been noted by the World Coast Conference '93 (WCC'93, 1994) that the selection of adaptation options requires making trade-offs among all the stakeholders in the coastal zone. These trade-offs include environmental, economic, social, and cultural values. Therefore, adaptation options need to be evaluated in the context of a country's or region's coastal management or development objectives, which could determine the evaluation technique to be applied (see Table 7.6). For example, economic cost-benefit analysis —which could include environmental values —would suffice if decisions are made primarily based on economic efficiency. If, however, sustainable development is a leading policy objective, adaptation options would also have to be evaluated based on their effects on intergenerational and intragenerational equity, and should include consideration of environmental impacts.

Table 7.6 Adaptation evaluation methods —showing from left to right increasing complexity and scale of analysis (adapted from Pearce and Turner, 1992).

Least complicated				Most complicated
Financial Analysis	Economic Cost-Benefit Analysis	Extended Cost-Benefit Analysis	Environmental Impact Assessment	Multi-Criteria Decision Methods
• financial profitability criterion • private costs and	• economic efficiency criterion • social costs and benefits	• sustainable development principles • economic efficiency and	• quantification of a diverse set of effects on a common scale, but no evaluation	• multiple decision criteria • monetary and non-

revenues • monetary valuation	• monetary valuation	equity trade-off environmental standards as constraints • partial monetary valuation	monetary evaluation

A practical application that combines cost-effectiveness analysis with multi-criteria analysis is the decision matrix developed by Smith (1996a) in the context of the US Country Studies Programme (see also Chapter 5). It is generically applicable for evaluating climate-change adaptation options for a range of socio-economic sectors, and could also be used for coastal zones. Published examples of its application include water-resources management (Smith, 1996b) and forestry (Smith et al., 1996).

Computer-based decision-support systems are increasingly being developed to assist policy-makers in selecting adaptation options. Examples include the Adaptation Strategy Evaluator (ASE), developed by the US Environmental Protection Agency (see Chapter 5) and the Coastal Zone Simulation Model (COSMO), developed for the World Coast Conference (Noordwijk, 1-5 November 1993) by the Dutch Coastal Zone Management Centre, The Hague , Netherlands. However, these generic software packages have limited utility to site-specific application (CZMC, 1993), although they do have educational value. One of the major drawbacks is the fact that, owing to the incomplete understanding of adaptation options, many aspects cannot yet be modelled satisfactorily, including social, cultural, and subsistence values.

7.6 Summary and implications

When conducting vulnerability assessment in coastal zones, it is important to recognise that climate change and sea-level rise will impact an evolving coastal landscape, which is experiencing a range of other pressures. Therefore, to be most effective, responses to sea-level rise need to be integrated with all the other planning taking place in the coastal zone.

At both the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, 3-16 June 1992) and the World Coast Conference, integrated coastal zone management (ICZM) has been recognised as the most appropriate process to deal with current and long-term coastal problems. There are many approaches as well as diverse institutional arrangements that can be tailored to the particular culture and style of governance (WCC'93, 1994; Bijlsma et al., 1996).

ICZM involves the comprehensive assessment, setting of objectives, planning and management of coastal systems and resources, while taking into account traditional, cultural, and historical perspectives and conflicting interests and uses. It is an iterative and evolutionary process, which includes adaptation to climate change and sea-level rise by developing and implementing a continuous management capability that can respond to changing conditions.

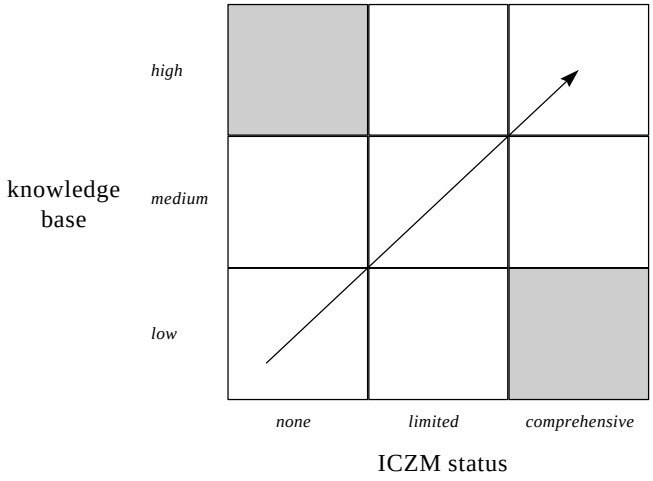

Figure 7.3 Knowledge base versus ICZM status, showing an evolution from a low knowledge base with no ICZM to a high knowledge base and comprehensive ICZM.

As shown in Figure 7.3, assessment of impacts of and adaptation to climate change and sea-level rise in coastal zones can be conducted in areas with low, medium, or high knowledge bases, and with no, limited, or comprehensive ICZM in place. Impact assessment is often described as one possible trigger for ICZM (WCC'93, 1994). Vice versa, ICZM will increase the need for more sophisticated and detailed assessment of the implications of climate change. Thus, an iterative evolution of such assessment within ICZM can be envisaged, progressively drawing from and also contributing to an improved knowledge base for decision making. As part of this evolution, climate-change impact and adaptation assessment will become embedded in wider issues, and with more focus on detailed responses, but it will remain an important element of the analysis for ICZM. Such an evolution can be seen for Egypt (the Nile delta) and Bangladesh (the Ganges-Brahmaputra delta), where initial studies raised significant concerns (Milliman et al., 1989). Numerous, more detailed and sophisticated studies have followed, combined with increasing emphasis on ICZM.

References

Badon Ghijben, W. 1889 (in Dutch). Nota in verband met de voorgenomen putboring nabij Amsterdam. *Tijdschrift van het Koninklijk Instituut voor Ingenieurs*. The Hague, 8-22.

Barbier, E.B. 1994. Valuing environmental functions: Tropical wetlands. *Land Economics* 70: 155-173.

Bateman, I.J., I.H. Langford, R.K. Turner, K.G. Willis, and G.D. Garrod. 1995. Elicitation and truncation effects in contingent valuation studies. *Ecological Economics* 12: 161-179.

Begon, M., J.L. Harper, and C.R. Townsend. 1996. *Ecology: Individuals, Populations and Communities*. 3rd edition. Blackwell Scientific Publications, Boston, Massachusetts, USA.

Bijlsma, L., C.N. Ehler, R.J.T. Klein, S.M. Kulshrestha, R.F. McLean, N. Mimura, R.J. Nicholls, L.A. Nurse, H. Pérez Nieto, E.Z. Stakhiv, R.K. Turner, and R.A. Warrick. 1996. Coastal zones and small islands. In *Climate Change 1995 —Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, R.T. Watson, M.C. Zinyowera and R.H. Moss (eds). Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 289-324.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Proceedings of the American Society of Civil Engineers, *Journal of the Waterways and Harbors Division* 88: 117-130.

Burton, I. 1996. The growth of adaptation capacity: practice and policy. In *Adapting to Climate Change: An International Perspective*, J.B. Smith, N. Bhatti, G.V. Menzhulin, R. Benioff, M. Campos, B. Jallow, F. Rijsberman, M.I. Budyko, and R.K. Dixon (eds). Springer-Verlag, New York, pp. 55-67.

Carter, T.R., M.C. Parry, S. Nishioka, and H. Harasawa (eds). 1994. *Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Report of Working Group II of the Intergovernmental Panel on Climate Change. University College London and Centre for Global Environmental Research, London and Tsukuba.

Costanza, R., S.C. Farber, and J. Maxwell. 1989. Valuation and management of wetland ecosystems. *Ecological Economics* 1: 335-361.

Custodio, E. (ed). 1987. *Groundwater Problems in Coastal Areas*. Studies and Reports in Hydrology No. 45, UNESCO, Paris.

CZMC. 1993. Coastal Zone Simulation Model (COSMO). Coastal Zone Management Centre, The Hague.

Dean, R.G. 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research* 7: 53-84.

De Groot, R.S. 1992. *Functions of Nature —Evaluation of Nature in Environmental Planning, Management and Decision Making*. Wolters-Noordhoff, Groningen.

Dennis, K.C., I. Niang-Diop, and R.J. Nicholls. 1995a. Sea-level rise and Senegal: potential impacts and consequences. *Journal of Coastal Research*, Special Issue 14: 243-261.

Dennis, K.C., E.J. Schnack, F.H. Mouzo and C.R. Orona, 1995b. Sea-level rise and Argentina: potential impacts and consequences. *Journal of Coastal Research*, Special Issue 14: 205-223.

Dixon, J.A. 1989. Valuation of mangroves. *Tropical Coastal Area Management* 4: 1-6.

Douglas, B.C., 1995, Global sea level change: determination and interpretation. *Reviews of Geophysics*, Supplement, July. U.S. National Report to the International Union of Geodesy and Geophysics 1991-1994. pp. 1425-1432.

Downing, T.E., A.A. Olsthoorn, and R.S.J. Tol (eds). 1996. *Climate Change and Extreme Events: Altered Risk, Socio-Economic Impacts and Policy Responses*. Institute for Environmental Studies report No. R-96/4, Environmental Change Unit report No. 12. Vrije Universiteit Uitgeverij, Amsterdam.

Ellison, J.C. and D.R. Stoddart. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research* 7: 151-165.

Emery, K.O. and D.G. Aubrey. 1991. *Sea Level, Land Levels and Tide Gauges*. Springer-Verlag, New York.

Frederic R. Harris BV, DHV Consultants BV and Institute of Hydro-engineering. 1992. *Vulnerability Assessment to Accelerated Sea Level Rise: Case Study Poland*. Ministry of Economic Affairs, Ministry of Transport, Public Works and Water Management and Polish Academy of Sciences, The Hague and Gdansk.

Fu, L.-L., C.J. Koblinsky, J.-F. Minster, and J. Picaut. 1996. Reflecting on the first three years of TOPEX/POSEIDON. *Eos*, Transactions of the American Geophysical Union 77: 109,111,117.

Gornitz, V.M. 1995. Sea-level rise: A review of recent past and near-future trends. *Earth Surface Processes and Landforms* 20: 7-20.

Gornitz, V.M., R.C. Daniels, T.W. White, and K.R. Birdwell. 1994. The development of a coastal risk assessment database: vulnerability to sea-level rise in the U.S. Southeast. *Journal of Coastal Research*, Special Issue 12: 327-338.

Han, M., J. Hou, L. Wu, C. Liu, G. Zhao, and Z. Zhang. 1995. Sea level rise and the North China coastal plain: a preliminary analysis. *Journal of Coastal Research* Special Issue 14: 132-150.

Healy, T. 1991. Coastal erosion and sea level rise. *Zeitschrift für Geomorphologie*, Supplement Band 81: 15-29.

Healy, T. 1996. Sea level rise and impacts on nearshore sedimentation: An overview. *Geologische Rundschau* 85: 546-553.

Herzberg, A. 1901. Die Wasserversorgung einiger Nordseebäder. *Journal für Gasbeleuchtung und Wasserversorgung* 44: 815-819.

Hoozemans, F.M.J., M. Marchand and H.A. Pennekamp. 1993. *A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production on a Global Scale*. 2nd edition. Delft Hydraulics and Ministry of Transport, Public Works and Water Management, Delft and The Hague.

Hopley, D. and D.W. Kinsey. 1988. The effects of a rapid short-term sea level rise on the Great Barrier Reef. In *Greenhouse: Planning for Climate Change*, G.I. Pearman (ed). Brill, Leiden, pp. 189-201.

IPCC CZMS. 1990. *Strategies for Adaptation to Sea Level Rise*. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the

Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, The Hague.

IPCC CZMS. 1992*a*. A common methodology for assessing vulnerability to sea level rise. 2nd revision. Appendix C of *Global Climate Change and the Rising Challenge of the Sea*, IPCC CZMS. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, The Hague.

IPCC CZMS. 1992*b*. Techniques to inventory and delineate coastal zones. Appendix E of *Global Climate Change and the Rising Challenge of the Sea*, IPCC CZMS. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, The Hague.

Jones, A.R. 1995. GIS in coastal management: a progress review. In *CoastGIS '95*, R. Furness (ed). Proceedings of the international symposium on GIS and computer mapping for coastal zone management, 3-5 February, University College Cork, Cork.

Kay, R.C. and J.E. Hay. 1993. A decision support approach to coastal vulnerability and resilience assessment: A tool for integrated coastal zone management. In *Vulnerability Assessment to Sea Level Rise and Coastal Zone Management*, R.F. McLean and N. Mimura (eds). Proceedings of the IPCC/WCC'93 Eastern Hemisphere workshop, Tsukuba, 3-6 August. Department of Environment, Sport and Territories, Canberra, pp. 213-225.

Klein, R.J.T. and R.J. Nicholls. In Press. Assessment of coastal vulnerability to climate change, *Ambio*.

Leatherman, S.P., R.J. Nicholls and K.C. Dennis. 1995. Aerial videotape-assisted vulnerability analysis: a cost-effective approach to assess sea-level rise impacts. *Journal of Coastal Research*, Special Issue 14: 15-25.

Leatherman, S.P. and G. Yohe. 1996. Coastal impact and adaptation assessment. In *Vulnerability and Adaptation Assessments —An International Handbook*, R. Benioff, S. Guill and J. Lee (eds). Version 1.1. Kluwer Academic Publishers, Dordrecht, pp. 5.63-5.76, H.1-H.39.

Lipton, D.W., K. Wellman, I.C. Sheifer and R.F. Weiher. 1995. *Economic Valuation of Natural Resources: A Handbook for Coastal Resource Policy Makers*. NOAA Coastal Ocean Program Decision Analysis Series No. 5. NOAA Coastal Ocean Office, Silver Spring, Maryland, USA.

Machida, S., N. Mimura, H. Harasawa and K. Yamada. 1993. Database system for vulnerability assessment to sea level rise: an Asia-Pacific vulnerability assessment. In *Vulnerability Assessment to Sea Level Rise and Coastal Zone Management*, R.F. McLean and N. Mimura (eds.). Proceedings of the IPCC/WCC'93 Eastern Hemisphere workshop, Tsukuba, 3-6 August 1993. Department of Environment, Sport and Territories, Canberra, Australia, pp. 69-77.

Maguire, D.J., M.F. Goodchild and D.W. Rhind (eds). 1991. *Geographical Information Systems: Principles and Applications*. Longman, London.

Mazure, J.P. 1936. *Geo-Hydrologische Gesteldheid van de Wieringermeer*. Rapporten en mededeelingen betreffende de Zuiderzeewerken No. 5, Algemeene Landsdrukkerij, The Hague.

McLean, R.F. and N. Mimura (eds). 1993. *Vulnerability Assessment to Sea Level Rise and Coastal Zone Management*. Proceedings of the IPCC/WCC'93 Eastern Hemisphere workshop, Tsukuba, 3-6 August. Department of Environment, Sport and Territories, Canberra, Australia.

Milliman, J.D., J.M. Broadus and F. Gable. 1989. Environmental and economic implications of rising sea level and subsiding deltas: The Nile and Bengal examples. *Ambio* 18: 340-345.

Mimura, N., M. Isobe and Y. Hosokawa. 1994. Impacts of sea level rise on Japanese coastal zones and response strategies. In *Global Climate Change and the Rising Challenge of the Sea*, J. O'Callahan (ed). Proceedings of the third IPCC CZMS workshop, Margarita Island, 9-13 March 1992. National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA, pp. 329-349.

Mimura, N. and H. Nobuoka. 1995. Verification of the Bruun Rule for the estimation of shoreline retreat caused by sea-level rise. In *Coastal Dynamics 95*, W.R. Dally and R.B. Zeidler (eds). American Society of Civil Engineers, New York, pp. 607-616.

Nicholls, R.J., K.C. Dennis, C.R. Volonté and S.P. Leatherman. 1993. Methods and problems in assessing the impacts of accelerated sea-level rise. In *The World at Risk: Natural Hazards and Climate Change*, R. Bras (ed). AIP Conference Proceedings No. 277, American Institute of Physics, New York, pp. 193-205.

Nicholls, R.J. and S.P. Leatherman. 1996. Adapting to sea-level rise: relative sea-level trends to 2100 for the United States. *Coastal Management* 24: 301-324.

Nicholls, R.J., S.P. Leatherman, K.C. Dennis and C.R. Volonté. 1995. Impacts and responses to sea-level rise: qualitative and quantitative assessments. *Journal of Coastal Research*, Special Issue 14: 26-43.

NRC. 1987. *Responding to Changes in Sea Level: Engineering Implications*. Report of the National Research Council. National Academy Press, Washington D.C.

Nunn, P.D., A.D. Ravuvu, W. Aalbersberg, N. Mimura, and K. Yamada. 1994a. *Assessment of Coastal Vulnerability and Resilience to Sea-Level Rise and Climate Change, Case Study: Yasawa Islands, Fiji*. Phase II: Development of methodology. Environment Agency Japan, Overseas Environment Cooperation Centre Japan, South Pacific Regional Environment Programme.

Nunn, P.D., A.D. Ravuvu, E. Balogh, N. Mimura, and K. Yamada. 1994b. *Assessment of Coastal Vulnerability and Resilience to Sea-Level Rise and Climate Change, Case Study: Savai'i Island, Western Samoa*. Phase II: Development of methodology. Environment Agency Japan, Overseas Environment Cooperation Centre Japan, South Pacific Regional Environment Programme.

O'Regan, P.R. 1996. The use of contemporary information technologies for coastal research and management —A review. *Journal of Coastal Research* 12: 192-204.

Otter, H.S., A. van der Veen and H.J. de Vriend. 1996. A methodology for the analysis of the effects of a sea level rise on the socio-economy of the Med-Deltas. In *Impact of*

Climatic Change on Northwestern Mediterranean Deltas —Volume II: The Present and the Future, Capobianco M. (ed). Report of the final MEDDELT workshop, Venice, 2-6 October. Tecnomare S.p.A., Venice, pp. 3.1-3.17.

Oude Essink, G.H.P. 1996. *Impact of Sea Level Rise on Groundwater Flow Regimes: A Sensitivity Analysis for the Netherlands*. PhD Thesis, Delft University of Technology. Delft University Press, Delft.

Parkinson, R.W., R.D. de Laune and J.R. White. 1994. Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. *Journal of Coastal Research* 10: 1077-1086.

Pearce, D.W., and R.K. Turner. 1992. *Benefits, Estimates and Environmental Decision-Making*. Organisation for Economic Cooperation and Development, Paris.

Peerbolte, E.B., J.G. de Ronde, L.P.M. de Vrees, M. Mann and G. Baarse. 1991. *Impact of Sea-Level Rise on Society: A Case Study for The Netherlands*. Delft Hydraulics and Ministry of Transport, Public Works and Water Management, Delft and The Hague.

Penning-Rowsell, E.C., C.H. Green, P.M. Thompson, A.M. Coker, S.M. Tunstall, C. Richards and D.J. Parker. 1992. *The Economics of Coastal Management: A Manual of Benefit Assessment Techniques*. Belhaven Press, London.

Pirazzoli, P.A. 1991. *World Atlas of Holocene Sea-Level Changes*. Elsevier Oceanography Series No. 58, Elsevier, Amsterdam.

SCOR Working Group 89. 1991. The response of beaches to sea-level changes: A review of predictive models. *Journal of Coastal Research* 7: 895-921.

Sem, G., J.R. Campbell, J.E. Hay, N. Mimura, E. Ohno, K. Yamada, M. Serizawa and S. Nihioka. 1996. *Coastal Vulnerability and Resilience in Tuvalu —Assessment of Climate Change Impacts and Adaptation*. Phase IV. South Pacific Regional Environment Programme, Environment Agency Japan, Overseas Environment Cooperation Centre Japan.

Shennan, I. and I. Sproxton. 1991. Impacts of future sea level rise on the Tees estuary: an approach using a geographical information system. In *Impact of Sea Level Rise on Cities and Regions*, R. Frassetto (ed). Proceedings of the first international meeting Cities on Water, Venice, 11-13 December 1989. Marsilio Editori, Venice, pp. 81-92.

Smith, J.B. 1996a. Assessment of adaptation policy options. In *Vulnerability and Adaptation Assessments —An International Handbook*, R. Benioff, S. Guill and J. Lee (eds). Version 1.1. Kluwer Academic Publishers, Dordrecht, pp. 7.1-7.8, I.1-I.26.

Smith, J.B. 1996b. Development of adaptation measures for water resources. *Water Resources Development* 12: 151-163.

Smith, J.B., S.E. Ragland, and G.J. Pitts. 1996. A process for evaluating anticipatory adaptation measures for climate change. *Water, Air, and Soil Pollution.* 92: 229-238.

Spencer, N.E. and P.L. Woodworth. 1993. *Data Holdings of the Permanent Service for Mean Sea Level*. Permanent Service for Mean Sea Level, Bidston Observatory, Birkenhead.

Stakhiv, E.Z., S.J. Ratick, and W. Du. 1991. Risk cost aspects of sea level rise and climate change in the evaluation of shore protection projects. In *Water Resources Engineering Risk Assessment*, J. Ganoulis (ed). Springer-Verlag, Heidelberg, pp. 311-335.

Titus, J.G. 1992. The costs of climate change to the United States. In Global Climate Change: Implications, Challenges, and Mitigation Measures, S.K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (eds). The Pennsylvania Academy of Science, Philadelphia.

Titus, J.G. and V. Narayanan. 1996. The risk of sea level rise. *Climatic Change* 33: 151-212.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Webb and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. *Journal of Water Resources Planning and Management* 113: 216-227.

Tol, R.S.J., R.J.T. Klein, H.M.A. Jansen and H. Verbruggen. 1996. Some economic considerations on the importance of pro-active integrated coastal zone management. *Ocean & Coastal Management* 32: 39-55.

Turner, R.K. and W.N. Adger. 1996. *Coastal Zone Resources Assessment Guidelines*. LOICZ Reports and Studies No. 4, Den Burg.

Turner, R.K., S. Subak, and W.N. Adger. 1996. Pressures, trends, and impacts in coastal zones: Interactions between socio-economic and natural systems. *Environmental Management* 20: 159-173.

Vellinga, P. and S.P. Leatherman. 1989. Sea level rise, consequences and policies. *Climatic Change* 15: 175-189.

Volonté, C.R. and R.J. Nicholls. 1995. Uruguay and sea-level rise: Potential impacts and responses. *Journal of Coastal Research*, Special Issue 14: 262-284.

Wang, B., S. Chen, K. Zhang, and J. Shen. 1995. Potential impacts of sea-level rise on the Shanghai area. *Journal of Coastal Research*, Special Issue 14: 151-166.

Warrick, R.A., J. Oerlemans, P.L. Woodworth, M.F. Meier, and C. le Provost. 1996. Changes in sea level. In *Climate Change 1995: The Science of Climate Change*, J.T. Houghton, L.G. Meira Filho and B.A. Callander (eds). Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp. 359-405.

WCC'93. 1994. *Preparing to Meet the Coastal Challenges of the 21st Century*. Report of the World Coast Conference, Noordwijk, 1-5 November 1993. Ministry of Transport, Public Works and Water Management, The Hague.

Wigley, T.M.L. 1995. Global-mean temperature and sea level consequences of greenhouse gas stabilization. *Geophysical Research Letters* 22: 45-48.

Yamada, K., P.D. Nunn, N. Mimura, S. Machida, and M. Yamamoto. 1995. Methodology for the assessment of vulnerability of South Pacific island countries to sea-level rise and climate change. *Journal of Global Environment Engineering* 1: 101-125.

Yim, W.W.-S. 1995. Implications of sea-level rise for Victoria Harbour, Hong Kong. *Journal of Coastal Research*, Special Issue 14: 167-189.

Yim, W.W.-S. 1996. Vulnerability and adaptation of Hong Kong to hazards under climatic change conditions. *Water, Air, and Soil Pollution* 92: 181-190.

Yohe, G. 1990. The cost of not holding back the sea: Toward a national sample of economic vulnerability. *Coastal Management* 18: 403-431.

Yohe, G., J. Neumann, and H. Ameden. 1995. Assessing the economic cost of greenhouse-induced sea level rise: methods and application in support of a national survey. *Journal of Environmental Economics and Management* 29: S.78-S.97.

Zeidler, R.B. 1997. Climate change vulnerability and response strategies for the coastal zone of Poland. *Climatic Change* 36: 151-173.

Zeidler, R.B., M. Skaja, G. Rózynski, and J. Kaczmarek. 1997. Wind- and sea level-induced shore evolution in Poland. In *Proceedings of the 25th International Conference of Coastal Engineers*. Orlando, September 1996. American Society of Civil Engineers, New York, pp. 4364-4375.

Zerbini, S., H. Plag, T. Baker, M. Becker, H. Billiris, B. Burki, H. Kahle, I. Marson, L. Pezzoli, B. Richter, C. Romagnoli, M. Sztobryn, P. Tomasi, M. Tsimplis, G. Veis, and G. Verrone. 1996. Sea level in the Mediterranean: A first step towards separating crustal movements and absolute sea-level variations. *Global and Planetary Change* 14: 1-48.

8 Agriculture

Lead Authors
Martin L. Parry [1]
Cynthia Rosenzweig [2]
Ana Iglesias [3]

Contributing Author
Lin Erda, China

8.1 Nature of the problem

8.1.1 Background to the problem

Providing sufficient food for the world's people is becoming more challenging as our numbers are increasing and as land, water, and vegetative resources are progressively degraded through prolonged overuse. There is now concern that the challenge will be exacerbated in the future by the process of global warming, with its potential for affecting the climate regimes of entire regions.

The Second Assessment Report of the IPCC concluded that "global agricultural production could be maintained relative to baseline production in the face of climate change . . . but focusing on global agricultural production does not address the potentially serious consequences of large differences at local and regional scales . . . many of the world's poorest people – particularly those living in subtropical and tropical areas – are most at risk of increased hunger" (IPCC, 1996). The effects of climate change on

[1] Jackson Environment Institute, University College, London, UK.

[2] NASA/GISS, New York, NY, USA.

[3] Intesca, Madrid, Spain.

agriculture are thus likely to vary between different regions and different scales (global, regional, and local).

The purpose of this chapter is to describe a set of approaches for evaluating climate impacts on arable agriculture and crop production. The overall goals of climate change impact research are to define more clearly the ranges of possible impacts, to determine which locations and farming systems may be most vulnerable, to identify their critical thresholds, and to explore adaptation strategies. An overall survey of the methods of climate impact and adaptation assessment is provided by Parry and Carter (1988).

8.1.2 Why is climate change of concern in agriculture?

World food production varies by several percent from year to year, largely as a result of weather conditions such as the El Niño phenomenon and inter-annual climatic variability in many regions. But agriculture in some regions is more sensitive to weather than in others. Typically, sensitivity to weather is greatest firstly in developing countries, where technological buffering to droughts and floods is less advanced, and secondly in those regions where the main physical factors affecting production (soils, terrain, and climate) are less suited to farming. A key task facing those concerned with conducting impact assessments is to identify those regions likely to be most vulnerable to climate change, so that impacts can be avoided (or at least reduced) through implementation of appropriate measures of adaptation.

8.1.3 Defining the objectives of the impact assessment

The first step is to clearly define both the objectives and the targeted users of the assessment. The general objectives of impact assessment may be concerned with one or several targets, such as evaluation of output, management, or adaptation options; identification of gaps in knowledge; or increased public awareness. The targeted users of the results determine the scope and the focus of the objectives. Users of impact assessment in the agricultural sector are varied and include the farmer, the agricultural extension or training expert, the scientist, the national agricultural policy maker, and the national climate change negotiator.

The emphasis here is on the choice of assessment methods which inform the national agricultural policy maker (although the methods suggested will be relevant to other users). With the national policy maker in mind, the key questions are likely to be:

- Will climate change significantly affect domestic agricultural production?
- Will climate change cause food shortages and lead to an increase in hunger?
- Will climate change threaten exports?
- Will climate change affect key government policies such as agricultural pricing, support, and research and development?

- Will climate change increase food prices to consumers?

- Will climate change, acting through agriculture, place greater stress on natural resources or contribute to environmental degradation (e.g., through land use change, soil degradation, changes in water supply and water quality, pesticide use)?

The nature of the assessment is likely to be shaped by key questions in the minds of the users. These may not be clearly articulated, particularly if relatively little is known (before the assessment) about the possible effects of climate change, and a pilot survey of literature (see below) may be needed to clarify them. For the national policy maker, the primary questions are likely to include:

- What components of the farming system are particularly vulnerable, and may thus require special attention?

- Can the water/irrigation systems meet the stress of changes in water supply/demand?

- What policies and programmes exist to protect populations from hunger/financial distress and how will they operate under climate change?

- Is the agricultural research/extension system capable of providing adaptation advice to farmers? What technological options should be investigated? Does the country have access to potentially useful options developed in other countries?

- Should domestic agricultural policies be reformed?

- Are the natural resource management programmes adequate?

- If domestic production is threatened, will the country be able to import food, and (if so) at what cost?

The last of these questions is of especial significance to the impact assessor because it provides a guide to the types of farming, the regions, and the communities that may deserve to be the focus of study. This is expanded upon in the next section.

8.1.4 What impacts are likely to be important?

Focus on priorities

Because of constraints of time and money, it will be unlikely that all agricultural activities in a country or region can be studied, or all parts of the country or region. Priority will need to be given to the most important activities and areas. This can be achieved by studying national production data to identify those:

- types of farming which involve or support the majority of the rural population;

- types of agricultural land use that account for most of the farmed area;

- crops which contribute most of national agricultural GDP; and
- crops which contribute most to national export earnings.

While the above assumes a focus on what type of agriculture is most important to a country, it may not identify those activities or populations which could be most vulnerable to climate change. This would require study of:

- rural populations with lowest income, or dependency on subsistence farming;
- farming characterised by greatest year-to-year variability in output; and
- regions with a history of stress from extreme weather conditions such as drought or flooding.

Whether the focus of study should be on the most important or the most vulnerable agriculture will depend upon the objectives of the study. It may be that multiple foci can be adopted, with the aim of assessing the major effects likely at the national level as well as on local vulnerable areas.

A pilot survey of the literature

Several hundred studies have now been completed of impacts of climate change on agriculture, and these can provide an indication of both the types and the magnitude of climate change likely to be most important. A survey of such studies can provide an approximate and initial indication of the types of impact to expect and, thus, the likely methods of analysis that will be most effective. The survey is important because different methods of impact assessment will yield information on some, but probably not all, types of impact. For example, analysis of large-area shifts of cropping zones will require broad-scale use of simple agro-climatic indices, whilst analysis of yields can best be achieved through the use of process-based crop growth models. Effects on income and employment can be assessed only using economic and social forms of analysis. A summary of the impacts of climate change on agriculture, drawn from this literature, is given in Table 8.1. More detailed surveys of existing research can serve to provide an information base for subsequent formal assessments based on expert judgement (see below).

Most pilot studies will serve only to identify the types of impact that may occur, and thus deserve further evaluation. Some regions have been thoroughly studied already, and their published studies provide suggestions of how an assessment can be developed and reported. By far, the largest effort in past evaluations has been the assessment of changes in optimal growing areas and final production. For example, in Europe, a large effort has been made in understanding the location of optimal growing areas for different crops (Saarikko and Carter, 1996; studies reported by Butterfield et al., 1997). These studies combine evaluations for impact assessment at different spatial scales ranging from the site to the continental scale.

Table 8.1 Types of climate change impacts likely in the agriculture sector.

1. Changes in the location of optimal growing areas for given crops, resulting in the shift of cropping zones.
2. Changes in crop yields.
3. Changes in the type, location, and intensity of pests and diseases.

As a consequence of one or more of the above there are:

1. Changes in the mix of crops grown and hence in the type of farming, and rural land use.
2. Changes in production, farm income, and rural employment.
3. Changes in rural income, contribution to national GDP, and agricultural export earnings.

In regions where current inter-annual climate variability is a major factor determining agricultural output, there is an additional challenge for projecting climate change impacts on crop patterns. For example, the effects of the El Niño/Southern Oscillation phenomenon in Southeast Asia have to be considered in climate assessment on agricultural production in that region (Iglesias et al., 1996). In Canada, the adaptability of agricultural systems to climate changes has been also evaluated from a geographical perspective with the aim of defining the options for future regional sustainability (Brklacich et al., 1997). In the United States, there have been efforts to evaluate changes in crops yields and their economic implications (Dracup et al., 1992; Adams et al., 1995a and b).

Fewer studies address changes in the interactions of crops with pests and diseases, although those are estimated to be responsible for about one-third of crop losses every year. Changes in the interaction of crops with weeds under CO_2 enriched environments show relative advantages of weeds over many important agricultural crops (Bazzaz and McConnaughay, 1992). Insect pests are often also favoured in CO_2 enriched environments (Fajer et al., 1989) and with changes in climatic variables (Sutherst et al., 1995).

The survey of available information is also useful to indicate the key aspects of climate and atmospheric variables that are likely to be most significant for the type of agriculture to be studied. Table 8.2 outlines the key environmental variables which recent research has shown to be important in affecting crop yields in most agricultural regions. The relative importance of a particular variable is bound to vary greatly between different crops and farming environments, and the choice of the most appropriate methodology will depend on good knowledge of the locally important variables (see Section 8.2).

General relationships between crop development and growth and meteorological variables are reviewed by Fitter and Hay (1987), Ellis et al. (1990), and Hodges (1991), among others. Several studies document crop responses to variations on atmospheric CO_2 levels (see, for example, Acock and Allen, 1985; Goudriaan and Unsworth, 1990). Some studies also consider the interaction of CO_2 with other crop environmental factors such as water stress or nutrients (Kraalingen, 1990; Diaz et al., 1993; Fredeen et al., 1995; Körner, 1995). A few studies report crop response to the increment of other gases in the atmosphere (Ashomore, 1988; Bosac et al., 1993; Manning and Tiedemann, 1995).

Table 8.2 Climatic and atmospheric variables which previous studies have shown to affect crop yields.

Climate
Temperature
monthly means and variability
daily maximum and minimum air temperature and variability
frequency with which temperatures fall above or below critical levels, such as $35^{o}C$ or $0^{o}C$
accumulated degree-days through the growing season
Precipitation
daily amounts and variability
Solar radiation
daily amounts and variability
Atmosphere
Mean annual CO_2 concentration
Duration of exceedance of toxic levels of O_3
Duration of exceedance of toxic levels of SO_2

Climate variability is emerging as an important issue to be considered in the impact studies, especially when evaluating associated risks of spatial agricultural production (see Katz and Brown, 1992; Karl et al., 1995). Recent studies consider explicitly the impact of climatic variability in addition to climate change in the evaluations of crop responses (see, for example, Mearns et al., 1996).

8.1.5 The definition of the study

Choice of the unit

The pilot study should provide information regarding the appropriate unit for study. It may, for example, be maize yields in high-input commercial farming or rice yields under subsistence conditions (indeed it could be both, if an assessment were required of effects on contrasting commercial and non-commercial farming both occurring within the study area); or an assessment may need to be taken further, starting with an indication of effects on yields and continuing to impacts on production and income. In any case, it is necessary to be clear about the units of study, because their selection will determine the research methods that can be employed and the data requirements.

Choice of study area

Selection of the study area is also likely to be affected by the goals of the study. Most analyses of climate impacts on crop yields are demanding of data and analyst time, and consequently may need to be based on a sample area of the exposure unit. If so, the sample needs to be representative of the key features of the area, so that results can be extrapolated appropriately. If, for example, the object is to provide a national-level assessment, it is probable that certain regions (or even local sites) will need to be selected as representative units for in-depth study.

Choice of time frame

The selection of a time horizon for the study is likely to be governed by both the goals of the assessment and the data available. Many climate projections rely on outputs from general circulation models (GCMs), and the time frame of the projections is therefore related to that of available GCM experiments. Up to 1990 these experiments were largely based upon a doubling of atmospheric CO_2 concentrations, assuming a time frame of 2050 to 2100 (see Chapter 3). Recently, transient climate projections derived from GCMs have become available, and these provide more specific (decadal) time frames that can be incorporated into studies of the effect on agriculture.

It is difficult to make accurate projections of rates of changes in agricultural factors (such as technological change or changes in crop varieties) or in related socio-economic factors (such as population or economic development) beyond 15-20 years into the future. Therefore, assessment of economic impacts over the larger time frame of the climate projections is subject to great uncertainty. As the time horizon increases, so the ability to project future trends declines rapidly. With these caveats in mind, the time frame of climate impact assessments most likely to be required and valued at present are for decade "slices" (e.g., 2020-2030) for each decade from 2000 to 2050 (see Chapters 2 and 3 for details).

Data needs

Which data are available or not can frequently affect the type of impact assessment that is made, particularly if time and money are limited. Studies of the impact of climate change on agriculture require a quantitative description of the exposure unit and the current (baseline) agricultural conditions in the study area. Data are also needed for projecting future (reference case) conditions in the absence of climate change (e.g., projected increases in agricultural technology or fertiliser use). Although specific data requirements will vary with the scope of the study and the methodology selected (these are discussed in more detail later), the following groups of data will generally be required:

- yields for the crops to be studied, both mean and time series (to evaluate natural yield variability);
- production (both regional and national statistics);
- crop management at the local and regional level (for example, crop sowing dates, crop varieties, labour, fertiliser and irrigation inputs);
- land use (to enable spatial extrapolation from sample sites across the study area); and
- general socio-economic data (e.g., the contribution of sample sites' agricultural production to total output of the study area, percentage of working labour in the agricultural sector).

Additional data may be needed for specific studies (for example, water irrigation requirements, rates of soil degradation and erosion).

The emphasis in this chapter is on a sound quantitative assessment of first-order effects as a basis for subsequent (quantitative or qualitative) second-order estimations. The reason for this is that robust first-order assessments are a prerequisite for higher order assessments (such as for production, employment, risk of hunger), and therefore a requirement common to almost all impact studies**.**

8.1.6 The design of the study

Impacts on agriculture can be assessed at various levels, depending on the requirements of the assessment. Four general levels can be identified:

- effects on crop yield;
- effects on farm and village level output and income;
- effects on regional and national production; and
- effects on global production and prices.

Each level requires a different set of research methods, which are discussed in this chapter. In general, there are advantages in moving from the first-order crop level impacts to the second-order farm level and so on, because the outputs of the first-order analyses are frequently required as inputs to the second. At the farm and regional levels of assessment, various forms of adaptation can be analysed. Although the sequence of stages may vary according to the study's requirements, a general stepwise sequence that has been found useful is as follows:

- Identify vulnerable regions and sub-sectors of agriculture that should be the focus for study.
- Analyse the yield-climate relationships for these selected exposure units, to determine the climate variables of importance.
- Consider the changes in these variables that are likely to be most significant.
- Analyse the effect of these on crop yields (and other first-order effects).
- Analyse the effect of altered yield on second-order aspects, e.g., farm output and income.
- Evaluate farm-level responses.
- Analyse the effect of farm-level output on regional production, employment, economic activity, etc.
- Evaluate regional-level responses.

- Analyse national- and global-level effects and responses.

A schematic representation of this step-wise approach is given in Figure 8.1, which distinguishes between three types of analysis that are threaded through the research sequence: the analysis of impacts, the selection of scenarios, and the evaluation of responses.

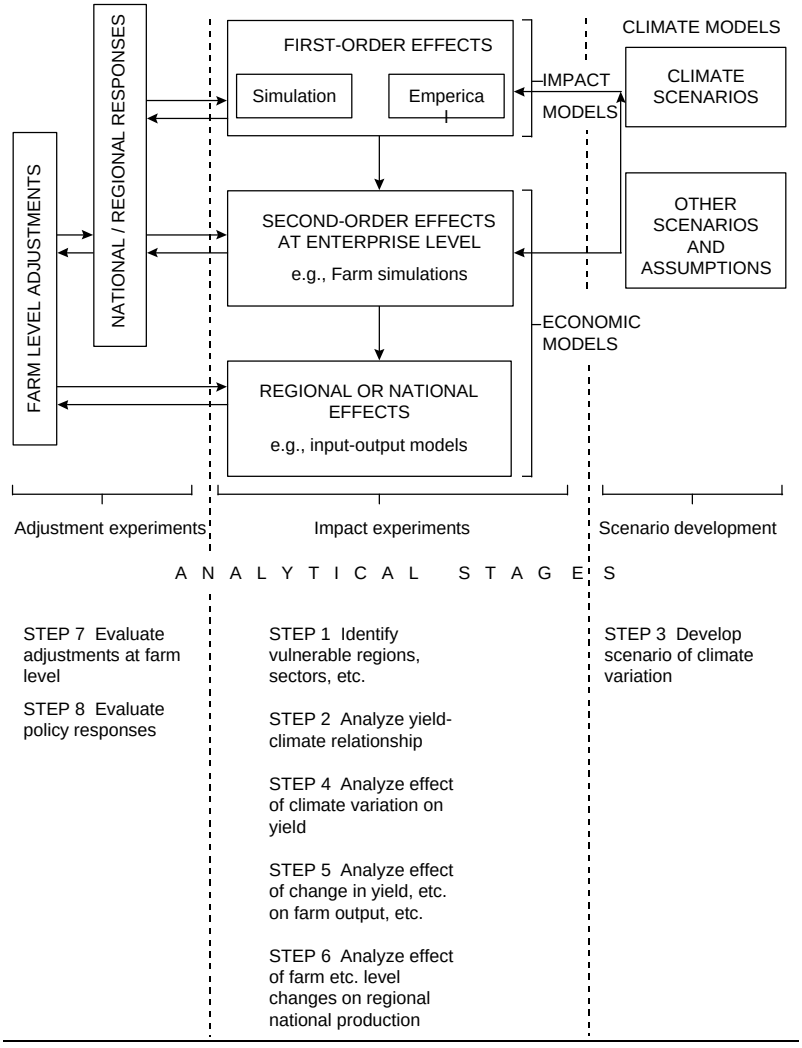

Figure 8.1. Types of model and stages of analysis in assessing the potential effects of climate change on agriculture. The approach adopted here was developed in the IIASA/UNEP study of effects of climate variations on marginal agriculture (from Parry and Carter, 1988).

8.2 An Array of Methods

This section provides a survey of the methods that can be used as basic tools for the analysis, and how these basic tools can be used at different scales of analysis. The basic tools for climate assessment fall into two broad categories: biophysical tools and socio-

economic tools. Because of the nature of the problem to be assessed, modelling has been and continues to be included in many of the studies. Nevertheless, there are other methodological approaches that can be very useful, and these range from experimentation (for some biophysical evaluations) to expert judgement.

8.2.1 Biophysical tools

Experimentation

In the physical sciences, a standard method of testing hypotheses or of evaluating processes of cause and effect is direct experimentation. In the context of climate impact assessment, however, experimentation has only a limited application. Clearly it is not possible physically to simulate large-scale systems such as the global climate, nor is it feasible to conduct controlled experiments to observe interactions involving climate and human-related activities. Only where the scale of impact is manageable, the exposure unit measurable, and the environment controllable can experiments be usefully conducted.

Up to now most attention in this area has been on observing the behaviour of agricultural plant species under controlled conditions of climate and atmospheric composition (e.g., see Strain and Cure, 1985; Geign et al., 1993). In the field, such experiments have mainly comprised gas enrichment studies, employing gas releases in the open air or in open or closed chambers, including greenhouses. The former experiments are more realistic, but are less amenable to control. The chamber experiments allow for climatic as well as gas control, but the chambers may introduce a new set of limiting conditions that would not occur in reality. The greatest level of control is achievable in the laboratory, where processes can be studied in more detail and can employ more sophisticated analyses.

The primary gases studied have been carbon dioxide, sulphur dioxide, and ozone, all of which are expected to play an interactive role with climate in future plant growth and productivity. Both temperature and water relations have also been regulated, to simulate possible future climatic conditions. To date, there have been experiments with agricultural plants (both annual and perennial crops) and on crop pests and diseases (often in conjunction with host plants). For an example of the effective combination of experimental and other approaches in western Europe and a technical explanation of the methods employed and the resources required, see Harrison et al. (1995) and Butterfield et al. (1997).

Few climate impact assessments, particularly those at national level, have the time or other resources sufficient to conduct worthwhile yield-climate experiments. A pragmatic approach is to survey the literature on experimentation and, with this as an information background, concentrate on the use of analogue or modelling approaches.

Agro-climatic indices

The agro-climatic indices are based on simple relationships of crop suitability or potential to climate (e.g., identifying the temperature thresholds of a given crop or using accumulated temperature over the growing season to predict crop yields). This type of empirically-derived coefficients is especially useful for broad-scale mapping of areas of potential impact.

The indices are derived variables that are defined either by manipulating values of a meteorological variable into a different form or by combining variables with empirically-defined coefficients into a composite term. The most common derived variable to describe the thermal agro-climate is the Effective Temperature Sum (ETS), usually measured in growing degree days. It is calculated as the excess of temperature above a fixed datum (base temperature) over a period required for a specific phase of crop development. Indices frequently used to measure moisture include Thornthwaite's Precipitation Effectiveness Index, the Palmer Drought Index, and the Relative Dryness Index. For a description of these, see Palmer (1965). Simple agro-climatic indices combined with geographical information systems have been used to provide an initial evaluation of the global agricultural climate change impacts (Leemans and Solomon, 1993) or shifts in agricultural suitable areas in particular regions. A large regional effort in the assessment of agro-climatic suitability and potential has been made in several African countries (see, for example, Fischer and van Velthuizen, 1996, for a review of the methodology and report of the results of studies in Kenya).

When combined with a spatially comprehensive data base and a geographic information system (GIS), simple agro-climatic indices enable the mapping of altered crop potential for quite large areas at relatively low cost. An example is given in Figure 8.2, where thermal requirements for commercial varieties of grain maize were identified from a survey of previous research and validated through comparison with actual land use. This enabled the identification of minimum levels of ETS required for maturation of grain maize. Present-day ETS limits were mapped, to define the current area suitable for production. Altered areas of suitability were then mapped for +1ºC increments in mean annual temperature. This combination of agro-climatic index, GIS, and a synthetic climatic scenario offers a rapid and inexpensive means of mapping the effects of climatic change on crop suitability.

Statistical models

Complex multivariate models attempt to provide a statistical explanation of observed phenomena by accounting for the most important factors (e.g., predicting crop yields on the basis of temperature, rainfall, sowing date, and fertiliser application). Statistical models are usually developed on the basis of present-day climatic variations. Thus, one of their major weaknesses in considering future climate change is their limited ability to predict effects of climatic events that lie outside the range of present-day variability. They may also be criticised for being based on statistical relationships between factors rather than on an understanding of the important causal mechanisms. However, where models are founded on a good knowledge of the determining processes and where there

are good grounds for extrapolation, they can still be useful predictive tools in climate impact assessment.

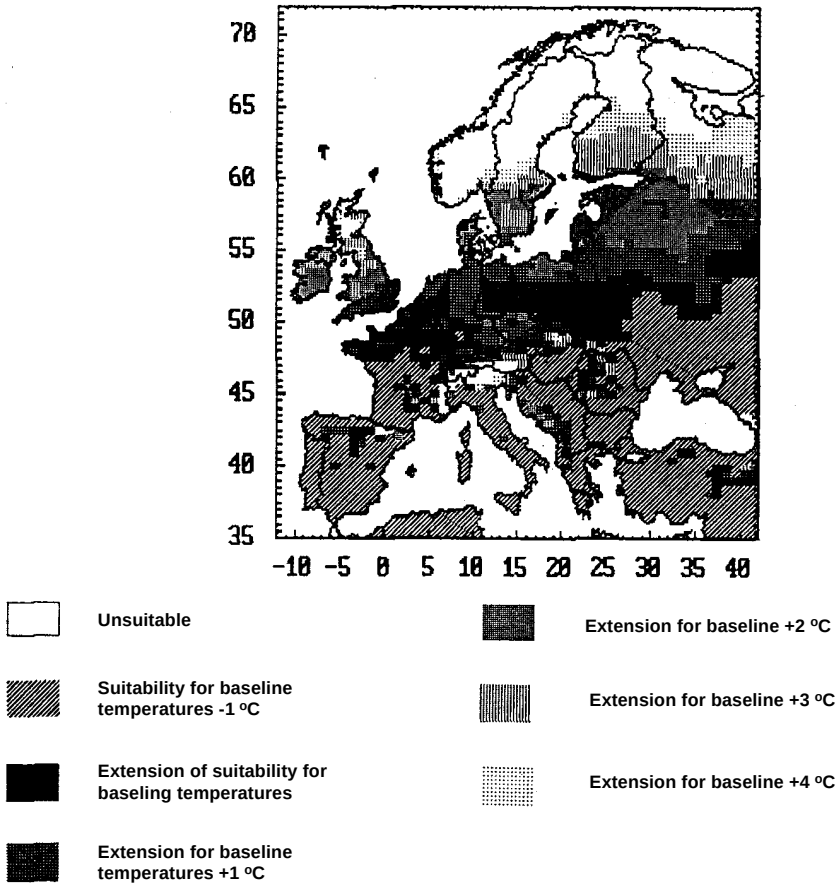

Figure 8.2 Sensitivity of grain maize to incremental changes in mean annual temperature (Carter et al., 1991).

While agro-climatic indices provide information on crop suitability and how this may be altered by climate change, statistical models can also be developed to describe how climate change may affect crop yields. These are developed by taking a sample of annual crop yield data together with a sample of weather data for the same area and time period, and relating them through statistical techniques such as multiple regression analysis. With well-informed selection of suitable explanatory variables, based on good understanding of basic crop physiology and careful model validation, this approach can provide a useful preliminary insight into climate change impacts. This is particularly the case because statistical models are often simple to apply and less demanding of input data than process-based models.

An example of their use is the effect of drought on wheat yield on the US Great Plains. This was estimated for each of 53 crop reporting districts, using a regression equation which expressed the relationship between actual yield and the weather experienced in each district in the 1930s (Warrick, 1984). Assuming a recurrence of 1930s conditions

and current technology, expected yields were thus mapped, relatively quickly, for a major wheat-producing region of the world (Figure 8.3).

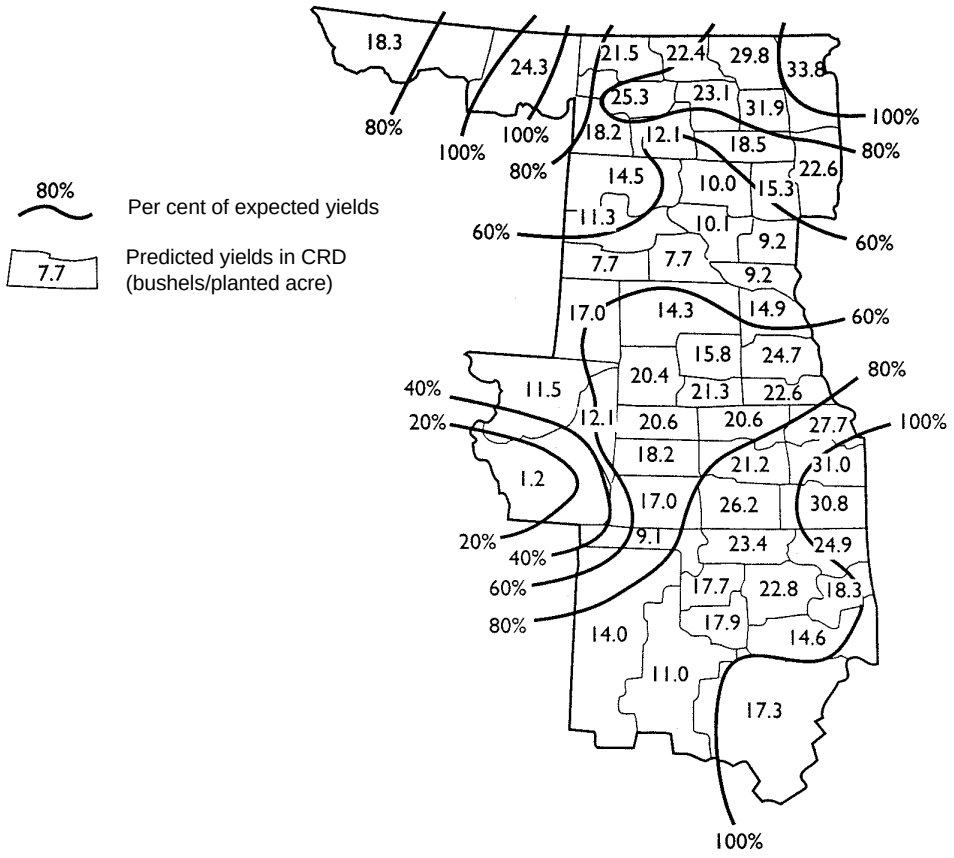

Figure 8.3 Simulated wheat yields on the US Great Plains assuming 1936 climate conditions and 1975 technology. CRD = crop reporting district (from Warrick, 1984).

The obvious drawback to this approach is the assumption of fixed technology and the use of the 1930s drought as an analogue of climate change. The latter, however, has the advantage of being based on a credible scenario (the climate conditions actually occurred in the past), while the former can be improved upon by allowing for developments in agricultural technology. A more recent study of climate change in the Great Plains (the MINK study) has combined process-based impact models with the 1930s analogue climate scenario (for a description of this, see Box 8.1).

Processed-based models

Process-based models employ simplified functions to express the interactions between the growth of crops and the major environmental factors that affect them (i.e., climate, soils, and management). Many have been used in climate impact assessments but some

are poorly documented and lack validation, and there are many different types of such models.

Box 8.1 Example: Agricultural impacts in the US Midwest.

Background: Missouri, Iowa, Nebraska and Kansas (the MINK region) are four adjacent states in the central United States which are dependent on resource sectors known to be sensitive to climate change: agriculture, forestry, water resources, and energy.

Problem: To study how climate change might affect the current and future functioning of regional-scale economies. This example summarises only the assessment of impacts on the agricultural sector. For the economy-wide assessment, see Chapter 4.

Method: A number of models were used to evaluate impacts of climate on individual sectors. For agriculture, a semi-empirical process model (EPIC) was adopted that simulates crop biomass and yield production, evapotranspiration, and irrigation requirements. The economy-wide effects of changes in productivity were studied using IMPLAN; see also Chapter 4.

Testing of methods/sensitivity: EPIC was validated against national agricultural statistics (county level) and observed seasonal yields in agronomic experiments for seven crops in the region. Evapotranspiration terms were compared with field observations. The model coefficients relating inputs and output flows between industries in IMPLAN were computed from regional data for 1982.

Scenarios: A temporal analogue was employed as the climate scenario, specifically the decade 1931–1940 in the MINK region. Overall, this period was one of severe drought—both drier and warmer than average in the region, consistent in sign with GCM projections. These conditions were assumed to occur in the present and also in 2030, along with an increase in CO_2 concentration of 100 ppm (to 450 ppm).

Impacts: In the MINK region of 2030 with a climate like that of the 1930s the main results of the study are as follows. Crop production would decrease in all crops except wheat and alfalfa, even accounting for CO_2 effects. However, impacts on agriculture overall would be small given adaptation, though at the margins losses could be considerable (e.g., a shift in irrigation from west to east). Rising costs of water extraction would make agriculture less competitive for surface water and groundwater supplies and would hasten the abandonment of irrigation in the western portions of the region. Unless the climate-induced decline in feedgrain production falls entirely on animal producers in MINK (which would lead to an overall loss to the regional economy of 10 percent), the regional economic impacts of the climate change would be small. This is because agriculture, while important relative to other regions of the United States, is still only a small (and diminishing) part of the MINK economy.

Adaptation: Most of the work on adaptation dealt with responses to impacts on crop production. Simulated adjustments included changed planting dates, altered varieties, and changed tillage practices. In addition, technological advances were assumed in irrigation efficiency and crop drought resistance as well as improvements in a number of crop-specific characteristics, including harvest index, photosynthetic efficiency, and pest management. In economic terms, in the absence of on-farm adjustments and CO_2 enrichment, the analogue climate would reduce the value of 1984–1987 crop production in MINK by 17 percent. The CO_2 effect would reduce the loss to 8 percent, and on-farm adjustments would reduce it further to 3 percent.

Source: Rosenberg, 1993.

Most of the models have been developed for purposes other than climate impact assessment. Most frequently they have been developed as tools in agricultural management, particularly for providing information on the optimal amounts of input (such as

fertilisers, pesticides, and irrigation) and their optimal timing. To achieve this they need to be based on information on the amount and timing of important crop requirements for water, heat, and nutrients. Such requirements vary between different crops and between different environments in which they are grown, and it is important that the assessor be familiar with these with respect to crops and environments.

One means of achieving this familiarity is to develop a schematic crop calendar to show the significant stages of crop growth and their requirements, thus indicating important variables affecting growth to be modelled. An example of one such crop calendar, for spring wheat, is given in Figure 8.4.

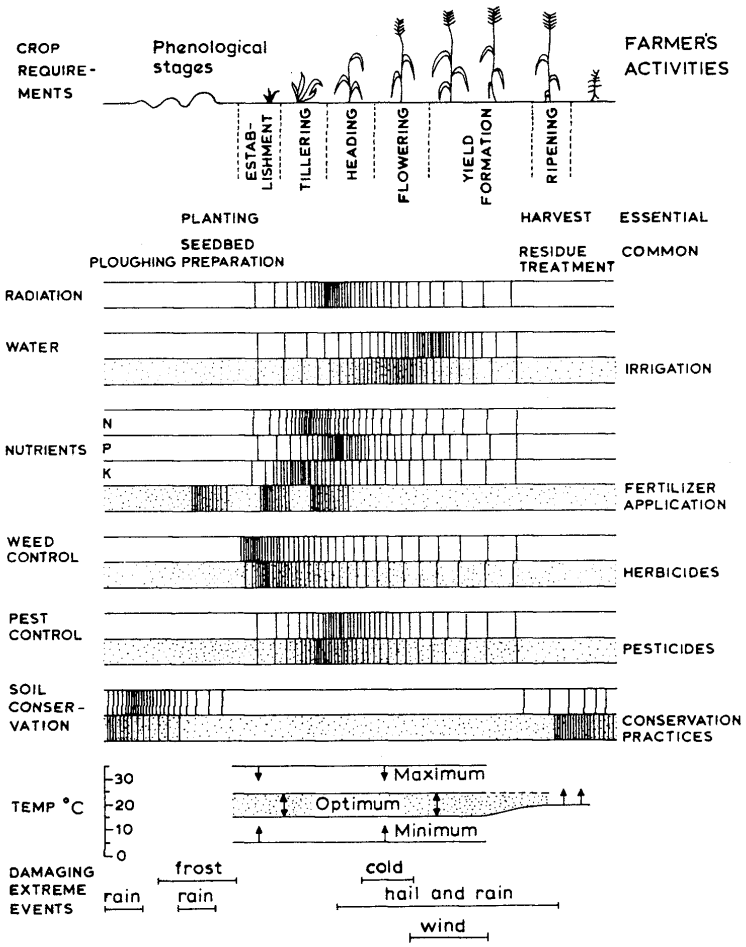

Figure 8.4. **A crop calendar for spring wheat. The timing of important crop requirements (listed in the left hand column) and the farmer's activities to help meet these requirements (listed to the right of the diagram) are indicated within the accompanying horizontal bars (unshaded bars for plant requirements; shaded bars for management activities) as vertical lines. The closer the lines in the bars, the more important the requirements or activities. The optimum range of temperatures and the sensitivity of a crop to extreme weather events are depicted in the lower part of the diagram (from Carter et al., 1988).**

In this case, where temperature is an important limiting factor on yield formation, the optimum range of temperatures is determined for different stages of crop development, and would feature prominently in the model functions that express the interactions between climate and yield.

Dynamic crop models are now available for most of the major crops; a selected list is given in Table 8.3. In each case, the aim is to predict the response of a given crop to specific climate and soils, and management factors governing production. Several published reviews describe the models and provide a full list of references, including references on model documentation (see, for example, Jones and Ritchie, 1990; US Country Studies Program, 1994; Rosenzweig and Iglesias, 1998). Comparisons between models for the same climate and soil data sets have given results that sometimes differ (GCTE, 1996), largely as a result of differences in complexity, structure, and parameterisation conditions.

Table 8.3 Selected crop models (adapted from Jones and Ritchie, 1990; US Country Study Program, 1994).

Crop(s)	Model name
Maize, wheat, sorghum, millet, barley, soybeans, peanuts, dry beans	ICASA/IBSANT (including all CERES and GRO models)
General model	EPIC
Water irrigation requirements for all crops	CROPWAT (CROPWAT, 1995)
Alfalfa	ALSIM, ALFALFA
Barley	CERES-Barley
Cotton	GOSSYM, COTCROP, COTTAM
Dry beans	BEANGRO
Maize	CERES-Maize, CORNF, SIMAIZ, CORNMOD, VT-Maize, GAPS, CUPID
Peanuts	PNUTGRO
Pearl millet	CERES-Millet, RESCAP
Potatoes	SUBSTOR
Rice	CERES-Rice, RICEMOD
Sorghum	CERES-Sorghum, SORGF, SORKAM, RESCAP
Soybeans	SOYGRO, GLYCIM, REALSOY, SOYMOD
Sugarcane	CANEMOD
Wheat	CERES-Wheat, TAMW, SIMTAG, AFRCWHEAT, NWHEAT, SIRIUS, SOILN-Wheat

The ICASA/IBSNAT dynamic crop growth models (International Consortium for Application of Systems Approaches to Agriculture - International Benchmark Sites Network for Agrotechnology Transfer) are structured as a decision support system to facilitate simulations of crop responses to management. The ICASA/IBSNAT models have been used widely for evaluating climate impacts in agriculture at different levels, ranging from sites to wide geographic areas (see Rosenzweig and Iglesias, 1994, 1998, for a full description of the methodology). This type of model structure is particularly useful in the evaluation of the adaptation of agricultural management to climate change. An outline of ICASA/IBSNAT models is given in Table 8.4.

The EPIC model (Erosion Productivity Impact Calculator; Sharpley and Williams, 1990) incorporates simplified crop growth functions that respond to climate, environment, and management; it has been used in some climate impact assessments (see Box 8.1).

Table 8.4 Description of the ICASA/IBSNAT crop models.

Description: The IBSNAT/ICASA models employ simplified functions to predict the growth of crops as influenced by the major factors that affect yields, i.e., genetics; climate (daily solar radiation, maximum and minimum temperatures and precipitation); soils; and management. Models are available for many crops (see Table 8.3); these have been validated over a wide range of environments and are not specific to any particular location or soil type. Modelled processes include phenological development, growth of vegetative and reproductive plant parts, extension growth of leaves and stems, senescence of leaves, biomass production and partitioning among plant parts, and root system dynamics. The models include subroutines to simulate the soil and crop water balance and the nitrogen balance.

Variables: The primary variable influencing each phase of plant development is temperature. Potential dry matter production is a function of intercepted radiation, the interception by the canopy being determined by leaf area. The dry matter allocation to different parts of the plant (grain, leaves, stem, roots, etc.) is determined by phenological stage and degree of water stress. Final grain yield is the product of plant population, kernels per plant, and kernel weight. To account for the effect of elevated carbon dioxide on stomatal closure and increased leaf area index, a ratio of transpiration under elevated CO_2 conditions to that under ambient conditions is added.

Inputs:

Type of data	Requirements	Source of data
Current climate	Daily maximum and minimum temperatures, and solar radiation for at least a 20-year period.	National meteorological or research institutions. Daily data may be simulated from monthly averages when not available.
Modified climate (climate change scenarios)	Modified daily maximum and minimum temperatures, precipitation and solar radiation for a period of the same length as the current climate.	National meteorological or research institutions.
Crop management	Crop variety, sowing date and density, fertiliser and irrigation inputs (dates and amounts).	Agricultural research institutions.
Soils	Soil albedo and drainage, and a description of the different layers of the soil profile (texture, water holding capacity, organic matter, and nitrogen).	Agricultural or hydrological research institutions.
Economics (optional)	Cost of labour and price of unit production.	Agricultural statistics.

Outputs: Variables included in the summary output file are the main phenological events, yield, and yield components.

For more information, see Rosenzweig and Iglesias, 1994 and 1998.

Advances in the interpretation of remotely sensed information and the combination of this information with crop models offer an important tool for evaluating spatial crop responses (see, for example, Maass, 1988a, 1988b, 1992).

Crop models provide some clear advantages in the assessment of climate impacts:

- Models are based on an understanding of how plants respond to weather.
- Direct physiological effects of CO_2 on crop growth and water use are included.
- Rainfed and irrigated cropping is included, validated over a wide range of environments.
- Improvements in crop varieties, irrigation scheduling, etc., can be tested.
- Although large amounts of weather data (e.g., daily variables) are needed, soil and management data can be substituted.
- Models can be linked to a decision support system which enables adaptation to be tested.

Among the sources of uncertainty derived from the use of crop models for impact assessment are the following:

- Simple, empirically-derived relationships do not completely mimic actual plant relationships.
- Conditions under climate change may be outside those data for which model was developed.
- Weeds, pests, and disease are assumed to be controlled.
- Not all future improvements in technology are included.
- There remain serious uncertainties about the effects of elevated CO_2 on crop plants.

As an example, Box 8.2 shows the approach for estimating climate change impacts on China’s agriculture.

Box 8.2 Estimating climate change impacts on China's agriculture.

Problem: Recent studies have confirmed the conclusion of the IPCC 1990 and 1995 assessment that the aggregate effects of climate change on global agricultural production are likely to be small to moderate. This conclusion rests on the assumption that without climate change, future agricultural production will rise at a rate that will keep pace with population growth, thus continuing a long-term historical trend of declining world food prices. An alternative view is that resource degradation and the failure of technology to keep up with population growth will reverse the historical trend of generally improving food supply. Simplifying the problem as one of global food supply and demand is partly misleading because of the high variation in local and regional studies which tend to show more negative impacts for some areas in East Asia. So the China Country Study Program identified different impacts of different locations in China through simulation methods.

Methodology: The simulation was conducted using monthly GCM scenarios and daily data for 1955-1985 and for a changed climate from the Chinese Weather Generator developed by the Agrometeorology Institute, the Chinese Academy of Agricultural Sciences (CAAS). Two hundred sample years were simulated for each crop and grass to allow probability distributions to be derived for the production potential of each crop and grass. Three different variability scenarios were used as a sensitive analysis. Three crop models and a grass-cattle model were adjusted where necessary to ensure that they could be applied to China (e.g., soil and genetic characteristics are incorporated into the models). The three crop models are a rice model (IRRI, 1993), a CERES-wheat model (Ritchie and Otter, 1985), and a CERES-maize model (Jones and Kinir, 1986). The grass-cattle model is the SPUR2 model (Hanson et al., 1992).

Scenarios: In China's country xtudy analyses, the results of three equilibrium GCMs and a regional climatic model (developed by the project) were used as the scenarios of climate change: Geophysical Fluid Dynamics laboratory (GFDL) (Mitchell et al., 1990), Max Planck Institute for Meteorology (MPI) (Cubasch et al., 1992) in Hamburg, Federal Republic of Germany, and United Kingdom Meteorological Office (UKMOH) (Mitchell et al., 1990). Depending on the scenarios, temperatures were estimated to increase 0.4-1.9°C and rainfall was estimated to change by -12.9% to +24.6% in China across different GCMs, and sites and seasons. The direct effects of CO_2 were not included in the simulations.

Impacts: The ranges of simulated changes in wheat and maize crop production under $2xCO_2$ and across GCM climate change scenarios and two types of water use are given in the table below.

Changes in average yield of wheat and maize compared to base (%) under different climate change scenarios in China

		2030			2050
Crop		GFDL	UKMOH	MPI	RCM
Wheat	Irrigated	-15 ~ +52%	-20 ~ +50%	-18 ~ +55%	-28 ~ +6%
	Rainfed	-10 ~ +35%	-21 ~ +32%	-15 ~ +42%	-40 ~ +19%
Spring maize	Irrigated	-8 ~ +3%	-9 ~ +1%	-6 ~ +4%	-21 ~ +4%
	Rainfed	-18 ~ +1%	-19 ~ 0%	-18 ~ +5%	-22 ~ +1%
Summer maize	Irrigated	-7 ~ -1%	-11 ~ -5%	-9 ~ +2%	-26 ~ -6%
	Rainfed	-8 ~ -2%	-12 ~ -6%	-10 ~ +1%	-26 ~ -6%

Changes in 90% cumulative frequency of rice yield (e.g., a year with good harvest) from simulation samples of 200 years compared to base under GCM climate change scenarios with incremental climate variability at three sites in southern China are given below.

Rice yield changes with incremental climatic variability at three sites

Site	GCM in 2030			RCM in 2050		
	GFDL	UKMOH	MPI	Var. +0%	Var. +10%	Var. +20%
Guangzhou	-6.27%	-8.05%	-8.09%	-7.44%	-7.78%	-8.12%
Changsha	-4.21%	-5.23%	-5.37%	-4.51%	-4.87%	-5.11%
Nanjing	-10.62%	-11.86%	-12.38%	-11.90%	-12.08%	-13.78%

The results of the current and past analyses show that with rises in temperature and changes in precipitation (mostly decreases, but some increases), the maximum gain production would probably drop at most about 10% due to the shortened growing period and the shortage of moisture. To meet the needs of the population and the need to improve the living standards, it is estimated that the average yield of grain production of China in 2030 –2050 will change to about 6 tons per hectare through improved technology and increased inputs. But, climate change could increase the barriers to this objective. The increased annual cost of government investment only (excluding farmers' additional costs) in agriculture due to climate change through 2050 has been estimated at US$3.48 billion (17% of the cost of government investment in agriculture in 1990).

Analogues

Two types of analogue study have been used for assessing impacts of climate change on agriculture: analogues of time and analogues of space.

Temporal analogues. In some cases, past time periods with adequate climatic and agricultural data have been used as analogues of possible future changes of climate due to greenhouse gas emissions. These periods can provide a useful insight both into the possible first-order effects of altered weather on (for example) crop yields and into second-order effects such as on production, profitability, food supply, and rural income. The approach can be illustrated from a study in northern Japan (Yoshino et al., 1988). An analysis of the climatic record for the island of Hokkaido indicated that the region had experienced a range of both warm and cool summers that had had a measurable effect on rice yields. A warm-type year (such as 1980) was taken as an analogue of weather that could be characteristic of a warmer climate. The average July-August temperature in 1980 was 3.5° C above normal and rice yields were 5 percent above average. District rice supply was 17 percent greater than normal. Warm periods have similarly been adopted as temporal analogues of warming in studies in Finland (Kettunen et al., 1988) and in Iceland (Bergthorrson et al., 1988). In each of these studies the existence of a comprehensive set of climate and yield data enabled altered suitabilities to be mapped. In a similar manner, the warm and dry period of the 1930s in the US Great Plains has been used as an analogue of the conditions that may result under climate change (Warrick, 1984).

Spatial analogues. Spatial analogues of future climate work on the same principle as analogues for present-day climate, except that here the analyst attempts to identify regions having a climate today which is similar to that projected for the future climate of the study region. The analogue region cannot be expected to exhibit complete similarity to the present study region, because many features may themselves change as a result of climatic change (e.g., soils, land use, vegetation). The overall characteristics should, however, provide indicators of how the landscape and human activities might change in the study region in the future. This principle has proved valuable in extending the range of applicability of some impact models. For example, a model of grass growth in Iceland was tested for species currently found in northern Britain, which is an

analogue region for Iceland under a climate some 4°C warmer than present (Bergthorsson et al., 1988).

Other aspects of the analogue region, however, would need to be assumed to be similar to the study region (e.g., daylength, topography, level of development, and economic system). Where these conditions cannot be met (e.g., daylength for grass growth in Iceland differs from that in northern Britain), the implications need to be considered on a case by case basis. One method of circumventing these problems is to consider altitudinal differences in the same region.

The twin advantages of the analogues are firstly that they incorporate observed climatic data (which thus have a greater degree of reality than those derived from scenarios), and secondly that they enable assessment of the responses in agriculture that may actually have occurred as a result of climatic events. Of course, the relevance of the event and the response depends on the appropriateness of the analogue of possible future climate change.

8.2.2 Economic tools

Economic considerations inevitably enter into the evaluation of climate changes impacts. Economic analysis considers both producers and consumers of agricultural goods. Economic considerations include the likely effect of changing conditions upon input and output market prices and the opportunities available individuals to minimise losses or maximise gains. Because climate change affects the costs of production, it also affects the price and quality of products, which, in turn, can lead to further market-induced output changes.

Economic models are designed to estimate the potential impacts of climate change on production, consumption, income, gross domestic product (GDP), employment, and farm value. These may be only partial indicators of social welfare, however. Not all social systems, households, and individuals (for example, subsistence farmers) may be appropriately represented in models that are based on producer and consumer theory. Furthermore, many of the economic models used in impact analyses to date do not account for the climate-induced alterations in the availability of land and water for irrigation, though such non-market aspects of a changing climate may be critical (Rosenzweig and Hillel, 1998).

Studies and models based on market-oriented economies assume profit and utility maximising behaviour. These models are data intensive and are relatively expensive to construct since they depend on access to detailed data regarding time series of price, quantities, resource use, and other economic information. Several different types of economic models have been used for climate change studies, including mathematical programming models at farm, regional, and national levels and econometric models at regional, national, and international levels. Because of the expense of model development, many climate change impact studies have utilised currently available models, which are relatively accessible and inexpensive to use. Such models have already been calibrated and validated to economic conditions in the present or recent

past, and have been subject to review. Constructing new models to specifically address climate change is desirable, but is an exacting and time-consuming process. A summary of the types of economic approaches that have been used for agricultural impact assessment is outlined on Table 8.5.

Table 8.5 Summary of economic approaches used in the assessment of climate impacts in agriculture (based on Rosenzweig and Hillel, 1998).

Method	References/Observations
Simple economic approaches	US Country Studies Program, 1994 Forecast based on a structured framework of available economic (production, consumption, and governing policies) and agricultural (production techniques and alternative crops) information to address vulnerability issues. Simple technique that can be used for the analysis and interpretation of most climate impact studies.
Economic regression models	Mendelson et al., 1994 Statistical relationships between climate variables and economic indicators. Farmer adaptation to local climate conditions is implicitly considered. World food prices and domestic farm output prices are considered constant.
Microeconomic models	Kaiser et al., 1993 Models based on the goal of maximising economic returns to inputs. Designed to simulate the decision-making process of a representative farmer in regards to methods of production and allocation of land, labour, existing infrastructure, and new capital.
Macroeconomic models	Adams et al., 1990 Equilibrium models that include price-responsive behaviour of both consumers and producers. For climate change purposes, the models allocate domestic and foreign consumption and regional production based on given perturbations of crop production, water supply, and demand for irrigation derived from biophysical techniques. Population growth and improvements in technology are set exogenously. These models measure the potential magnitude of climate change impacts on the economic welfare of both producers and consumers of agricultural goods. The predicted changes in production and prices from agricultural sectoral models can then be used in general equilibrium models of the larger economy.

8.2.3 Scales of analysis

There is a wide range of applications of the methods for impact assessment at different levels: farms and villages, regional and national, and global. The methods of analysis of field crop responses are derived from the basic tools described above, and constitute, in many cases, a first step in the evaluation of responses at other spatial levels.

The merits of each approach vary according to the level of impact being studied, and they may frequently be mutually supportive. For example, experiments often provide the necessary information on how crops respond to varying weather, and this can be

used to develop models to predict responses to future climate, that can in turn be used as a component for an economic model that analyses regional vulnerability or national production risks. Therefore, a mix of approaches is often the most rewarding.

Assessment of farm and village effects

In most impact assessments, it will be necessary to translate changes in crop yield into changes in output and income. In some cases the objectives may require further translation, for example, into changes in employment and activity rates. This can best be achieved, first, by assessment of effects at the farm and village level. Aggregation of these effects to the regional level can then be made if required.

Two broad types of approach can be used, their appropriateness depending very much on the economic character of the agriculture under study. In regions of commercial farming, where agriculture is characterised by farms under single ownership, farm models may be used to analyse the effect of altered crop productivity on output and income. In less developed areas that are characterised by a pooling of resources or some common ownership and where the village is the dominant unit of enterprise, village models will be more appropriate.

Farm models. These have most often been developed as tools for rural planning and agricultural extension, being used to simulate the effect of changes in inputs (e.g., fertilisers, irrigation, credit, management skills) on farm strategy (e.g., cropping mix, employment). They tend to be optimising economic models using linear programming and requiring quite specific data and advanced analytic skills. Many take a range of farm types that are representative of those existing in a region and, for each type, simulate the mix of crops and inputs that would maximise farm income under given conditions. These conditions may be varied (such as through variation of weather, prices of crops, and fertilisers) and the appropriate farm response modelled. Changes of climate, instead of variations of weather, can be input, and the farm-level response in output and income then simulated.

Models of this kind have been used in climate impact studies in Saskatchewan (Canada) (Williams et al., 1988), Minnesota (USA) (Kaiser et al., 1993), and for a multi-state study in the United States (the MINK study; Easterling et al., 1993; Rosenberg, 1993). The MINK study makes use of a farm-response component in the EPIC model, thus combining crop and farm-level response in a single model. Further discussion of this approach is given below and in Box 8.1.

Given their specific data requirements, it is unusual for farm models to be developed specifically for climate impact studies. Most of those used have been developed for other purposes and have been taken “off the shelf” for use in climate impact assessment. An alternative to such models is to convene groups of experts in agronomy, agricultural economics, and agricultural extension to provide advice on the likely farm-level response to climate-induced changes in crop yields. Expert judgement of this kind, particularly where it is based on careful formatting of prepared information, can provide useful information on farm response to climate.

Household and village models. In semi-commercial economies, it may be more appropriate to focus on the household or village as the unit of response. Here the objective may be to secure a minimum level of income rather than to maximise it, and the focus of analysis should be on the strategies developed to reduce the negative effects of crop yield changes rather than on those to increase the positive ones. Frequently referred to as coping strategies, these have been analysed in particular detail in the context of risk of hunger (often related to drought). As with farm models, those climate impact assessments which included successful analyses on responses at the household and village level tended to borrow from existing studies, adapting them to consider changes in climate rather than variations of weather. For specific examples of their use in climate impact assessment in Kenya and India, see Akong'a et al. (1988) and in Gadgil et al. (1988) in Parry et al. (1988). For a more general discussion, see Downing et al. (1993).

Assessment of regional and national effects

Regional assessments. Scaling up the impact assessment to a regional level is, as in most scaling exercises, not an easy task. Ideally one might use information from farms that are representative of agriculture in the region; and the degree of their representativeness would need to be established. More frequently, regional assessments have relied upon the judgement of regional planners and economists as to regional-scale effects, based upon local data supplied to them and discussed in workshops with local-level analysts (see, for example, the UNEP South-East Asia study in Parry et al., 1992). Where, however, representative farm data are available in addition to economic data for each of the main sectors of the regional economy, then the farm data can be used as altered inputs.

Two studies that have use input-output (I-O) models in agricultural impact assessment are those for Saskatchewan (Canada) and the MINK study (USA) (Williams et al., 1988; Rosenberg, 1993). In the Saskatchewan study, the I-O model served as a bridge between representative farm models and a province-level employment model. In the MINK study, it was linked to an analysis of parallel climate-induced effects in other sectors (e.g., energy) (see Box 8.1). For many studies, however, the data requirements of I-O modelling will be too onerous. Carefully developed expert judgement of the regional-level implications of climate change may be more practicable.

National assessments. National assessments of impacts on agriculture have more generally been based on a synthesis of knowledge, leading to reviews that describe (largely qualitatively) the likely points of greatest impact, their implications for policy, and the research required to improve understanding. Examples are the national impact assessments of the United Kingdom (UK Department of the Environment, 1996) and Japan (Nishioka et al., 1993). This approach may be rapid and inexpensive, but may lack quantitative detail.

A more formal and quantitative approach is the use of national agricultural or land use models. These are generally economic optimising models developed to assist national and regional planning by "allocating" land or other resources in the national agricul-

tural sector to their highest value use, in order to match demand and supply. Using estimates of climate-affected changes in yield, they can be used to re-allocate land to meet demand. The altered sectoral activity or land use is the modelled impact. A recent development is the input of global climate-change effects as altered food prices, and the use of the models to optimise land allocations by matching altered supply (reflecting climate-related yield changes) to altered demand (reflected in price). These approaches are analytically complex and require comprehensive national data on agricultural land use and production. Thus far they have largely been limited to developed countries, e.g., the United Kingdom (Parry et al., 1996a and b) and the United States (Adams et al., 1995a). However, a similar study has been successfully completed in Egypt, and it indicates the value of attempting to upscale impact assessment to the national level. This is described in Box 8.3.

Box 8.3 Example: Agricultural impacts in Egypt.

Background: Agriculture in Egypt is restricted to the fertile lands of the narrow Nile valley from Aswan to Cairo and the flat Nile Delta north of Cairo. Together this comprises only 3 percent of the country's land area. Egypt's entire agricultural water supply comes from irrigation, solely from the Nile River. In 1990, agriculture (crops and livestock) accounted for 17 percent of Egypt's gross domestic product.

Problem: The study sought to assess the potential impact of a change in climate and sea level on Egypt's agricultural sector, accounting for changes in land area, water resources, crop production, and world agricultural trade. The aim was not to predict Egypt's future under a changed climate, but rather to examine the combined effects on agriculture of different natural factors and the adaptability of the economic system. This example summarises only the agricultural component of the study (for the economy-wide assessment, see Chapter 4).

Methods: A physically-based water balance model of the Nile Basin was used to evaluate river runoff and thus enable inferences to be drawn concerning water supply for agriculture. Process-based agronomic models were used to estimate crop yields and crop water requirements.

External factors such as world food prices were introduced from a study of climate change which used a global food model to assess climate change impacts on world food supply and demand (Rosenzweig and Parry, 1994). Supply and demand at the national level were then input to a national agricultural sector model to determine effects on land use, water use, agricultural employment, etc.

Testing of methods: Each of the submodels used in the study was validated against local data.

Scenarios: The current baseline adopted for the socio-economic projections was 1990 and the climatological baseline was 1951-1980. The time horizon of the study, 1990-2060, was largely dictated by the climate change projections.

Impacts: An agricultural water productivity index was used to measure impacts on agriculture: total agricultural production (tonnes) divided by total agricultural water use (cubic metres). Under these 2 x CO_2 GCM-derived scenarios the index declined between 13 and 45 percent.

Adaptive responses: Adaptations in water resources (major river diversion schemes), irrigation (improved water delivery systems), agriculture (altered crop varieties and crop management), and coastal protection against sea-level rise were all tested. They achieve a modest 7–8 percent increase in agricultural sector performance compared to no adaptation, but together would be extremely expensive to implement. However, investment in improving irrigation efficiency appears to be a robust, "no regrets" policy that would be beneficial whether or not the climate changes.

Source: Strzepek and Smith (1996).

Many studies are beginning to consider the interactions and feedbacks between crop response to climate and the factors that determine final agricultural output, such as agrarian policies (FAO, 1993; Rowntree, 1993; Brklacich et al., 1996; Binswanger and Deininger, 1997) and other economic issues (Martin et al., 1990; Kaiser et al., 1993; Reilly and Hohmann, 1993), especially when considering the importance of predicting possible adaptation (Darwin et al., 1995; Darwin, 1997). Water availability and quality and soil limitations are additional biophysical factors essential for a comprehensive and meaningful agricultural climate impact evaluation (Gleick, 1993; Rosenzweig and Hillel, 1998).

Methods have recently been developed that enable the analyst to incorporate the effect of farm, village, and national level responses in the impact assessment. Mendelsohn et al. (1994), for example, use a statistical approach to analyse cross-sectional data of current agricultural production across both warmer and cooler regions. They examine the relationship between agricultural land values and climate using county-level data in the United States. This approach is often called the Ricardian (or duality) approach because of its focus on land values. It side-steps the problems of understanding explicit crop and farmer responses to climate by implicitly assuming that the biophysical and economic adjustments imposed by climate change will be made automatically (an assumption that can be confirmed today by examining crops and behaviours in warmer climates). In other words, farmers adapt to new environmental conditions by altering input choices, production technologies, and crop mixes. The approach is based on the theory that in competitive market economies, land value is measured by the present value of expected net revenues that are derived from the most economically efficient management and use of land.

Specifically, the Ricardian approach uses regression techniques to estimate the marginal effects of various climate, economic, and other factors on farmland values. Data requirements include farmland values, climate variables such as mean monthly temperatures and precipitation, data on soil and land conditions, e.g., salinity, permeability, moisture capacity, erodability, and any other factors (e.g., socio-economic and cultural characteristics) that would help explain farming practices and land values.

In contrast, Darwin et al. (1995) develop and combine a global computable general equilibrium (CGE) model with a GIS model to analyse potential climate change impacts on US agriculture, taking into account both interactions with both non-agricultural sectors and other global regions. The GIS component describes regional characteristics of land, climate, water, and agricultural suitability. In this approach, climate change is assumed to shift the regional land class and water characteristics, thus altering the production possibilities for a given region. The CGE component then estimates the resulting economic changes and the effects on regional and global production and price.

The strength of spatial-analogue approaches is that structural changes and farmer responses are implicit in the analysis, freeing the analyst from the burden of estimating the effects of climate change on particular region-specific crops and farmer responses. Mendelsohn et al. (1994) argue that these approaches account for changes in production possibilities better, by implicitly capturing substitution and adaptation more than is

possible in structural models (because the analyst cannot imagine and account for all the adaptations farmers can make).

The weakness, however, is that these approaches assume a long-run equilibrium that ignores short- and medium-run adjustment costs. For example, the spatial-analogue model abstracts from the issues and costs of changes in structural characteristics such as irrigation systems that may be necessary to mimic warmer climate practices — presuming also that the necessary surface- or groundwater is available to service the system. The CGE/GIS approach of Darwin et al. (1995) provides linkages with projected global changes, which Mendelsohn et al. (1994) do not; however, these models are data intensive at a global scale and sacrifice some of the spatial richness afforded by country-level data. The Ricardian approach, however, does not account for likely changes in output and input prices that result from global changes in production, and which affect farm-level adaptation decisions. These approaches also assume that farmers will automatically know how and when to respond to climate changes.

Assessment of global effects

Climate change may alter the competitive position of countries with respect, for example, to exports of agricultural products. This may result from yields increasing as a result of altered climate in one country, whilst being reduced in another. The altered competitive position may affect not only exports, but also regional and farm-level income, rural employment, and the type of crops grown in a region. While most studies are unlikely to include an analysis of competitiveness itself, it is possible to evaluate the relative position of a country by studying the few analyses of climate change effects on global food trade. Indeed, some data on country-level output are available as part of the global studies (the Egypt example in Box 8.2 shows how such data can be used).

Two general equilibrium models have also been used to evaluate effects on global food supply: the Basic Linked System (BLS) (Rosenzweig and Parry, 1994) and SWOPSM (Reilly et al., 1994). Both derive their information on climate-change induced alterations of supply from ICASA/IBSNAT crop yield studies. The estimates of yield changes were interpolated from 112 sites in 18 countries across the geographical area of all countries and from the modelled crops to crops (such as cassava, oil palm) and livestock not modelled. The BLS model used these inputs, in combination with assumed changes over time in demand (due to population growth and per capita consumption resulting from economic growth) and in supply (due to technological change leading to increased yields), to estimate changes in food prices and risk of hunger that might result from climate change (examples of the altered yield levels are shown in Figure 8.7). Once a global estimate of impact of this kind has been made, this information can serve as an exogenous control in regional impact studies.

8.2.4 A summary of the advantages and disadvantages of different approaches

The approaches described above each have their merits and their limitations. Frequently they are suited to some purposes and not to others, and they vary greatly in relation to (1) the temporal and spatial scales they address; (2) the time, data, and analytic skills they require; and (3) their cost. Table 8.6 summarises these characteristics.

Table 8.6 List of methods and characteristics for selecting an appropriate analytic approach (Adams et al., 1990).

Method/approach	Temporal scale of results	Spatial scale of results	Time to conduct analysis	Data needs	Skill or training required	Technological resources	Financial resources
Experimental	Season to decades	Site	high	low	high	high	high
Analogue							
spatial	Decades	Nation to region	low	low	low	low	low
temporal	Decades	Site to nation	low	low-medium	low-medium	low	low
Agro-climatic indices	Season to decades	Nation to globe	low-medium	medium	medium	low	low
Crop yield models	Season to decades	Site to nation	medium	medium-high	high	medium	medium
Process-based							
generic	Daily to centuries	Site to globe	medium	medum-high	medium	medium	medium
crop-specific	Daily to centuries	Site to region	high	high	high	high	high
Regional models	Years to decades	Sub-national	high	high	high	medium	medium
National models	Years to decades	Nation	high	high	high	medium	medium
National models, integrated into global food models	Years to decades	Nation to globe	high	high	high	medium	medium
Expert judgement	Years to decades	Site to region	low	low	high	low	low

8.2.5 Impact estimates

In this section we consider the different ways in which assessments of impacts due to climate change can best be presented. In general, such estimates are calculated as the differences between those conditions that are projected with climate change and those conditions projected to exist under the future baseline (i.e., without climate change). A wide array of adaptations is likely in anticipation of such impacts, and those need to be incorporated in the impact assessment in order for sufficient reality to be maintained. In practice, however, it is sometimes easier first to conduct impact assessments assuming a limited range of adaptation in order to reduce the degree of complexity of the problem. Subsequently different forms of adaptation can be introduced to the analysis in order to assess their effectiveness in modifying the magnitude and rate of impact.

The impact models which have been selected as most appropriate for use should be run first for observed (current) conditions, then for projected reference conditions (without climate change), and finally for future conditions under climate change. Comparison of results under current and future reference conditions allows analysis of the extent of impact due to non-climate factors such as technological change. The series of analytical steps is given in Figure 8.5.

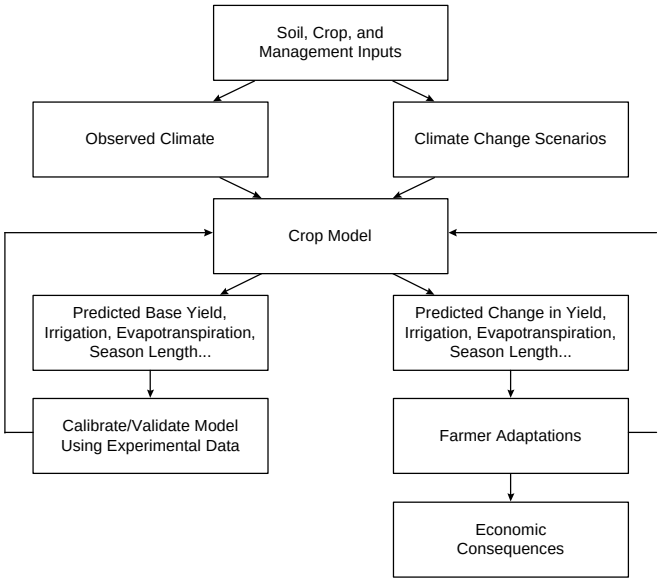

Figure 8.5 Flow diagram for the agriculture sector assessment in the US Country Studies Program (Smith et al., 1996).

8.2.5.1 Quantitative analysis

Effects at site scale. Most model-based impact assessments provide quantitative measures of impact that express changes from the reference case. Because impact models often require considerable amounts of input data for testing and calibration, their use may be restricted to only a limited number of point locations or sites. Figure

8.6 illustrates tabulated changes in yields of maize in Zimbabwe for three sites under current climate (i.e., the base case), under three scenarios of altered weather due to climate change and under the same scenarios of altered weather together with the direct effects of higher levels of ambient atmospheric CO_2 on plant photosynthesis and water use. The sites have been selected to represent a range of different agro-climatic environments in Zimbabwe and assume, unrealistically, no adaptation. At the bottom of Figure 8.6 is a tabulated representation of the effects of two forms of adaptation (fertilising and irrigation) in reducing the negative effects of the most extreme of the three climate change scenarios.

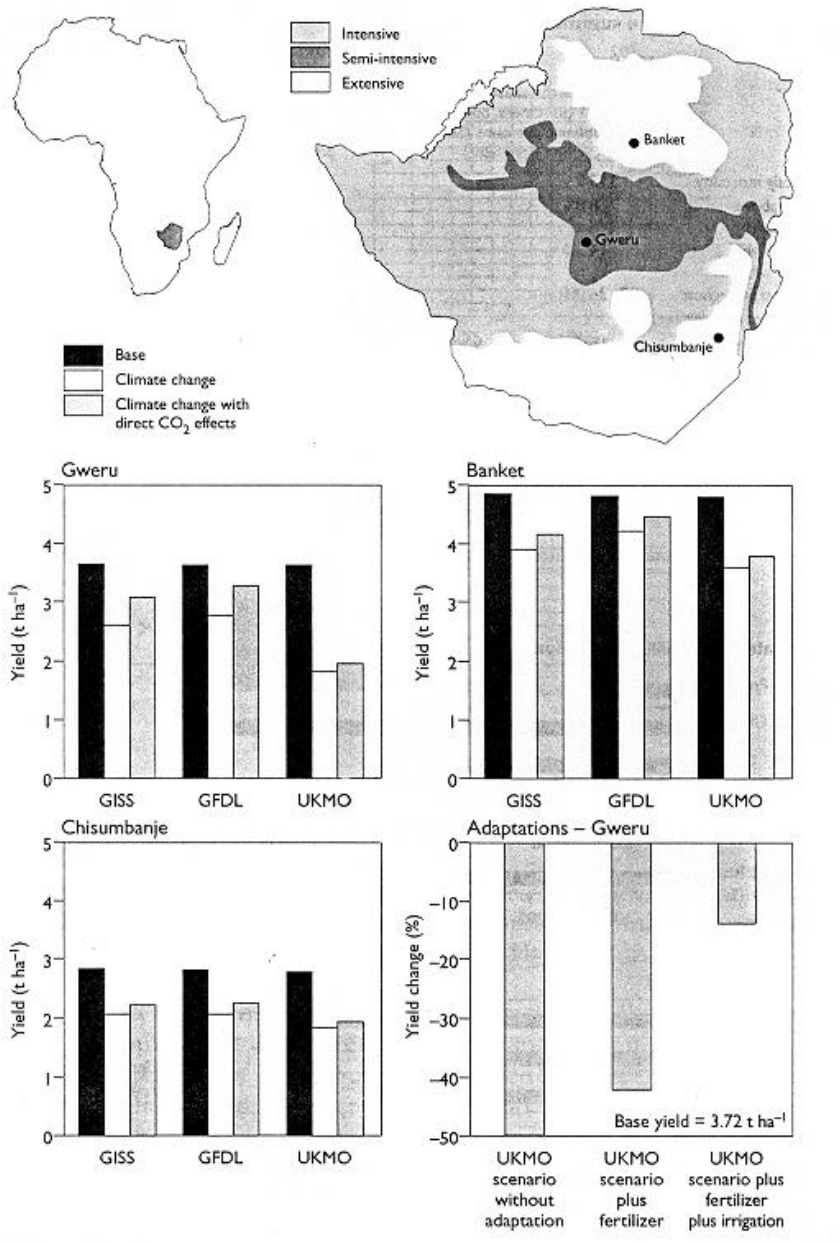

Figure 8.6 Effects of climate change on maize yields in Zimbabwe (from Muchena and Iglesias, 1995).

Changes in geographical distribution. Since climate varies over space, its effect on agriculture also varies spatially and its spatial pattern is likely to change as the climate changes. By mapping these altered distributions, it is possible to provide place-specific information for policy makers concerning altered levels of resource availability due to climate change. Our ability to conduct such analyses has been improved with the development of computer-based GIS, which can be used to store, analyse, and depict spatial information.

For example, where several compatible regional studies have been completed it is possible to expand the scale of estimates from a regional to a global level. For example, the estimates of impact on maize yields in Zimbabwe were one of a set of estimates derived as part of the international study of global yield changes described above. The global pattern of results is shown in Figure 8.7. Under all three scenarios of climate change considered in this study, effects on yield levels of food grains are generally negative at lower latitudes (where higher temperatures and changes in precipitation exacerbate existing problems of water limitation on crop plants) and are generally positive at middle and high-middle latitudes (where high temperatures are either beneficial for crops through a lengthened growing season, or if they are not beneficial, their negative effect on yield is more than compensated by the direct effects of CO_2). It should be noted, however, that no forms of adaptation (such as changes in crop cultivar, irrigation, or cropping patterns) were incorporated in the foregoing analysis.

Changes in risk. Since many impacts from climate change are expected to occur through the incidence of extreme weather (such as droughts, floods, hurricanes), an effective way of characterising a change in climate is as a change in the level of risk of such damaging effects. An important point emerging from such analyses is that probabilities of exceedance of given values frequently alter non-linearly, indeed quasi-exponentially, with changes in the mean value due to climate change.

An alternative to portraying altered risk values at a point is to map the spatial shift of given risk values due to climate change. For example, where there is a linear decrease in thermal resources either upslope due to the lapse rate of temperature or poleward in mid-latitude areas due to shorter and less intense growing seasons, the risk of there being insufficient warmth to permit crops to reach maturity increases quasi-exponentially. Lines of equal value of probability of crop failure can be mapped, and the shift of location of these due to climate change can be plotted (see, for example, Parry and Carter, 1985).

Costs and benefits. One of the most valuable forms in which results of impact assessments can be provided is as costs or benefits. Methods of evaluating these range from formal economic techniques such as cost-benefit analysis to descriptive or qualitative assessments.

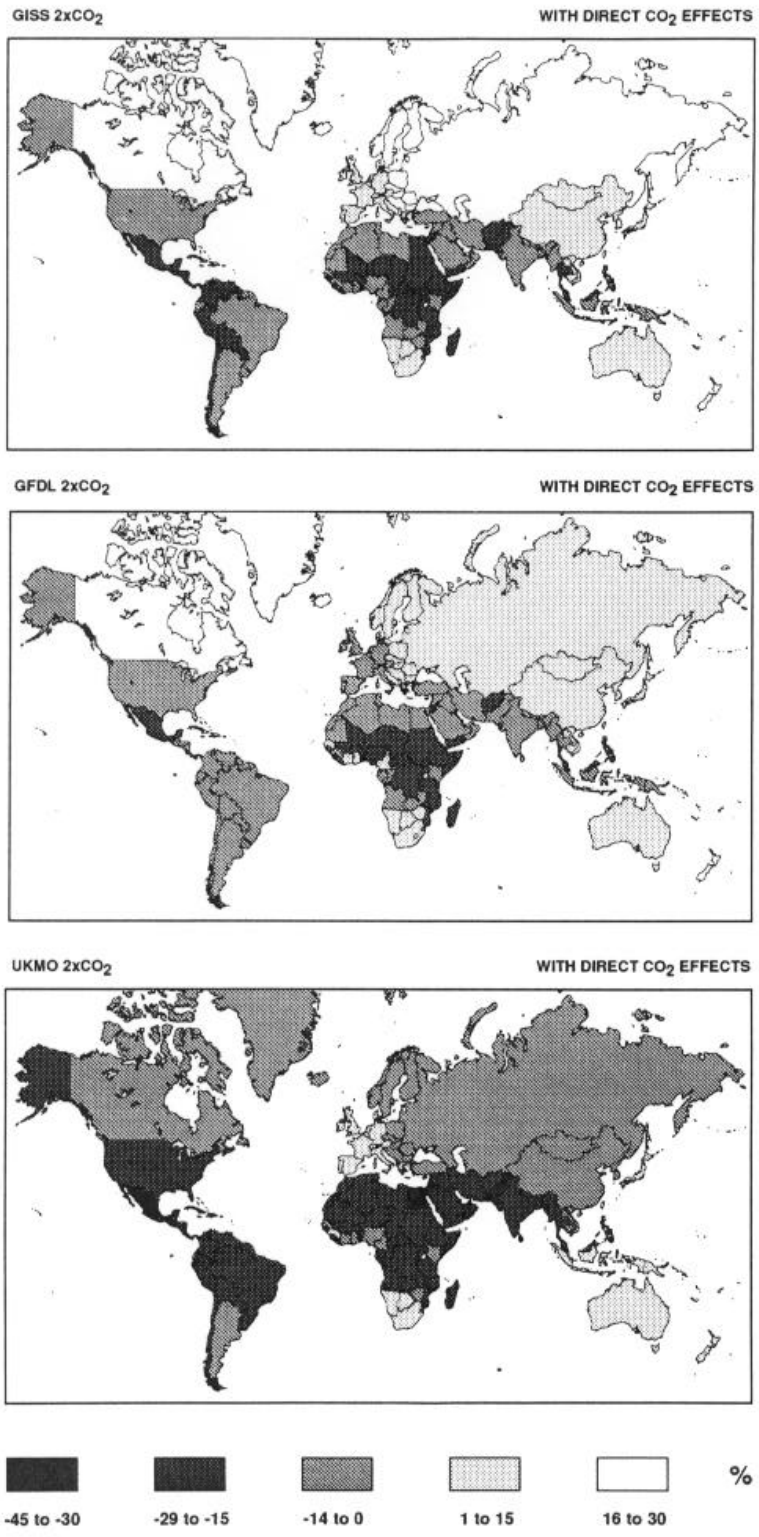

Figure 8.7 Estimated change in average grain yield (wheat, rice, coarse grains, and protein feed) for GISS, GFDL and UKMO climate change scenarios within direct CO_2 effects (from Rosenzweig and Parry, 1994).

Cost-benefit analysis is often employed to assess the most efficient allocation of resources. This is achieved by balancing or optimising various costs and benefits anticipated in undertaking a new project or implementing a new policy, accounting for the reallocation of resources likely to be brought about by external influences such as climate change. The approach makes explicit the expectation that a change in resource allocation is likely to yield benefits as well as costs, a useful counterpoint to many climate impact studies, where negative impacts have tended to receive the greatest attention.

Whatever measures are employed to assess costs and benefits, they should employ common units of value. Thus, for example, where monetary values are ascribed, this is usually calculated in terms of net present value, i.e., the discounted sum of future costs and benefits. The choice of discount rate used to calculate present value will vary from nation to nation depending on factors such as the level of economic development, debt stock and social provision. Moreover, the depreciation of capital assets with time, which varies from country to country, should be explicitly considered in the calculations. For a discussion of these issues and of methods for evaluating costs and benefits, see Pearce (1993).

8.2.5.2 Qualitative analysis

Some assessments need to be conducted rapidly and at little expense, perhaps to give a preliminary indication of impacts for more detailed subsequent study. In such cases there is frequently resort to expert judgement. The success of such evaluations usually rests on the experience and interpretative skills of the analysts, particularly concerning projections of possible future impacts of climate. The disadvantages of subjectivity have to be weighed against the ability to consider all factors thought to be of importance (something that is not always possible using more objective methods such as modelling). The most successful qualitative analyses are those which integrate what is known (as a result of formal research) with what is unknown, and such a mixture of information can assist in this integration. Those are techniques of analysis that can serve to integrate quantitative and qualitative information, such as cross impacts analysis. For information on this, see Martin and Lefebvre (1993).

8.3 Adaptation strategies

Historically agriculture has shown a considerable ability to adapt to changing conditions, whether these have stemmed from alterations in resource availability, technology, or economics. If climate change is gradual, it may be that adjustment goes largely unnoticed as part of responses to more profound changes due to technology and policy and that the process is one largely of autonomous adjustment. Many adaptations will thus occur autonomously and without the need for conscious response by farmers and agricultural planners. For example, as crop yields are affected by climate, different areas of land will be allocated to new, highest-value, uses. As far as possible these adjustments should be incorporated in the assessments of impact.

However, it is likely at least in some or most parts of the world that the rate and magnitude of climate change will exceed that of normal change in agriculture and that specific technologies and management styles will need to be adopted to avoid the most serious of effects. There is therefore much to be gained from evaluating the capability that exists in currently available technology and the potential capability that can developed in the future.

8.3.1 On-farm adaptation

There is a very wide array of methods in crop husbandry that have been developed both to make the most of what climate offers and to minimise the adversity that it sometimes brings. The most relevant of these are methods designed to "weather-proof" agriculture and these can often be adapted to afford some protection against climate change. We can consider these in three categories: (1) altered choice of crops, (2) altered tillage and crop management, and (3) altered inputs. Table 8.7 lists the options within these categories, along with the action to be taken and the impacts avoided.

Table 8.7 On-farm adaptation choices.

Adaptation by crop choice	Action	Impact avoidance
All seasonal crops	Plant quicker (or slower) maturing varieties	Ensure maturation in growing season shortened by reduced moisture or thermal resources; or maximise yields under longer growing seasons
All crops	Plant drought (or heat) resistant crops	Reduce crop loss or yield reductions under reduced moisture conditions; or reduce irrigation requirement
All crops	Plant pest resistant crops	Reduce yield reduction where altered climatic conditions have encouraged increases in weeds or insect pests
All seasonal crops	Use altered mix of crops	Reduce overall yield variability due to climate change
Adaptation by altered tillage and husbandry	**Action**	**Impact avoidance**
Altered tillage	Use minimum or reduced tillage	Reduce loss of soil organic matter, reduce soil erosion, reduce nutrient loss
	Use terracing, ridging	Increase moisture availability to plants
	Level land	Spread water and increase infiltration
	Use deep ploughing	Break up impervious layers or hardpan, to increase infiltration
	Change fallow and mulching practices	Retain moisture and organic matter
	Alter cultivations	Reduce weed infestation
Altered timing of operations	Switch seasons for cropping	For example, change from spring to winter crops to avoid increased summer drought
	Alter times of sowing, etc.	For example, to match altered precipitation pattern
Altered crop husbandry	Alter row and plant spacing	Increase root extension to soil water
	Intercropping	Reduce yield variability, maximise use of moisture
Adaptation by alteration of inputs	**Action**	**Impact avoidance**
Altered irrigation	Introduce new schemes to dryland areas	Avoid losses due to drought
	Improve irrigation efficiency, e.g., drip-feed irrigation	Avoid moisture stress
	Use water harvesting	Increase moisture availability
Altered use of fertilisers	Vary amounts of application	For example, increase nitrogen to take full advantage of CO_2 effects; or decrease to minimise input costs
	Alter timing of application	Match applications to, for example, altered pattern of precipitation
Altered use of chemical control	Vary timing and amounts of application	Avoid pest, weed, and disease damage

8.3.2 Household and village adaptation

There is a wide range of coping strategies used by semi-commercial farmers in all parts of the world to mitigate the effects of weather. The best developed of these, and probably the best understood, are those coping strategies for drought in India and Africa. These are generally characterised by a mix of technological, economic and social responses which can operate best for a short period (perhaps a few months).

Table 8.8 illustrates the range of coping strategies adopted by smallholders in central and eastern Kenya. It includes many of the farm-level adaptations considered above but most noticeably adds to these an array of strategies to maintain income through re-deployment of assets and labour.

8.3.3 National level adaptation

While most agricultural adaptation to climate change will ultimately be characterised by responses at the local level, the encouragement of response by national policymakers will affect their speed and extent of adoption. Response at the national level will also be necessary to encourage research, training, and communication concerning the most appropriate adaptive measures. The most important of these, summarised by the IPCC (1996), are as follows:

- Improved training and general education of populations dependent on agriculture, particularly in countries where education of rural workers is currently limited.
- Identification of the present vulnerabilities of agricultural systems.
- Agricultural research to test the robustness of new farming strategies and develop new crop varieties.
- Education and communication to bring research results to farmers.
- Food programs and other social security programs to provide insurance against local supply changes.
- Transportation, distribution, and market integration to provide the infrastructure to supply food during crop shortfalls.
- Removal of subsidies, which can, by limiting changes in prices, mask the climate change signal in the marketplace.

Evaluating the effectiveness of these and other national responses requires information of their costs and benefits and a comparison of their efficacy toward meeting national objectives. A formal method of conducting such an assessment is multi-criteria analysis, in which each strategy is evaluated with respect to maximising the level of achievement of some objectives.

Table 8.8 Characteristics of selected coping strategies in central and eastern Kenya[a] (from: Akong'a et al., 1988).

Response/ coping strategy	Prevalence	Effectiveness			Recovery	Constraints				
			Drought							
		Normal	Moderate	Severe		Labor	Capital	Technology	Education/ information	Land
Subsistence production										
Soil conservation	M-H	M	M	L	0	-	-	-	+	-
Water conservation	L	M	H	L	0	-	-	-	+	-
Irrigation	L	H	H	H?	+	-	+	+	+	+
Multiple farms	L	M	M	L	0	-	+	-	-	+
Inter/relay cropping	H	H	H-L	L	+	-	-	-	+	-
Dry planting	M	H	H	L	0	-	-	+	-	-
Mixed livestock herds	M-H	H	H	M	+	+	-	-	-	+
Dispersed grazing	H	H	H	M	+	+	-	-	-	+
Fodder production[b]	M	H	H	M	+	+	-	+	+	+
Drought-resistant crops	H	M	H	M	+	-	-	+	+	-
Monetary activity										
Local wage labor	M-H	H	H	H	+	+	-	-	+	-
Migrant wage labor	M	H	H	H	-	+	-	-	+	-
Permanent employment	M	H	H	H	+	+	-	-	+	-
Local business	L	M	M	L	0	+	+	-	+	-
Cash crop[c]	M	M	LM	L	+	+	+	+	+	+
Sell capital assets	M	M	LM	L	-	-	-	-	-	+
Livestock sales	H	M-H	M-H	M-L	-	-	-	-	+	=
Remittances/donations										
Relatives/friends	M-H	M	H	H	+	-	-	-	-	-
Government and others[d]	M-H	?	H	H	?	-	-	-	+	-
Loans/credit	L	H	H	H	+	-	+	-	+	-

Key	*Effectiveness*	*Prevalence*	*Constraints*
	H = High	>50%	- = negative, i.e., impedes recovery, is a constraint
	M-H = Mod. high	30-50	+ = positive, i.e., aids recovery, is not a constraint
	M = Moderate	15-30	0 = neutral, i.e., no effect on recovery
	L = Low	0-15	? = uncertain or variable

[a] Consensus agreement by case study authors based on available data. Ratings are intended to be qualitative and relative as no systematic survey data are available. In many cases, these are hypotheses to be verified. [b] Very common in the upper zones, almost non-existent in the lower zones. [c] Does not include food crops. Very common in upper zones, rare in lower zones. [d] High in the lower zones, low in the upper zones.

The upper half of Figure 8.8 portrays a multi-criteria analysis. Each row represents a different management measurement and each column a different management objective. The shaded areas show the most effective measures for satisfying the objective in column 1, and the solid areas show the most effective measures for satisfying the objective in column 2. The lower half of the figure shows how these management measures might be organised into alternative strategies.

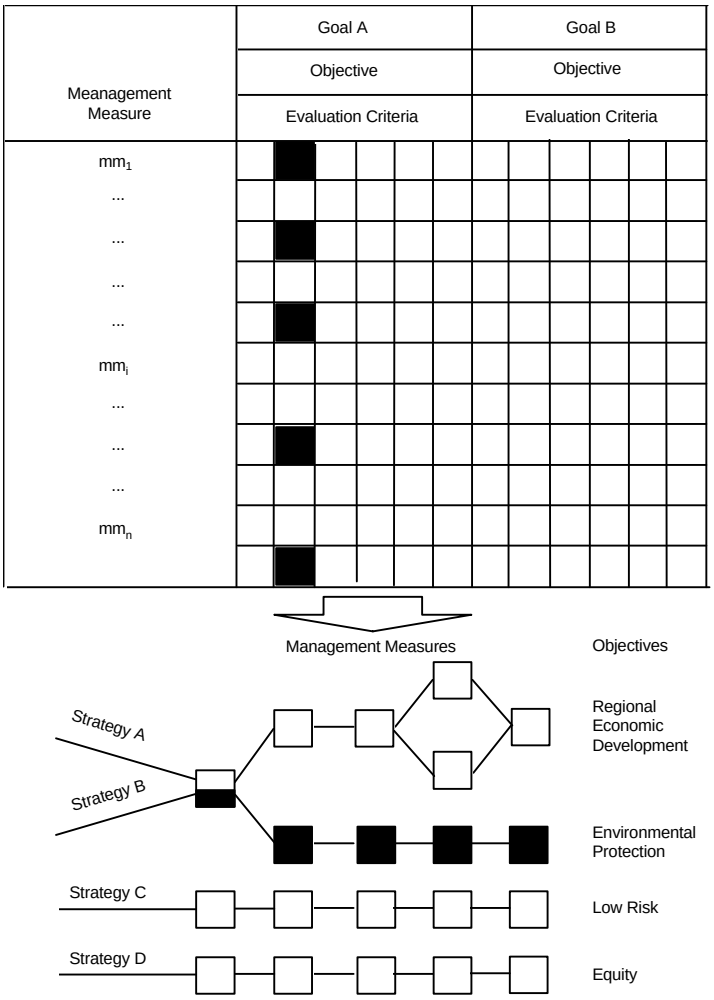

Figure 8.8 Some procedures for formulating adaptation strategies (top: multi-criteria analysis; bottom: multi-objective strategy formulation) (from Parry and Carter, 1988).

Selecting preferred strategies will almost always involve trade-offs between meeting different objectives. One possible method of evaluating these trade-offs is the policy exercise. This combines elements of a modelling approach with expert judgement. Policy makers in government and agriculture are encouraged to participate with senior scientists in exercises (often based on the principle of gaming), where they are asked to judge appropriate policy responses to a number of given impacts which may result from

climate change. Their decisions are then evaluated using impact models. A description of the procedure is given in Toth (1989), and an example can be found in the climate impact assessment conducted in South-East Asia (Parry et al., 1992).

8.4 Summary and implications

In this chapter we have reviewed a number of approaches that are useful in analysing impacts and adaptations in agriculture. No single approach should be considered optimal, because research objectives and data availability differ from one study to another. Indeed, it is quite likely that a mix of approaches will be the most effective in some circumstances; for example, using detailed models for a limited number of sites (these models are often data-hungry) and then extrapolating their outputs across larger areas which have been characterised by more simple agro-climatic indices. This will generate estimates of climate-change induced yield effects, and is generally the first step in agricultural impact studies.

A frequent second step is to evaluate these yield changes in terms of their economic and social implications such as farm income, rural employment, and contribution to national income. This requires the use of economic models and other techniques with which the climatologist and agronomist are often unfamiliar. There are, therefore, great advantages to be gained from the creation of a research team with experts from a number of disciplines, including agricultural economists and rural planners.

As the results of the research are scaled up from effects on yields to those on income and employment, the uncertainties become greater. It is important that these are adequately described, so that the policy maker can weigh what is known against what is not.

Finally, it is important to provide an estimate (perhaps through expert judgement, although preferably by some of the formal methods that have been described) of the relative roles of climate and non-climate factors in affecting agriculture in the study over the period in question. In most parts of the world, changes in government policy, prices, and technology will be just as important as climate change in affecting agriculture in the future. The effects of climate change should be placed in the context of these.

References

Acock, B. and L.H. Allen, Jr. 1985. Crop responses to elevated carbon dioxide concentrations. In B.R. Strain and J.D. Cure (eds). *Direct Effects of Increasing Carbon Dioxide on Vegetation*. DOE/ER-0238. US Department of Energy. Washington DC. pp. 53-97.

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen. 1990. Global climate change and US agriculture. *Nature* 345: 219-224.

Adams, R.M., R.A. Fleming, C-C. Chang, B.A. McCarl, and C. Rosenzweig. 1995a. A reassessment of the economic effects of global climate change on U.S. agriculture. *Climatic Change* 30(2), 147-167.

Adams, R.M., B.A. McCarl, K. Segerson, C. Rosenzweig, K.J. Bryant, B.L. Dixon, R. Connor, R.E. Evenson, and D. Ojima. 1995b. *The Economic Effects of Climate Change on U.S. Agriculture. Final Report.* Electric Power Research Institute, Climate Change Impacts Program, Palo Alto, California, USA, 45 pp.

Akong'a, J., T.E. Downing, N.T. Konijn, D.N. Mungai, H.R. Muturi, and H.L. Potter. 1988. The effects of climatic variations on agriculture in central and eastern Kenya. In *The Impact of Climatic Variations on Agriculture, Volume 2. Assessments in Semi-Arid Regions,* M.L. Parry, T.R. Carter, and N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 121–270.

Ashomore, M.S. 1988. A comparison of indices that describe the relationship between exposure to ozone and reduction in the yield of agricultural crops. *Atmospheric Environment* 22, 2060-2060.

Bazzaz, F.A. and K.D.M. McConnaughay. 1992. Plant-plant interactions in elevated CO_2 environments. *Australian Journal of Botany* 40, 547-563.

Bergthorsson, P., H. Bjornsson, O. Dyrmundsson, B. Gudmundsson, A. Helgadottir, and J.V. Jomnundsson. 1988. The effects of climatic variations on agriculture in Iceland. In *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions,* M.L. Parry, T.R. Carter, and N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 381–509.

Binswanger, H.P. and B. Deininger. 1997. Explaining agricultural and agrarian policies in developing countries. *Journal of Economic Literature* XXXV, 1958-2005.

Bosac, C., V.J. Black, C.R. Black, J.A. Roberts, and F. Lockwood. 1993. Impact of O_3 and SO_2 on reproductive development in oilseed rape (*Brassica napus* L.). I. Pollen germination and pollen tube growth. *New Phytology* 124, 439-446.

Brklacich, M., P. Curran, and D. Brunt. 1996. The application of agricultural land rating and crop models to CO_2 and climatic change issues in northern regions: The Mackenzie Basin case study. *Agricultural and Food Science in Finland* 5, 351-365.

Brklacich, M., D. McNabb, C. Bryant, and J. Dumanski. 1997. Adaptability of agricultural systems to global climatic change: a Renfrew county, Ontario, Canada pilot study. In *Agricultural Restructuring and Sustainability: A Geographic Perspective,* B. Ilbery, T. Rickard, and Q. Chiotti (eds). Commonwealth Agricultural Bureau International, Wallingford, United Kingdom, pp. 185-200.

Butterfield, R.E., K.G. Lonsdale, and T.E. Downing. 1997. *Climate Change, Climatic Variability and Agriculture in Europe: An Integrated Assessment*. Annual Report. Environmental Change Unit, University of Oxford, Oxford, United Kingdom, 283 pp.

Carter, T.R., N.T. Knonijn, and R.G. Watts. 1988. The choice of first-order impact models. In *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions,* M.L. Parry, T.R. Carter and N.T. Konijn. (eds). Kluwer, Dordrecht, The Netherlands, pp. 97-123.

Carter, T.R., T.R. Porter, and M.L. Parry. 1991. Climatic warming and crop potential in Europe: Prospects and uncertainties. *Global Environmental Change* 1, 219-312.

CROPWAT. 1995. A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46. CROPWAT Version 5.6 (1991). FAO, Rome, Italy.

Cubasch, U. K. Hasselmann, H. Hock, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer, and R. Sausen. 1992. Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate Dynamics 8, 55-69.

Darwin, R. 1997. World agriculture and climate change: Current questions. *World Resource Review* 9, 17-31.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses. 1995. World Agriculture and Climate Change: Economic Adaptations. Economic Research Service, AER-703, US Department of Agriculture, Washington, DC.

Diaz, S., J.P. Grime, J. Harris, and E. McPherson. 1993. Evidence of a feedback mechanism limiting plant response to elevated carbon dioxide. *Nature* 364, 616-617.

Downing, T.E., M.J. Watts, and H.G. Bohle. 1993. Climate change and food security: Towards a sociology and geography of vulnerability. In *Climate Change and World Food Security*, T.E. Downing (ed). Springer-Verlag, Berlin, 662 pp.

Dracup, J.A., S.D. Pelmulder, R. Howitt, J. Horner, W.M. Hanemann, C.F. Dumas., R. McCann, J. Loomis, and S. Ise. 1992. The Economic Effects of Drought Impacts on California Resources: Implications for California in a Warmer World. National Institute for Global Climate Change, University of California, Davis, California, USA, 112 pp.

Easterling, W.E., P.R. Crosson, N.J. Rosenberg, M.S. McKenney, L.A. Katz, and K.M. Lemon. 1993. Agricultural impacts and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. *Climatic Change* 24, 23-61.

Ellis, R.H., P. Hadley, E.H. Roberts, and R.J. Summerfield. 1990. Quantitative relations between temperature and crop development and growth. In *Climatic Change and Plant Genetic Resources*, M.T. Jackson, B.V. Ford-Lloyd, and M.L. Parry (eds). Belhaven Press. London, pp. 85-115.

Fajer, E.D., M.D. Bowers, and F.A. Bazzaz. 1989. The effects of enriched carbon dioxide atmospheres on plant-insect herbivore interactions. *Science* 243, 1198-1200.

FAO. 1993. Agriculture: Toward 2010. 27th Session, 6-25 November, Rome.

Fischer, G. and H.T. van Velthuizen. 1996. Climate Change and Global Agricultural Potential Project: A Case Study of Kenya. WP-96-71. International Institute for Applied Systems Analysis, Laxenburg, Austria, 96 pp.

Fitter, A.H. and K.M. Hay. 1987. *Environmental Physiology of Plants*. Second Edition. Academic Press, London, 423 pp.

Fredeen, A.L., G.W. Koch, and C.B. Field. 1995. Effects of atmospheric CO_2 enrichment on ecosystem CO_2 exchange in a nutrient and water limited grassland. *Journal of Biogeography* 22, 215-219.

Gadgil, S., A.K.S. Huda, N.S. Jodha, R.P. Singh, and S.M. Virmani. 1988. The effects of climatic variations on agriculture in dry tropical regions of India. In *The Impact of Climatic Variations on Agriculture. Volume 2. Assessments in Semi-Arid Regions*, M.L. Parry, T.R. Carter and N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 495–578.

GCTE. 1996. GCTE Focus 3 Wheat Network. 1996 Model and Experimental Meta Data. Second Edition. J. Ingram (ed). GCTE Report Series No. 2. GCTE Focus 3 Office, Wallingford, United Kingdom, 147 pp.

Geign, S.C. van de, J. Goudriaan, and F. Berendse. (eds). 1993. Climate change; crops and terrestrial ecosystems. *Agrobiologische Thema's 9*, CABO-DLO, Centre for Agrobiological Research, Wageningen, The Netherlands, 144 pp.

Gleick, P.H. 1993. *Water in Crisis*. Oxford University Press, Oxford, United Kingdom.

Goudriaan, J. and M.H. Unsworth. 1990. Implications of increasing carbon dioxide and climate change for agricultural productivity and water resources. In *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture*, B.A. Kimball, N.J Rosenberg, and L.H. Allen Jr. (eds). ASA Special Publication Number 53. American Society of Agronomy, Inc. Madison, Wisconsin, USA, pp. 71-82.

Hanson, J.D., B.B. Baker, and R.M. Bourdon. 1992. *SPUR2 Documentation and User's Guide*. U.S. Department of Agriculture, ARS, Great Plains Systems Research Technical Report-1, Fort Collins, Colorado, USA.

Harrison, P.A., R.E. Butterfield, and T.E. Downing (eds). 1995. *Climate Change and Agriculture in Europe.* Research Report No. 9. Environmental Change Unit, University of Oxford, Oxford, United Kingdom, 413 pp.

Hodges, T. (ed). 1991. *Predicting Crop Phenology*. CRC Press, Boca Raton, Florida, USA, 233 pp.

Iglesias, A., L. Erda, and C. Rosenzweig. 1996. Climate change in Asia: A review of the vulnerability and adaptation of crop production. *Water, Air, and Soil Pollution* 92, 13-27.

IPCC. 1996. *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* J.J. Houghton, L.G. Meiro Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, 572 pp. *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds). Cambridge University Press, Cambridge, United Kingdom and New York, 880 pp.

IRRI. 1993. *IRRI Rice Almanac 1993-1995*. International Rice Research Institute, Los Banos, Philippines.

Jones, C.A. and J.R. Kiniry (eds). 1986. *CERES-Maize: A Simulation Model of Maize Growth and Development*. Texas A&M University, College Station, Texas, USA.

Jones, J.W., and J.R. Ritchie. 1990. Crop growth models. Chapter 4 of *Management of Farm Irrigation Systems*, G.J. Hoffman et al. (eds). American Society of Agricultural Engineers Monograph, St. Joseph, Missouri, USA.

Kaiser, H.M., S.J. Riha, D.S. Wilks, and R. Rampath. 1993. Adaptation to climate change at the farm level. In *Agricultural Dimensions of Global Climate Change*, H.M. Kaiser and J.E. Drennen (eds). St. Lucie Press, Delray Beach, Florida, USA, pp. 87-116.

Karl, T.R., R.W. Knight, and N. Plummer. 1995. Trends in high-frequency climate variability in the twentieth century. *Nature* 377, 217-220.

Katz, R.W. and B.G. Brown. 1992. Extreme events in a changing climate: Variability is more important than averages. *Climatic Change* 21(3), 289-302.

Kettunen, L., J. Mukula, V. Pohjonen, O. Rantanen, and U. Varjo. 1988. The effect of climatic variations on agriculture in Finland. In *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions,* M.L. Parry, T.R. Carter, and. N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 513-615.

Körner, C. 1995. Towards a better experimental basis for upscaling plant responses to elevated CO2 and climate warming. *Plant, Cell and Environment* 18, 1101-1110.

Kraalingen, D.W.G. van. 1990. Effects of CO_2 enrichment on nutrient-deficient plants. In *The greenhouse Effect and Primary Productivity in European Agro-Ecosystems*, J. Goudriaan, H. van Keuten, and H.H. van Laar (eds). Pudoc, Wageningen, Netherlands, pp. 42-54.

Leemans, R, and A.M. Solomon. 1993. Modelling the potential change in yield distribution of the earth's crop under a warmer climate. *Climate Research* 3, 79-96.

Maass, S.J. 1988a. Use of remotedly sensed information in agricultural crop growth models. *Ecological Modelling* 41, 247-268.

Maass, S.J. 1988b. Using satellite data to improve model estimates of crop yield. *Agronomy Journal* 80, 655-662.

Maass, S.J. 1992. GRAMI: A Crop Growth Model that Can Use Remotely Sensed Information. ARS-91. US Department of Agriculture, Washington, DC, USA.

Manning, W.J. and A.V. Tiedemann. 1995. Climate change: Potential effects of increased atmospheric carbon dioxide (CO_2), ozone (O_3), and ultraviolet-B (UV-B) radiation on plant diseases. *Environmental Pollution* 88, 219-245.

Martin, P. and M. Lefebvre. 1993. 9 to 5. 9 approaches to tackle 5 aspects of climate change. *Climatic Change* 25, 421–438.

Martin, R.J., M.J. Salinger, and W.M. Williams. 1990. *Agricultural Industries in Climate Change: Impacts on New Zealand*. Ministry of the Environment, Wellington, New Zealand.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1996. The effects of changes in daily and interannual climatic variability on CERES-wheat: A sensitivity study. *Climatic Change* 32(1), 257-292.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. The impact of global warming on agriculture: A Ricardian analysis. *American Economic Review* 84(4), 753-771.

Mitchell, J.F.B, S. Manabe, T. Tokioka, and V. Meleshko. 1990. Equilibrium change. In *Climate Change: the IPCC Scientific Assessment*, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds). Cambridge University Press, New York.

Muchena, P. and A. Iglesias. 1995. Vulnerability of maize yields to climate change in different farming sectors in Zimbabwe. In *Climate Change and Agriculture: Analysis of Potential International Impacts.* ASA Special Publication No 59, American Society of Agronomy, Madison, Wisconsin, USA pp. 229-240.

Nishioka, S., Harasawa, H., Hashimoto, H., Ookita, T., Masuda, K. and Morita, T. (eds). 1993. *The Potential Effects of Climate Change in Japan*. Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 94 pp.

Palmer, W.L. 1965. Meteorological Drought. Research Paper No. 45. US Department of Commerce, Weather Bureau, US Government Printing Office, Washington, DC

Parry, M.L. and T.R. Carter. 1985. The effect of climate variations on agricultural risk. *Climatic Change* 7, 95-110.

Parry, M.L. and T.R. Carter. 1988. The Assessment of Effects of Climatic Variations on Agriculture: Aims, Methods and Summary of Results. In *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions*, M.L Parry, T.R. Carter, and N.T. Konijn. (eds). Kluwer, Dordrecht, The Netherlands, pp. 11-96.

Parry, M.L., T.R. Carter, and N.T. Konijn. (eds). 1988. *The Impact of Climatic Variations on Agriculture. Vol. 1 Assessments in Cool Temperate and Cold Regions. Vol. 2 Assessments in Semi-arid Regions*. Kluwer, Dordrecht, The Netherlands. 876 pp. and 764 pp.

Parry, M.L., M. Blantran de Rozari, A.L. Chong, and S. Panich. 1992. The Potential Socio-Economic Effects of Climate Change in South-East Asia. United Nations Environment Programme, Nairobi, 126 pp.

Parry, M.L., J.E. Hossell, P.J. Jones, T. Rehman, R.B. Tranter, J.S. Marsh, I. Carson, and R.G.H. Bunce. 1996a. Integrating global and regional analyses of the effects of climate change: A case study in England and Wales. *Climatic Change* 32, 185-198.

Parry, J.L., R.E. Hossell, R. Bunce, P.J. Jones, T. Rehman, R.B. Tranter, J.S. Marsh, C. Rosenzweig, and G. Fischer. 1996b. Global and regional land-use responses to climate change. In. *Global Change and Terrestrial Ecosystems*, B. Walker and W. Steffen. (eds). Cambridge University Press, Cambridge, United Kingdom, pp. 466-483.

Pearce, D.W. 1993. *Economic Values and the Natural World.* Earthscan, London.

Reilly, J. and N. Hohmann. 1993. Climate change and agriculture: The role of international trade. *American Economic Association Papers and Proceedings* 83, 306-312.

Reilly, J., N. Hohmann, and S. Kane. 1994. Climate change and agricultural trade. Who benefits, who loses? *Global Environmental Change* 4(1), 24-36.

Ritchie, J.T., and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat yield model. In *ARS Wheat Yield Project*. ARS-38. W.O. Willis (ed). US Department of Agriculture, Agricultural Research Service, Washington, DC, pp. 155-175.

Rosenberg, N.J. (ed). 1993. *Towards an Integrated Impact Assessment of Climatic Change: The MINK Study*. Kluwer, Dordrecht, The Netherlands, 173 pp.

Rosenzweig, C. and D. Hillel. 1998. *Climate Change and the Global Harvest*. Oxford University Press., New York and Oxford. 234 pp.

Rosenzweig, C. and A. Iglesias. (eds). 1994. *Implications of Climate Change for International Agriculture: Crop Modelling Study*. US Environmental Protection Agency, Washington DC.

Rosenzweig, C. and A. Iglesias. 1998. The use of crop models for international climate change impacts. In *Understanding Options for Agricultural Production*, G.Y. Tsuji et al. (eds). Kluwer Academic Publishers, Dordrecht, The Netherlands.

Rosenzweig, C. and M.L. Parry. 1994. Potential impact of climate change on world food supply. *Nature* 367, 133-138.

Rowntree, P. 1993. Workshop on socio-economic and policy aspects of change of incidence and intensity of extreme weather events. Institute for Environmental Studies, W93/15, Free University, Amsterdam, The Netherlands, June 24-25.

Saarikko, R.A. and T.R. Carter. 1996. Estimating the development and regional thermal stability of spring wheat in Finland under climatic warming. *Climate Research* 7, 243-252.

Sharpley, A.N. and J.R. Williams. 1990. EPIC - Erosion Productivity Impact Calculator: Vol. I. Model Documentation. USDA Technical Bulletin No. 1768. US Department of Agriculture, Washington, DC, 235 pp.

Smith, J.B., Lenhart, S., Huq, S., Mata, L.J., Nemosova, I., Toure, S. (eds). 1995. *Vulnerability and Adaptation to Climate Change: Interim Results from the U.S. Country Studies Program*. Dordrecht: Kluwer Academic Publishers.

Smith J.B., N. Bhatti, G. Menzhulin, R. Benioff, M. Campos, B. Jallow, F. Rijsberman, M.I. Budyko, R.K. Dixon. (eds). 1996. *Adapting to Climate Change: An International Perspective*. Springer-Verlag, New York. 476 pp.

Strain, B.R. and J.D. Cure. (eds). 1985. *Direct Effects of Increasing Carbon Dioxide on Vegetation*. DOE/ER–0238. US Department of Energy, Office of Energy Research, Washington DC, 286 pp.

Strzepek, K.M. and J.B. Smith. (eds). 1996. *As Climate Changes: International Impacts and Implications*. Cambridge University Press. Cambridge, United Kingdom.

Sutherst, R.W., G.F. Maywald, and D.B. Skarrate, 1995. Predicting insect distributions in a changed climate. In *Insects in a Changing Environment*, J.L. Hatfield and I.J. Thomason, (eds). Academic Press, London, pp. 59-91.

Toth, F.L. 1989. Policy Exercises. IIASA Research Report RR-89-2. Reprinted from *Simulation and Games* 19 (3). International Institute for Applied Systems Analysis, Laxenburg, Austria.

US Country Studies Program. 1994. *Guidance for Vulnerability and Adaptation Assessments.* Argonne National Laboratory, Argonne, Illinois, USA, 205 pp.

UK Department of the Environment. 1996. *Review of the Potential Effects of Climate Change in the United Kingdom*. Second Report of the UK Climate Change Impacts Review Group, 248 pp.

Warrick, R.A. 1984. The possible impacts on wheat production of the 1930s drought in the U.S. Great Plains. *Climatic Change* 6, 5-26.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart, and E.E. Wheaton, 1988. Estimating effects of climatic change on agriculture in Saskatchewan, Canada. In *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions*, M.L. Parry, T.R. Carter, and N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 219-379.

Yoshino, M.M, T. Horie, H. Seino, H. Tsujii, T. Ushijima, and Z. Uchijima. 1988. The effect of climatic variations on agriculture in Japan. In *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions*, M.L. Parry, TR. Carter, and N.T. Konijn (eds). Kluwer, Dordrecht, The Netherlands, pp. 725-865.

9 Rangeland and Livestock

Lead Author
Barry Baker [1]

Contributing Author
Ernesto F. Viglizzo, Argentina

9.1 Nature and scope of the problem

Rangeland and livestock ecosystems are complex, with myriad interactions among the biotic and abiotic components of the system as well as the economic and social components. Consequently, the effects of a changing climate will have direct (first order) and indirect (second or higher order) impacts at many different spatial and temporal scales. Examples of these impacts include changes in forage yield, changes in livestock productivity, changes in ecological processes, alterations in farm level profitability, changes in regional farm incomes, and possibly modification of regional and national food production and incomes. Therefore, understanding lower order impacts are crucial for anticipating and predicting higher order effects (Parry and Carter, 1989).

The goals of the rangeland and livestock assessment are to (1) identify rangeland production areas that are sociologically, economically, and ecologically vulnerable to changes in climate; (2) evaluate how climate affects management practices and ecological processes of rangeland and livestock systems; and (3) identify possible adaptation strategies to minimise adverse effects and, where possible, optimise positive benefits of climate change. The methods described in this chapter are meant to provide the means for accomplishing these goals.

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[1] Ecosystems Research International, Fort Collins, Colorado, USA.

Rangelands, which can be defined as unimproved grasslands, savannahs, shrublands, hot and cold deserts, and tundra, cover approximately one-fifth of the world's land surface and provide food for approximately 50 percent of the world's ruminate livestock and countless numbers of wild herbivores (WRI, 1996). Billions of people around the world either directly or indirectly derive food or income from livestock that graze or browse on these lands.

Increases in atmospheric carbon dioxide (CO_2) can raise plant productivity and cause changes in temperature, precipitation, solar radiation, and wind patterns that could have important effects, either positive or negative, on animal and plant production in rangeland ecosystems. Consequently, climate driven changes in the sustainability and productivity of rangeland and livestock systems could have profound direct and indirect effects on human populations, local, regional, and national food supplies, and economic security for most nations in the world.

9.1.1 Impacts on livestock

The IPCC (1996) summarised research on the potential impacts of climate change for livestock and listed four possible effects: (1) changes in livestock feedgrain availability and price; (2) direct effects of climate on animal health, growth, and reproduction; (3) impacts on pasture and forage crops; and (4) changes in distribution of disease and parasites.

Although the primary focus of this chapter is concerned with rangeland and livestock systems, some mention should be given to the possible effects of climate change on more intensively managed livestock production schemes. A review of available research suggests that direct impacts may be minor for intensively managed livestock production systems such as confined poultry, swine, and beef operations (IPCC, 1996). These systems already have a great deal of built-in climate control through the use of shade, misting devices, and mechanical heat regulation. However, there are important indirect effects on these systems, for example, costs and availability of feedgrain, water quality and quantity, and cost, availability, and type of energy sources.

The well being and productivity of livestock in natural conditions depend on the animal's ability to cope with environmental challenges such as nutritional and thermal environments and exposure to disease and parasites. The direct effects from heat and water stress on grazing or browsing livestock are most likely to be manifested as decreases in feed intake, milk production, and rates of reproduction.

The indirect effects of climate driven changes on animal performance result from alteration in the animal's nutritional environment. Research suggests that changes in climate are most likely to influence the quality and quantity of forage produced (Walker, 1994; Van den Pol van Dasselaar and Lantinga, 1995; De-Xing Chen et al., 1996; Fuller and Prince, 1996; Topp and Doyle, 1996a; Thornley and Cannell, 1996). Consequently, these changes in forage may alter the productivity of grazing livestock (Baker et al., 1993; Eckert et al., 1995; Topp and Doyle, 1996b).

Climatic restrictions on vectors, environmental habitats, and disease causing agents are important for keeping many animal diseases in check (Stem et al., 1989). Alterations of temperature and precipitation regimes may result in a spread of disease and parasites into new regions or produce an increase in the incidence of disease. Changes in the incidence and spread of disease and parasites would reduce animal productivity and possibly increase animal mortality.

9.1.2 Impacts on rangelands

Climatic changes such as increased atmospheric concentration of CO_2, changes in temperature, and changes in precipitation patterns have the potential to affect rangeland ecosystems. An in-depth description and literature review of the current state of knowledge regarding the effects of these driving forces on plant and ecosystem physiology and biogeochemistry are beyond the scope of this chapter. Instead, a summary of direct and indirect impacts and feedbacks of climate change is provided here. Detailed reviews and studies regarding these processes can be found in IPCC (1996) and Breymeyer et al. (1996).

The direct effects of climate and climate change on rangeland ecosystem processes are fairly well described, have relatively short response times, and are somewhat easier to predict than the indirect effects. The direct effects of climate change on rangeland ecosystems from alterations in precipitation regimes, temperature, and atmospheric concentrations of CO_2 include (1) changes in decomposition rates; (2) changes in aboveground net primary production (ANPP); (3) shifts in C_3/C_4 species of grasslands; (4) changes in fluxes of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), nitric oxide (NO), and nitrous oxide (N_2O); (5) changes in evapotranspiration and runoff; and (6) changes in forage quality (Ojima et al., 1991; Breymeyer et al., 1996; IPCC, 1996).

The indirect effects are less well understood. Because of lags in the response time of the system and the complexity of the feedbacks that are involved, the impacts of climate change take longer to identify. Also human activities, including burning, cropping, and management of grazing animals, have the potential to modify indirect effects by either accelerating or slowing these processes. Thus predicting the direction and magnitude of the impact is more difficult. Examples of the indirect effects of climate change on rangeland ecosystems include (1) changes in the structure of vegetation communities; (2) changes in vegetation cover that could alter surface albedo, humidity, and ground level wind patterns; (3) changes in the C:N ratios or lignification of vegetation that alter litter quality and affect soil nutrients; (4) alterations in soil characteristics; (5) changes in biogeochemical cycles that lead to the invasion of exotic species of plants; and (6) possible influence on frequency of wildfires in some areas (Ojima et al., 1991; IPCC, 1996).

9.1.3 Socio-economic impacts

Climate induced changes on rangelands and livestock production would have effects on economies and societies at farm, national, and international levels. These impacts are likely to be seen as changes in income and prices, and hence changes in livelihood, employment, and investment. Analysing such impacts would require an economic model, more specifically a (recursive) applied (or computable) general equilibrium model. Such models have been applied to climate change impacts on agriculture, though not on livestock, and are discussed in Chapter 8, Agriculture.

Social systems in some parts of the world may be stressed beyond their ability to cope with any further changes in climate. In areas where livestock are forced to graze on marginal lands (either by social structure, economic conditions, or governmental regulations), further degradation or reductions in forage productivity could result in political unrest, famine, or other social disturbances.

9.1.4 Areas and extent of impacts

The rangeland and livestock sector is most likely to be vulnerable in countries in the poorer regions of the world and least capable of adapting to change in climate or other environmental perturbations (Antle, 1995). Many of the countries in these regions are experiencing high population growth that forces expansion of grazing into areas of marginal productivity, which places extreme pressures on an already stressed ecosystem (Parry et al., 1988).

The potential negative impacts of climate change on livestock production are likely to be greater in those areas of the world where production is already operating at the margins. Traditional pastoralist systems that are seen in many regions of the developing world are less likely to have the flexibility built into the system for adapting to extreme climatic events (such as changing the type or mix of grazing livestock, cross-breeding, relocating), whereas modern industrialised livestock production systems in the western regions of the United States, Canada, and parts of South America are more likely to make adjustments to mitigate many of the potential negative effects of climate change.

Changes in precipitation are especially important in regions where lack of rainfall is already a limiting factor (Parry et al., 1990). At a regional level, alterations in rainfall patterns are likely to have a greater ecological and socio-economic impact than the direct effects of small increases in mean annual temperature (IGBP, 1992). Although, in those areas of world where daytime temperatures are at the limits or approach the upper limits for livestock production, higher temperatures at night may cause heat stress in animals.

The negative effects of increases in concentrations of atmospheric CO_2 are most likely to be experienced in tropical and sub-tropical rangelands. The IPCC Working Group II (IPCC, 1996) listed the extent of known regional impacts of altered climate regimes and the relative degree of confidence in their prediction. They predicted with medium

confidence that increased atmospheric concentrations of CO_2 are likely to alter the carbon and nitrogen ratios of some forage plants. The result of this phenomenon would be manifested in a decreased palatability and nutritional quality of the forage. This is most likely to occur in lower latitude rangelands where forage quality is already low.

The IPCC also predicted with a high degree of confidence that small changes in the frequency of extreme climatic events may have disproportionate effects on what managers and herders have to cope with in rangeland systems. Changes in climate are likely to produce alterations in the boundaries between rangelands and other biomes, such as deserts and forests, directly through shifts in species composition and indirectly through changes in wildfire regimes, opportunistic cultivation, or agricultural release of the less arid margins of the rangeland territory (IPCC, 1996). They predicted that these effects will be more common in temperate rangelands.

9.1.5 Identification of impacts and adaptations options

To keep the task of impact assessment manageable, the range of climatic impacts to be included in the assessment should be listed and prioritised within the goals of the assessment. Table 9.1 contains a list of the possible types climate driven impacts that are likely to occur in the rangeland and livestock sector.

Table 9.1 Likely impacts in rangeland and livestock sector.

Livestock impacts	Shifts in rangeland vegetation structure or boundaries Changes in forage quality and quantity Changes in length of growing season Changes in livestock productivity Changes in water quality and quantity.
Ecological impacts	Alteration in carbon storage capacity of the ecosystem Alterations in greenhouse gas emissions Disturbances in ecosystem functions (e.g., alterations in biogeochemical cycling, incidence of wild fires, etc.) Change in soil quality and productivity Changes in biodiversity Changes in habitat suitability for wildlife.
Socio-economic impacts	Changes in food production and security (locally, regionally, and nationally) Changes to incomes derived from livestock production, wildlife, and other rangeland outputs Changes in land use Changes in recreational use of rangelands Alteration in scenic quality.

As can be seen from Table 9.1, there are many potential cross-sectoral impacts to be considered in the assessment. The team designing the assessment for this section is strongly urged to co-ordinate their effort with the water resources (Chapter 6), agriculture (Chapter 8), energy (Chapter 11), forests (Chapter 12), and biodiversity (Chapter 13) sectors.

Once the impacts to be included in the assessment are identified, a list of indicator variables, those variables used to evaluate change in the system (see Table 9.2), and adaptation options should be identified. Some of the methods presented in the next section are better than others at producing outputs that can be used for adaptation assessments or incorporation into policy assessments. Therefore, a particular method or suite of methods should be chosen based on impacts and adaptation strategies to be used in the assessment.

9.2 An array of methods

This section presents an array of methods for conducting climate change impact assessments for rangeland and livestock systems.

9.2.1 Description of methods

9.2.1.1 Experimentation

A wealth of data and knowledge has been gleaned from experiments on the effects of environmental stresses on the physiology and production of plants and animals. Also there is a growing amount of information available on the effects of atmospheric concentrations of CO_2 on plant production (Gonzàlez-Meler et al., 1996; IPCC, 1996; Long et al., 1996; Shaver and Aber, 1996), plant quality and decomposition (Melillo, 1996), and soil carbon storage (Paustian et al., 1995; Tate et al., 1995). Because of the long time delays in response, complex interactions, and lack of feedbacks, experimentation has limited application with regard to impact assessment. But the data produced and understanding gained in the workings of individual components of the system are extremely useful for other assessment methods.

Even though the usefulness of experimentation is limited and may be considered impractical in the context of programs or projects with limited funding, like climate change country studies, the establishment of long-term field experiment sites is extremely valuable, and usually needs to be budgeted for separately. This type of research program could be considered as a future research priority should funding or collaborative arrangements with other national or international agencies become available. For example, since the establishment of the first six sites in the United States during the early 1980s, the National Science Foundation's Long Term Ecological Research program has been conducting research on long-term ecological phenomena in the United States and developing a network of sites in other countries throughout Asia, Australia, South America, Africa, and Europe. These long-term field experimental sites represent a unique source of information on long-term ecological processes and are a principal component necessary for regional assessments of the effects of climate on those processes (Hall et al., 1995; Paustian et al., 1995).

Table 9.2 Possible climate induced changes, indictor variables, controlling climatic factors, rangeland and livestock, ecological, and socio-economic impacts.

Category	Indicator variables	Controlling climatic factors	Rangeland and livestock impacts	Ecological impacts	Socio-economic impacts
Below ground nutrient pools	Soil carbon, nitrogen, and phosphorus	Temperature and precipitation	Changes in forage resources, shifts in vegetation structure or boundaries	Changes soil quality and productivity, alteration in plant productivity, cover, and shifts in species.	No first order impacts but many second order impacts because of alterations in plant structure and function. Impacts listed in following rows.
Plant or forage quantity	Peak standing crop, annual production, length of growing season	CO_2, temperature, and patterns of precipitation	Reduced feed intake and livestock productivity, reduction in harvested forage	Changes in carbon storage, community structure, changes in water storage, alteration in biodiversity, and changes in habitat suitability.	Changes in land-use, and change income. Second order impacts such as changes in food production and security.
Plant or forage quality	Carbon to nitrogen ratio or digestibility	CO_2 and temperature	Changes in livestock production, such as milk production, growth rates, reproduction, etc.	Changes in carbon storage, greenhouse gas emission, soil quality and productivity, habitat suitability and biodiversity.	Changes in food production and security.
Plant adaptability or shifts in species	Water use efficiency	Temperature, precipitation, and CO_2	Changes in livestock production and utilisation, shift in type of herbivores	Changes in community structure and function, biodiversity, habitat suitability.	Changes to food production, incomes, land-use, and maybe scenic quality.
Livestock heat stress	Cow weight at weaning, body condition scores	Temperature, humidity, and night time cooling	Changes in mortality, milk production, decreased animal intake, and weight gain	Changes to ecosystem structure due to increased grazing should conditions be positive.	Alteration in food production, food security, and incomes.
Voluntary feed intake	Diet quality, intake of grazed forage, and forage to supplement ratios	Temperature	Changes in growth rates, milk production, reproduction, and mortality	Changes to ecosystem structure due to increased grazing should conditions be positive.	Alteration in food production, food security, and incomes.
Young nursing animal production	Mother's milk production, weights at weaning, and growth rate	Temperature	Changes in growth rate and mortality	Changes to ecosystem structure due to increased grazing should conditions be positive.	Alteration in food production, food security, and incomes.

9.2.1.2 Screening techniques

The purpose of preliminary screening is to identify those areas where more detailed analysis may be needed or to develop some initial quantitative assessments of an area's vulnerability and response to climatic change. Regions of vulnerability may be spatially defined by administrative, geographic, or ecological boundaries. Methods used in a screening analysis include the construction and utilisation of simple indicators or indices, geographical analyses, the use of remotely sensed data, or a combination of the three methods.

Indicators or indices

Two basic characteristics can be used to define indicators (Hammond et al., 1995). First, they must quantify information so that the significance of the data is more readily apparent. Second, they must improve communication by simplifying information about complex phenomena.

In the development of indices, administrative or geographic boundaries can be used to delineate areas that are economically or sociologically dependent on livestock production from rangelands (Baker et al. 1993; Eckert et al., 1995). Clearly, areas that are economically dependent on rangelands for livestock production are susceptible to the positive as well as the negative effects of changes in climatic conditions.

Ecological boundaries can also be used to define areas that are ecologically at risk from changes in climate. These areas can be defined by their susceptibility to degradation, loss of biodiversity, desertification, and so on. Economic and demographic data can be combined with ecological data to develop a socio-ecological risk index (Baker and Hanson, 1993). However, the construction of this type of index is not an end in and of itself. Careful analyses must be conducted to determine the nature and degree of the risk. For example, rangelands at the northern or wetter edge of an ecological boundary may not be at risk or at much less risk than rangelands at the southern or drier edge of the boundary.

Geographic analysis

Another approach that can be used to determine and analyse areas that are sensitive to changes in climate is the use of GIS (Du Preez et al., 1990; Baker and Hanson, 1993; Baker et al., 1993). It allows for the integration and summarisation of environmental information using natural units such as watersheds, rangeland areas, and soil units. Indices can be included in a GIS to demonstrate spatially where the impacts of climate change such as degradation of rangeland resources are most likely to occur and where degradation would have economically significant societal impacts.

Satellite remote sensing enables scientists to make direct observations of the land surface at frequent and repetitive intervals, hence allowing for the mapping and monitoring of changes in land use and cover at a variety of spatial and temporal scales. Other applications of remotely sensed data include inventory of pasture and rangeland vegetation, changes in forage condition, monitoring soil erosion and soil moisture, and detection of episodic events on rangelands.

There is an extensive body of literature within many natural science disciplines that document the development and potential for satellite sensor data analysis techniques for use in climate change research. A partial and very abbreviated list of related papers on this topic is provided in Table 9.3.

Not all remotely sensed data come from satellites. Aerial photography is also a very useful method for collecting information regarding rangeland systems. The Systematic Reconnaissance Flight (SRF) is the best known and most widely used method. It employs a combination of photographs or video imagery with visual observations to estimate the numbers and spatial distribution of human settlements, livestock, wildlife, land use, and land cover types (Norton-Griffiths, 1988). The SRF method provides a rapid and relatively inexpensive means for gathering a systematic sample of remotely sensed imagery and field observations (Hassan and Hutchinson, 1992).

Table 9.3 A partial bibliography of the application of satellite sensor data for vegetation analysis and monitoring.

Author[1]	Title
Hobbs and Mooney, 1990	Remote sensing of biosphere functioning.
Wylie et al., 1991	Satellite and ground-based pasture production assessment in Niger: 1986-1988.
Prince, 1991	A model of regional primary production for use with coarse resolution satellite data.
Tucker et al., 1991	Expansion and contraction of the Sahara Desert from 1980 to 1990.
Ehrlich et at., 1994	Applications of NOAA AVHRR 1-km data for environmental monitoring.
Goward et al., 1995	Transient effects of climate change on vegetation dynamics: satellite observations.
Fuller and Prince, 1996	Rainfall and foliar dynamics in tropical Southern Africa: Potential impacts of global change on savannah vegetation.

[1] Published sources may be found in the reference list.

9.2.1.3 Expert judgement

There is no more simple or inexpensive method for rapid assessment of the state of knowledge of the effects of climate change on rangeland and livestock systems than asking the opinion of experts. Experts on animal science, range science, agricultural economics, soil science, climatology or meteorology, and social sciences may be solicited for their opinions on possible impacts.

The use of indigenous knowledge may be valuable for filling information gaps in data and understanding as well. There are three global centres, the US based Center for Indigenous Knowledge for Agriculture and Rural Development (CIKARD) at Iowa State University; LEAD in The Netherlands; and CIRAN; two regional centres in Nigeria and the Philippines, and several national centres in, Mexico, Indonesia, Ghana, Kenya, Sri Lanka, Brazil, Venezuela, South Africa, Burkina Faso, and Germany that provide training, data, and establish lines of communication between citizens and the development community. CIKARD is currently in the process of compiling a method for the use of indigenous knowledge in a training manual.

In many data poor areas, expert judgement from resource experts may be used as data by utilising the Delphi method. Clearly, the success of the Delphi and other methods of utilising expert judgement depends greatly on the proper selection of the group of experts, who should have access to the best available information and most recent research in their respective fields of study. The usefulness of expert opinion also depends on the scope and depth of the expert's experiences and understanding of the problem.

9.2.1.4 Analogue scenarios

Another way to examine the possible effects of climate change on rangeland and livestock production systems is to use an analogous scenario from either another place or another time. There are four types of analogies, historical event, historical trend, regional analogies of present climate, and regional analogies of future climate.

Little research has been conducted using analogue scenarios to examine the potential effects of climate change on rangeland and livestock systems. Easterling et al. (1992) constructed a historical analogue climate scenario from climate records during the Dust Bowl era (1930-1940) in the Great Plains of the United States to determine the effects of climate change on agricultural production in the Missouri, Iowa, Nebraska, and Kansas region. Although this study did not analyse the effects of climate change on rangeland livestock, the team did examine the indirect effects of a changing climate on feed sources for animal production. An overview of this study can be found in Chapter 4, Integration.

An example of an analogue scenario would be examining rangeland livestock production practices in a region that has a current climate similar to the projected change in climate, in the region under study. Alternatively, the impact of historical events such as protracted drought or monsoons on livestock production could also be incorporated into the analysis, as described above. In each of these examples, the analysis would provide a basis for creating a qualitative or even a semi-quantitative description of potential impacts.

9.2.1.5 Empirical-statistical models

An empirical-statistical model can be used to explain system dynamics by empirically analysing the relationships between some defined input and output variable such as a particular climate variable and forage yield on livestock production. This type of model is relatively simple to develop and can have a very high accuracy of prediction over the range of data for which it was developed. However, these models do have limitations. Statistical models are descriptive and not mechanistic in nature. Thus they provide only limited insight into the mechanisms underlying the particular patterns of interest. They are also unsuited for predicting responses to novel situations for which no data are available.

The statistical model lends itself quite nicely, however, to predicting first-order effects of climate change on forage and livestock production. Bergthorsson (1985) developed a model from climate and livestock data to compute the potential of livestock production in Iceland. The computational accuracy of the model was tested against historical data. He then used temperature deviations from historical records to determine the potential impacts of climate change, with regard to temperature, on livestock production. For another application of the empirical-statistical method, see Box 9.1.

9.2.1.6 Life zone, bioclimatic, or eco-classification models

Life zone, bioclimatic, or eco-classification models are actually another type of empirical-statistical model. These models range from very simple models such as the Holdridge Life Zone model (Holdridge, 1967) to the more complex models as presented in Prendergast and Hattersley (1985), Rizzo and Wiken (1992), Wang Futang and Zhao Zong-Ci (1995), and Li Xia (1995). This modelling approach is useful for examining impacts of climate on regional vegetation. However, because bioclimatic models are based on correlation they are subject to all of the limitations of empirical-statistical models as discussed above.

9.2.1.7 Processed based simulation models

Over the past 20 to 25 years many simulation models have been constructed to simulate rangelands and livestock production. These models can be divided into three major categories: biophysical models, decision support systems, and integrated models. In keeping the discussion within the context of the goals of this Chapter, the group of models under the heading of ecosystem or biophysical models can be further subdivided into rangeland process models and rangeland livestock ecosystem models. This last group also includes pastoral livestock production systems.

The intent of this discussion is not prescriptive in nature nor is the list of models presented all inclusive. Rather, the discussion is meant to provide an overview of the models and methods that have been used and cited in the literature for the assessment of

climate change in rangeland and livestock production systems. More information regarding model requirements and source contacts is listed in table 9.10.

Box 9.1 Example: Adaptation to climate change in the Argentine Pampas.

The region and the problem: The Argentine Pampas is a wide plain with approximately 60 million hectares of land mainly suited for cattle rearing and crop production. Based on its rainfall and soil quality patterns, the region may be divided in humid, sub-humid, and semi-arid zones. During the last century, various crop and cattle production activities were combined in different ways in each zone in response to the permanent environmental constraints and the cyclical climate variability. However, land-use options were also sensitive to economic conditions and technological factors. In this case, the problem was to assess how the rural sector has adapted to varying climate conditions by adjusting land-use strategies and other technological tactics.

Methods: Following a scheme suggested by Steffen and Ingram (1995) to integrate information, geographical and historical data were displayed along three intersecting axes: space, time, and adaptation response (Viglizzo et al., 1995, Viglizzo et al. 1997). The last one was not quantifiable, but it was necessary to identify different land use options that arose when a multilevel approach was utilised. Therefore, to understand the adaptive response of land-use to climate change, geographical data sets were analysed by scaling down along the space axis from the whole region to agro-ecological zones and specific sites. Similarly, historical sets of data were manipulated following a scale-dependent analysis which involved the last century as well as shorter periods of no more than three decades. Considering that rainfall was the climate variable which provided the greatest statistical variability both in space and time, a broad transect was displayed in the study region to cut across a wide rainfall gradient. Different sites were analysed along different periods of time. Thus different geographical and historical scales were combined in a multilevel approach. Long-term data sets on land use were compared with long-term data on climate (rainfall), economic (price of products), and technological (yield trend) factors. Comparisons were made within the transect for the whole region, the main agro-ecological zones (humid, sub-humid and semi-arid), and specific sites (political districts). Because price and production level of different farming activities were not comparable in absolute terms, relative indices were utilised for statistical analysis. Simple linear and quadratic regression analysis were used to associate the climate, economic, and technological factors with land-use change.

Adaptation assessment: The formal hypothesis was that climate might be the main force explaining changes in land use at the wider geographical space and the longer term, but factors other than climate (e.g., price and yield) would be explaining most of the land-use variance at the lower scales of time (few decades) and space (specific sites). But the results suggested that the hypothesis was partially wrong. Land-use variability tended to respond to climate variability only in the long term, but not to the variability of climate across the whole region. Thus the adaptive response of land use to climate change appeared to be a site-specific and a time-dependent function, mainly in the humid environments. As the environmental conditions turn drier in the western zones, the technology to improve water utilisation in soil appears to have more weight than land use in the adaptation process.

Policy options: Considering that the adaptation to climate change seems to be a site-specific and a time-dependent function, adaptive policies in the Pampas should be oriented to long-term strategies on specific sites instead of a generalised strategy for the whole region. Given that climate can drive both the relocation and translocation of the farming activities, a better climate scenario may show a negative impact on soil conservation, mainly in the fragile lands of the semi-arid zone, due to the uncontrolled expansion of crops at the expense of pastures and natural areas. A dramatic agro-ecological collapse of this kind occurred in the region during the 1930s and the 1940s. Since the natural reaction of farmers is to grow more annual crops when rainfall increases, a long-term land preservation strategy should be encouraged to counteract the potential undesirable effects of improved climate conditions.

The importance of this kind of historical assessments is that they can help to understand the autonomous adaptive behaviour of farmers to different climate conditions. This human dimension of the adaptive

response would complement other options that can be assessed through the use of GIS, mathematical modelling, expert systems, and decision-support tools.

Sources: Steffen and Ingram (1995); Viglizzo et al. (1995); Viglizzo et al. (1997).

Where possible, the use of validated simulation models developed in or near the region of interest is highly recommended. These models are more likely to use data that are available for the region and incorporate system processes that are unique to the area of interest.

Biophysical models

Biophysical simulation models mechanistically simulate ecological and physiological processes. Because these models are process driven, they can be applied to many different environments and can also be used to test the sensitivity and stability of the system to a range of changes in climatic conditions. Box 9.2 is an example of the application of the process-based vegetation model BIOME to an analysis of rangelands in Southern Africa.

Box 9.2 Example: Rangelands and climate change in Southern Africa.

Hulme (1996) discusses the potential impacts of climate change on the 12 countries of the Southern African Development Community (SADC). Substantial attention is paid to rangelands, as pastoralism and ecotourism are major income earners in these countries.

Three climate scenarios were evaluated, one with reduced precipitation, one with unchanged precipitation, and one with increased precipitation. The scenarios are based on different GCMs. All three have higher temperatures. The climate scenarios were used as input to a generic model of potential vegetation (BIOME). Two of the three scenarios show a tendency towards more arid vegetation. Increased temperatures outweigh the enhanced water use efficiency due to higher ambient concentrations of carbon dioxide. Only the scenario with increased precipitation shows a modest tendency towards more moist vegetation.

The distribution of 44 wildlife species was assessed using regression models developed specifically for this project. The models consider only direct climatic influences on species distribution. For all three scenarios, an increase in species diversity was found, possibly furthering opportunities for tourism. The models also indicate that species are likely to move to different locations than where they can now be found. A similar exercise was undertaken for tsetse flies, mosquitoes and ticks. The spread of tsetse flies – a limiting factor to cattle – was found to decrease under all three scenarios.

The impact of these changes on livestock and pastoralists was assessed based on expert judgement. Two of the three scenarios were concluded to worsen production and development potentials for the regions as a whole, and perhaps substantially so in certain areas. The wet scenario was found to lead to little change or perhaps a slight improvement. Climate change thus seems to enhance current problems of population growth, weather variability, and soil degradation.

However, these models are very data intensive, and their major disadvantage is that complete data sets for parameterising and validating them rarely exist. Also, the models tend to be extremely complex, and a certain level of training and expertise is required to use the model effectively. Lastly, many of the models that have been used in this approach are point models, which require making simplifying assumptions when results are aggregated to the regional level.

Rangeland ecosystem

Currently, there are four well recognised models that have been used under a variety of environmental conditions and geographical locations to simulate the potential effects of climate change, including the effects of atmospheric concentrations of CO_2, on rangeland or pasture ecosystems (Table 9.4). The models either do not have an animal component or the herbivore model has been simplified, thus limiting livestock management options and the analysis of indirect effects of impacts on animal productivity.

Rangeland and livestock

The three models presented in Table 9.5 all contain a pasture or grassland model at the same level of detail as the animal model. As above, these models also simulate the effects of atmospheric concentrations of CO_2 and climate change impacts on the rangelands. The direct effects of climate change on animal production are simulated only by SPUR2. The indirect effects of climate change, reduction in performance due to changes in forage quality and quantity, are simulated by all three models. Only the Hurley pasture model simulates or considers carbon as contributed by methane.

One of the major limitations to all of the animal models listed in Table 9.5 is that they were developed in countries that have a livestock management system vastly different than the nomadic pastoralist systems often found elsewhere in the world. Therefore, adapting these models to this type of situation may be a daunting if not impossible task.

Decision support systems

Decision support system (DSS) models allow the user to examine the potential effects of management decisions in a given system based on a set of decision rules that have been formulated in the model. One such DSS, GRASSMAN, has been used to evaluate the effects of climate on livestock and pasture production as well as to predict changes in emissions and productivity (McKeon et al., 1993; Howden et al., 1994). GRASSMAN is an agricultural decision support model that allows users to investigate the effect and interactions between tree clearing, livestock and pasture management, and climate on pasture condition, animal performance, and paddock financial returns (Scanlan and McKeon, 1990). The model has been modified to include sources, sinks,

and storage of greenhouse gases (CO_2, CH_4, N_2O, CO, and NO) in tropical and sub-tropical savannah woodlands of northern Australia (Howden et al., 1994).

Table 9.4 Rangeland ecosystem models that have been used for climate change impact assessment.

Model	Objective	Management options	Country of origin	Published international application	Advantages/ Disadvantages	Citation
CCGRASS	Evaluate the long-term effects of management and various environmental condition of soil carbon sequestration	Effects of grazing and mowing incorporated from experimental data.	The Netherlands	Unknown at the time of publishing	Well suited for management and climate interaction on soil and plant dynamics. Does not include the effects of herbivores.	Van den Pol van Dasselaar and Lantinga, 1995
CENTURY	Simulate C, N, P, and S dynamics for the plant-soil system for grassland and agricultural production	Seasonal effects of burning and grazing simulated.	United States	Africa, Asia, Europe, North America, and South America	Well suited for studying the long term effects of climate change on biogeochemical cycling; Seems to be very transportable to different regions of the world. Only simplified herbivore routine	Parton et al., 1987. This model has been widely used and cited. Recent review of model in Breymeyer et al., 1996
GEM	Explore the interactions of elevated CO_2 and changes in climate on grassland production, decomposition, and nutrient cycling.	Effects of grazing not simulated as the model is written.	United States	Not at the time of publishing (Personal communication, W. Hunt, NREL, 1997)	Well suited for studying the effects of climate on biogeochemical cycling. Model suited for temperate grasslands. Only simplified herbivore model	Hunt et al., 1991; De-Xing Chen et al., 1996
GRASS	Simulate shoot number, C, and N budget, energy balance, and water budget.	Original model design to assess impact of grazing on African grassland systems	Kenya and United States	Africa and North America	Well suited to African savannahs and grazing. Improved below ground model. Very physiologically based.	Coughenour, 1984 and Breymeyer et al., 1996

Table 9.5 Rangeland livestock production models that have been used for climate change impact assessment.

Model	Objectives	Management	Animal model	Country of origin	Published international applications	Advantages/Disadvantages[a]	Citation
Hurley Pasture Model	Simulate the fluxes of C, N, and water in linked soil, plant, and animal systems	Grazing is simulated	Mature, non-lactating sheep	England and Scotland	Unknown at the time of publishing	Allows for the study of soil-grass-animal interactions. The only model reviewed that has a sheep model. Like all the other models, many parameters are needed.	Thornley and Cannell, 1997
SPUR2	Simulate C and N dynamics for plant-soil system, simulate beef cattle production, and simulates plant herbivore interactions	Simulates simple to complex grazing management schemes. Multi-site or pastures	Contains 2 beef cattle models. A complex life cycle individual cow-calf model and a simple single yearling beef cattle model.	The United States	Asia, North America, and South America	Allows for the simulation of multiple sites, rotational type grazing, and simulates herd dynamics. However, herd model is complicated. Not suited for tropical or phosphorous limited soils.	Hanson et al., 1992
Topp and Doyle Model	Simulate changes above and below ground plant production, simulate grazing and dairy cow production.	Application of fertiliser, mowing, and grazing	Dairy cow production model that simulates growth, milk production, and grazing	Scotland	Unknown at the time of publishing	Allows for the simulation of dairy type cattle. Grass model is well suited for temperate conditions. Unsure of model performance in tropical conditions.	Topp and Doyle, 1996a&b

[a] The authors recommend that the steward of the model be consulted before deciding on the suitability of a particular model.

Integrated models

Integrated models can be considered to be a special case of process-based models in that they usually incorporate some type of process based simulation model with other methods such as GIS or databases or economic models. The objectives of these models are usually to attempt to model regional biophysical and socio-economic processes and interactions simultaneously (Rosenberg, 1993). The site or regional impacts can then be aggregated, where appropriate to regional or global impacts. Examples of this method included the integration of a site specific grassland ecosystem model, CENTURY, and a GIS (Burke et al., 1990); two regional models, CLIMPACTS (New Zealand focus) the US effort VEMAP (Kenny et al., 1995; Kittel et al., 1995); and a global model TEM (Melillo et al., 1993). The International Geosphere-Biosphere Programme's terrestrial transect program provides an excellent example of how many methods may be combined to examine climate driven impacts on terrestrial ecosystems. The transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities organised along existing gradients of underlying global change parameters, such as temperature, precipitation, and land-use. The transects are 1000 kilometres long and are wide enough to encompass the dimensions of remote sensing images. They will be used to determine changes in terrestrial biogeochemical cycling, study the effects of global change on ecosystem composition and structure, and serve as a platform for studying the impacts of global change on various aspects of terrestrial ecosystems, such as production systems, soil processes, and ecological complexity. The initial set of transects are located in four key regions: (1) the humid tropics of the Amazon basin, central Africa, and Southeast Asia; (2) the semi-arid tropics in savannahs of west Africa, Kalahari (southern Africa), and northern Australia; and (3) the mid-latitude semi-arid grasslands of the US Great Plains, the Patagonia of Argentina; and north-eastern China; and (4) the high latitude boreal forest-tundra of Alaska, Canada, Scandinavia, and Siberia (IGBP, 1995).

9.2.1.8 Economic models

Several types of models can be used to evaluate the economic implications of the direct effects (first order impacts) of climate change on rangeland and livestock production systems for local and regional economies. Some of these models use outputs that are collected from the methods describe above as inputs for stand-alone economic models, and others are linked or integrated into biophysical simulation models. Chapter 8 describes relevant economic models in detail.

9.2.2 Selection of the method

Selection of the appropriate method to be used in the analysis is an extremely important step in conducting a meaningful impact analysis. The first and most important step in this process is defining a clear and concise statement of the problem and setting

quantifiable goals and objectives for the assessment. Other issues that need to be considered are:

- Defining the scale, scope, and time horizon of the assessment;
- Assessing the availability, resolution, and quality of the data;
- Assessing the availability of human, technological, and financial resources.

It is important to think about method selection as an iterative process that is based on limiting factors. For example, goals and objectives may be set that require data that are unavailable or the institutional infrastructure may be unable to support computer intensive analyses.

Selection of the appropriate method may also be determined in context of the temporal and spatial resolution of results and time frame for conducting the analysis. The matrix presented in Table 9.6 combines these criteria with a ranking of data and resource needs presented above. Where a range of scores are provided, it is assumed that techniques may range from the very simple to the extremely complex.

9.3 Scenarios

Discussions of socio-economic and climate change scenario development are covered in detail in Chapters 2 and 3, respectively. Regardless of what future climates have in store for the world, establishing climatological and socio-economic baselines is essential for detecting and measuring change.

9.3.1 Climatological baseline

Rangeland ecosystems are event driven systems in that the amount and timing of precipitation, fire, and grazing, as well as other activities, have the capacity to alter the structure and function of the ecosystem. Extreme climatic events such as prolonged droughts or monsoons also have the potential to alter the trajectory of these systems. Therefore, baseline climate data should be from as long a period as possible to capture the frequency of extreme events. The usual climate variables needed for rangeland livestock production systems include temperature, precipitation, solar radiation, wind run, and in some cases humidity. The resolution of the data, maximums and minimums, daily, monthly, seasonal, or yearly averages, will depend on the method or model employed.

Table 9.6 Summary of methods.

Method	Temporal scale of results	Spatial scale of results	Time to conduct analysis	Data needs	Skill or training required[a]	Technological resources	Financial resources $ -Low; $$-Moderate; $$$-High
Experimental	Season to decades	Site	Months to years	Needs little data. The data are generated.	Specialised training in the discipline of study.	Depends on the complexity of the study. Farming Systems oriented research to long term ecological studies.	Dependent on the scope of the project. Can vary from farming systems research to long-term ecological studies. $ to $$$
Screening techniques (including GIS & remote sensing)	Snapshot at a particular time	Site to national	Several week to months. If monitoring changes in systems then possibly years.	Simple screening processes can be accomplished with little data. The purpose is to identify not only risk but also gaps in knowledge and data.	Training required in area of study. GIS and remote sensing techniques require specialised training.	Complexity of the analysis will determine. Simple map, tabular data, personal computers. Even satellite data may be utilised on PC's if technically expertise is available.	Dependent on the complexity of the analysis, techniques being utilised and if equipment is needed. $ to $$
Expert judgement	Years to decades	Site to region	Days, weeks, or a few months	Very little data needed.	Requires wide experience in field of study and good understanding of processes involved.	Little technology is needed.	Depends on the number of consultants being employed and fees being paid for local and international consultants. $ to $$
Analogue	Decades	Site to national	Weeks to months. Depends on the availability of data	Data dependent. The quality and quantity of data must be sufficient to construct a meaningful analogy.	Training required in area of data analysis.	Very little technical resources are needed. Most can be accomplished on a personal computer.	Depends on data availability, personnel, and if additional equipment is needed for the analysis. $$
Empirical-statistical	Season to decades	Site to national	Weeks to months. Dependent on the availability of data.	Requires enough data to construct a meaningful statistical model. For example, data of several decades would be required to capture normal fluctuations in climate data.	Requires specialised training in statistical analyses.	Very little technical resources are needed. Most can be accomplished on a personal computer. Sophistication of necessary software is model dependent.	Depends on data availability, personnel, and if additional equipment is needed for the analysis. $$

9.3.2 Socio-economic baseline

The socio-economic baseline describes the present state of non-climatic factors that affect rangeland livestock production systems. Information needed to establish this baseline may include the following variables: vegetation cover (type and extent); soil characteristics (depth, texture, properties, etc.); estimations of soil organic matter, topography, and mean atmospheric concentration of CO_2 or other trace gases; and other non-climatic environmental variables. Socio-economic factors include land use, water use, management practices (e.g., grazing management schemes), economic factors (e.g., contribution to GNP, price of market outputs such as meat, milk, hide, wool, etc.), food demand, social variables (employment, settlements), structure or land tenure. Socio-economic factors are not likely to remain static; therefore, it is important that baseline conditions of the most important and relevant factors are considered in the assessment.

9.4 Autonomous adaptation

Adaptations may be classified as either autonomous, which usually refers to adjustments made within the system, or planned, which refers to adjustments that are external to the system such as adjustments that are initiated or prompted by public policy (Smit, 1993; Carter et al., 1994). Clearly, rangelands and the people who derive their livelihood from these systems have some degree of inherent adaptability. The degree to which these systems can adapt and remain productive for their defined use depends on the magnitude, timing, frequency, and duration of the disturbance.

Autonomous adaptation in rangeland livestock production systems can be defined in terms of ecological processes and human management decisions. From an ecological standpoint the limit of the system's ability to adapt depends on the rate of change of the disturbance relative to the inherent rate of change in the system and to changes that have occurred during the evolution of the system. The sustainability of the system as a productive source of food for livestock and wildlife is directly related to how human management practices adjust to the disturbance as well.

In terms of human adaptation, the nature and processes of adaptation to climate are poorly understood and rarely directly investigated (Smithers and Smit, 1997). Although the process and nature of adaptation may be elusive given the current state of knowledge, evidence does exist, through the persistence of agricultural practices, that cattle farmers make autonomous changes, both tactically and strategically, to offset the effects of disruptions in the system (Table 9.7).

Table 9.7 Possible types of climate induced autonomous adaptations in rangeland livestock production systems.

Rangeland ecosystems	Shifts in biological diversity Shifts in species composition Shifts in species distribution
Livestock farmers	Change in grazing management (timing, duration, and location) Change in mix of grazers or browsers Change in supplemental feeding Change in location of watering points Change in breeding management Changes in rangeland management practices Change in operation production strategies Change in market strategies

The selection of impact method will determine the type of adaptation analysis that can be performed. Some of the methods will allow for conducting the assessment directly whereas in other cases, the adaptation assessment will have to conducted by using output generated from the impact assessment (Table 9.8).

Table 9.8 Suitability and scale of impact method for adaptation assessment.

Impact analysis method	Suitability for adaptation assessment	Scale of assessment
Expert judgement	Information used to conduct separate assessment	Farm level to national (possibly global)
Analogue	Output used to conduct separate assessment	Regional to national
Empirical-statistical	Output used to conduct separate assessment	Farm level to national
Life zone or bioclimatic model	Output used to conduct separate assessment	Regional to global
Biophysical models, decision support systems, integrated models	Assessment may be conducted within the context of the model	Farm level to global
Economic models	Assessment may be conducted within the context of the model	Farm level to global

In the discussion on the usefulness of experimentation for impact assessment, the statement was made that this method had limited application. However, if improvements are to be made on the estimates of potential impacts of climate change on agriculture, there is a need to know more about the processes in which ranchers perceive and respond to changes in climate (Smit et al., 1996). Perhaps an empirical analysis of autonomous adaptation, such as the method used by Smit et al. (1996), should be included into the impact and adaptation assessment or conducted as a corollary.

9.5 Planned adaptation

Smit et al. (1996) state that a distinction can be made between effects that are direct, short-term changes made in response to climate change, and responses and adaptations that are purposeful and conscious decisions made in reaction to the effects, which alter the nature of farming and regional agricultural systems. The focus of this section is on those strategic adaptations that would change the face of rangeland livestock production for a given region. Adaptations such as these are usually a result of governmental or public policy actions. (However, some of the measures mentioned here could be classified as autonomous agriculturist adaptations as well.) The following lists were compiled from recommendations made by IPCC WG II (1996).

Adaptations that facilitate production under a changing climate. The actions would be undertake by individual ranchers, but incentives, information, and assistance may be provided by governmental agencies.

- use vegetative barriers or snow fences to catch snow and increase soil moisture;
- use windbreaks to protect soil from erosion;
- reduce stocking rates;
- use feed conservation techniques and fodder banks;
- improve nutritional plane by using protein, vitamin, and mineral supplements;
- change in mix of grazing or browsing animals;
- alter animal distribution by the use of mineral blocks, watering points, and fences;
- start weed management program;
- restore degraded areas;
- increase native rangeland vegetation or plant adapted species.

Adaptations that are undertaken by government and are purposeful and strategic, although, they can be either short or long in duration.

- modify price supports and other governmental programs to encourage cattle farmers to respond quickly to climate change such as commodity co-operatives and marketing boards, stabilisation programs and subsidies, and tariffs and other trade barriers;
- develop large-scale watershed projects;

- encourage production in the most efficient area by discouraging the use of marginal lands and protecting areas that are degraded;
- if shifts in location occur, establish new farm to market links if necessary; purchase rights of way before land appreciates;
- prepare for veterinary animal health services for the spread of diseases and parasites;
- develop breeding programs;
- develop agroforestry systems;
- if production is declining, allow for more importation;
- if climate change seriously undermines the viability of the animal production sector, develop support measures to fulfil other social objectives such as food security and preservation of the rural community, induce a movement out of agriculture through macroeconomic policies to assure that employment will be available outside of agriculture, develop policies and institutions that facilitate movement between sectors, create positive incentives for people to leave agriculture, stable economic growth, and provide education.

All adaptive responses to climate change have associated pros and cons that will be experienced biophysically, socially or culturally, and economically. The IPCC WG II on rangelands developed a matrix of possible practices to mitigate the impacts on climate change in rangeland production systems. A modified version of the matrix is presented in Table 9.9.

Table 9.9 Pros and cons of selected adaptation strategies.

Strategy	Biophysical	Social or cultural	Economic	Comment
Reduce stocking rates	Increase in plant cover, soil organic matter, and improve productivity on unhealthy rangelands	Country dependent and the value of animals as a social resource	Depends on the value of livestock products to local and national economies	May require changes in regional or national food production policies
Change the mix of grazing or browsing animals	Potential shift in plant species composition	Country dependent and the cultural value of specific types of animals	Depends on the value of livestock products	In general would produce positive effect through more efficient use of resources
Change animal distribution via mineral supplement blocks	Depends on minerals present in the rangeland	Not appropriate where animals are herded	Cost of purchase and distribution	Generally positive but not applicable to herding systems
Change animal distribution by water points	Developed water source may not be sustainable	May affect territory and property boundaries	Motorised sources too costly	Negative impacts if used to increase stocking rate
Use fences	Benefit to control domestic animals	Country dependent and livestock/wildlife system	Varies depending on country, source, and kind of material used for construction	Potential to interfere with wildlife migration
Use feed supplements	May reduce extensive grazing	Possible where animals are herded	Cost are often large but may increase production may offset cost	Potentially difficult to distribute to local areas
Increase native vegetation or plant adapted species	Benefit in retention of native species for gene conservation	Local people may rely on native species for medicines, etc.	Depends on the value of livestock and wildlife products, and the value of herbal medicine	Potential unknown benefits from native species; adapted species survive over the long term
Use herbicides	Cost if non-target species affected water pollution, damage to food chain	Same as biophysical plus possible removal of firewood sources	Varies depending on country and source of herbicide	Costs or benefits depend on meeting management goals
Implement agroforestry systems	Possible benefit with increased plant cover, diversity, and productivity	Potential benefit with change in grass/browse forage mix for livestock and wildlife	Cost of planting and maintaining	Increases carbon storage in trees; benefit in diversity and productivity if adapted species used
Develop large-scale watersheds	Potential for large land disturbances. Benefit to human and animal populations because of regulated and regular water supply. Harm to aquatic ecosystems	Potential for improved food production for both plants and animals	Costs of dam, etc.; benefit of hydroelectric power	Potential for increased human and animal populations because of increased water availability

Source: IPCC (1996)

9.6 Summary and implications

A variety of methods and modelling approaches have been presented in this chapter to assess the impacts of climate change on rangeland and livestock production systems. The choice of method to be used depends on the goals and objectives of the assessment, the quality and quantity of data available, and the availability of human, technological, and financial resources for the assessment. The scope of the analysis should be limited to those areas where impacts are likely to be the greatest and where the most meaningful analysis can be performed.

Often in climate change impact assessments more time and capital is spent investigating first order biophysical responses to climate driven impacts. The authors wish to stress the importance of spreading resources evenly among the assessment of second order responses to impacts and conducting thorough and meaningful adaptation assessments. Only by carefully assessment and reporting of these higher order effects can the importance of the potential impacts be conveyed to policy makers.

A spatial or geographical dimension is a feature common to most of the outputs or variables that indicate change in the impact analysis. Consequently, a quick and powerful way to display the results of the analysis is through the use of maps. These maps may be created by sophisticated computer GIS software or by hand. Other more conventional methods such as clear and concise charts or table are also useful for presentation of results.

What lies in the future for rangeland and livestock impact analyses? Many studies have been conducted on the potential effects of climate change on rangeland ecosystems. Most of this work has been directed toward examining climate driven impacts on ecological processes in rangelands. As a result, several models have been developed and validated for predicting changes in rangeland ecosystem processes.

However, by comparison, little work has been done to assess the effects of climate change on livestock production in rangeland ecosystems. The majority of the studies that have included livestock have been conducted in developed countries. Consequently, the models used in these studies tend to reflect the conditions and assumptions that exist in these more intensively managed production schemes. There is a definite need for the development of a robust model or suite of models that can be used to examine climate impacts on livestock and rangelands over a wide range of environments and management practices. These models should be developed in such a manner that output variables would be meaningful and useful as inputs to economic, socio-economic, and adaptation assessment analyses. The development of such methods will improve our ability to assess the future of the people whose livelihoods depend on the sustainability of rangelands.

Table 9.10 Documentation and source for grassland and grassland/livestock models.

Model name	CCGRASS Carbon Cycle of Grasslands
Model type	Mechanistic simulation model
Model purpose	To simulate the carbon cycle of grassland soils. Simulates the effect of atmospheric concentrations of CO_2 on biogeochemical processes
Citation information	Van den Pol van Dasselaar and Lantinga, 1995
Model developer	A. Van den Pol van Dasselaar
Model validated	Yes
Model input data requirements	Site specific data (above and below ground C, N application, mowing and grazing regimes) and climate data
Model output data	Carbon fluxes
Temporal scale	annual to several decades
Spatial scale	Site
Programming language	
Computer requirements	
Agency	Wageningen Agricultural University
Office location	Wageningen, The Netherlands
Office name	Dept. of Theoretical Production Ecology
Contact	A. Van den Pol van Dasselaar
Title	
Address	P.O. Box 430, NL-6700 AK Wageningen, The Netherlands
Telephone	
Fax	
E-mail	

Model name	Century
Model type	Predictive, simulation, process, deterministic
Model purpose	Analysis of soil organic matter dynamics in response to changes in management and climate
Citation information	Parton, et. al., 1987
Model developer	W.J. Parton et al. Agricultural Research Service and CSU support through NREL
Model validated	Yes
Model input data requirements	Driving variables: monthly mean max. and min. air temperatures, mean precipitation. State variables: soil texture, soil depth, vegetation types, management system type (e.g., grasslands, agroecosystems, forest), CO_2 levels, and C14 enrichment.
Model output data	Carbon, nitrogen, and phosphorous fluxes, net primary production, seasonal organic matter
Temporal scale	One month to thousands of years
Spatial scale	point model (1 square meter)
Programming language	FORTRAN 77, possibly recoding to C, DOS, and UNIX versions
Computer requirements	Information available from Bill Parton
Agency	Colorado State University
Office location	Fort Collins, CO, USA
Office name	Natural Resource Ecology Laboratory
Name	Bill Parton
Title	Senior Ecologist
Address	NREL, Colorado State University, Fort Collins, CO 80523 USA
Telephone	970-491-1987

Table 9.10 Documentation and source for grassland and grassland/livestock models - continued.

Model name	GEM and GEM2 Grassland Ecosystem Model
Model type	Predictive, simulation, process, deterministic
Model purpose	Interprets the results of field experiments on two different grassland ecosystems (native shortgrass prairie C4 and old stand of introduced perennial C3). Explores interactions of elevated CO_2, and elevation of temperature on grassland production, decomposition, and nutrient cycling.
Citation information	Hunt et al., 1991 (GEM); De-Xing et al., 1996 (GEM2)
Model developer	H.W. Hunt
Model validated	Yes
Model input data requirements	Driving variables: daily precipitation, weekly max. and min. air temperatures, wind speed, relative humidity, monthly mean soil temperatures. State variables: soil and inorganic ammonium nitrate data. Other data requirements for other situations, e.g., growth parameters
Model output data	State variables versus time (can be short-term weekly, or long-term). Main focus is seasonal
Temporal scale	
Spatial scale	Point model
Programming language	FORTRAN 77 6600 lines of code
Computer requirements	Sun SPARC1
Agency	Colorado State University
Office location	Fort Collins, Colorado, USA
Office name	Natural Resource Ecology Laboratory
Name	H. William Hunt
Title	

Model name	GRASS
Model type	Ecophysiologically processed based simulation model
Model purpose	Simulates physiological and morphological traits of plants, tillering and C and N budgets, light penetration, and soil water and heat budgets. Originally developed to simulate the effects of grazing on African grasslands. Effects of atmospheric CO_2 simulated
Citation information	Coughenour, 1984
Model developer	M.B. Coughenour
Model validated	Yes
Model input data requirements	driven daily weather data and initial conditions for state variables
Model output data	C and N fluxes, net primary production, seasonal organic matter
Temporal scale	time step of two hours for diurnal processes and two days for other plant growth processes. One month to decades
Spatial scale	Point or site model
Programming language	FORTRAN
Computer requirements	Personal computer
Agency	Colorado State University
Office location	Fort Collins, CO USA
Office name	Natural Resource Ecology Laboratory
Name	Michael Coughenour
Title	Senior Research Scientist
Address	NREL, Colorado State University, Fort Collins, CO 80523 USA
Telephone	970-491-5572
Fax	970-491-1965

Table 9.10 Documentation and source for grassland and grassland/livestock models - continued.

Model name	Hurley Pasture Model
Model type	A generic ecophysiologically processed based simulation model
Model purpose	To simulate the fluxes of carbon, nitrogen, and water in a grazed soil-pasture-atmosphere system, coupling the C an N fluxes, and modulating the fluxes by the plant and soil water status.
Citation information	Thornley and Cannell, 1997
Model developer	J.H.M. Thornley
Model validated	yes
Model input data requirements	Latitude, N input, windspeed, relative humidity, photosynthetically active radiation, air temp, soil temp, precip., stocking rate for sheep. [Plant submodel: 21 state variables and 60 parameters; Soil and Litter submodel: 15 state variables and 68 parameters; Animal submodel: 2 state variables and 9 parameters; Water submodel: 3 state variables and 40 parameters]
Model output data	C and N fluxes and state variables versus time:
Temporal scale	yearly to decades
Spatial scale	site
Programming language	unknown at time of publishing
Computer requirements	unknown at time of publishing
Agency	Institute of Terrestrial Ecology
Office location	
Office name	
Name	Dr. J.H.M. Thornley
Title	
Address	Bush Estate, Penicuik, Midlothian, EH26 0QB, UK

Model name	SPUR — Simulating Production and Utilization of Rangelands (version 2.0)
Model type	Predictive, simulation, process, deterministic
Model purpose	To determine and analyse management scenarios as they affect rangeland sustainability. Examines the effect of climate change on livestock production and grassland productivity.
Citation Information	Hanson et al., 1992
Model developer	Jon Hanson
Model validated	Yes
Model input data requirements	Driving variables: daily precipitation, max. and min. air temperatures, wind run and solar radiation. State variables: soil and plant data, CO_2 levels, animal performance data. See simulation set-up handbook
Model output data	State variables versus time plant and soil carbon and nitrogen, animal production data
Temporal scale	Daily time step; 1 to 80 years
Spatial scale	Point model applied up to 36 sites
Programming language	FORTRAN 77 (enhanced) 20,000 lines of code
Computer requirements	minimum requirements 486 CPU and 8 MB RAM
Agency	Agricultural Research Service
Office location	Fort Collins, Colorado USA
Office name	Great Plain Systems Research Unit
Name	Jon Hanson
Title	Supervisory Range Scientist
Address	USDA, ARS, NPA P.O. Box E , Fort Collins, CO 80522 USA

Table 9.10 Documentation and source for grassland and grassland/livestock models - continued.

Model name	Topp and Doyle Model
Model type	Predictive, simulation, process, deterministic
Model purpose	Simulate pure grass and grass-white clover swards. Examine the effects of changes in temperature and precipitation regimes and CO_2 on herbage production. Simulate grazing by dairy cattle. Examine the effects that changes in temperature and precipitation regimes and CO_2 may have on milk production and silage conservation.
Citation information	Topp and Doyle (1996a &b)
Model developer	Cairistiona Topp and Christopher Doyle
Model validated	yes
Model input data requirements	Five driving variables, mean daily temperature, photosynthetically active radiation, atmospheric [CO_2], available moisture, and available nitrogen. Initial conditions for 5 plant model state variables. For the animal model there are 8 state variables.
Model output data	State variables versus time plant and animal production data
Temporal scale	Daily
Spatial scale	Site
Programming language	Unknown at the time of publishing
Computer requirements	Unknown at the time of publishing
Agency	The Scottish Agricultural College
Office location	
Office name	
Name	Cairistiona Topp and Christopher Doyle
Title	
Address	Auchincruive, Ayr KA6 5HW, UK

References

Antle, J.M. 1995. Climate change and agriculture in developing countries. *American Journal of Agricultural Economics* 77, 741-746.

Baker, B.B., and J.D. Hanson. 1993. Simulating the effects of climate change on beef cattle production: A methodology for determining simulation sites. In *Proceedings of 46th Annual Meetings, Society Range Management.* pp. 9-10.

Baker, B.B., J.D. Hanson, R.M. Bourdon, and J.B. Eckert. 1993. The potential effects of climate change on ecosystem processes and cattle production on U.S. rangelands. *Climatic Change* 25, 97-117.

Bergthorsson, P. 1985. Sensitivity of Icelandic agriculture to climatic variation. *Climatic Change* 7, 111-127.

Breymeyer, A.I., D.O. Hall, J.M. Melillo, and G.I. Ågren (eds). 1996. *Global Change: Effects on Coniferous Forests and Grasslands.* Scientific Committee on Problems of the Environment 56, John Wiley & Sons, Chichester, United Kingdom.

Burke, I.C., D.S. Schimel, C.M. Yonker, W.J. Parton, L.A. Joyce., and W.K. Lauenroth. 1990. Regional modeling of grassland biogeochemistry using GIS. *Landscape Ecology* 4, 44-54.

Carter, T.R., M.L. Parry, S. Nishioka, and H. Harasawa. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* University College, London, and Center for Global Environmental Research, Tsukuba, Japan.

Coughenour, M.B. 1984. A mechanistic simulation analysis of water use, leaf angles, and grazing in east African graminoids. *Ecological Modelling* 26, 203-230.

De-Xing Chen, H.W. Hunt, and J.A. Morgan. 1996. Responses of a C_3 and C_4 perennial grass to CO_2 enrichment and climate change: Comparison between model predictions and experimental data. *Ecological Modelling* 87, 11-27.

Du Preez, J.H., W.H. Giesecke, and P.J. Hattingh. 1990. Heat stress in dairy cattle and other livestock under southern African conditions. I. Temperature-humidity index mean values during the four main seasons. *Onderstepoort Journal of Veterinary Research* 57, 77-89.

Easterling, W.E., N.J. Rosenberg, M.S. McKenney, and C.A. Jones. 1992. An introduction to the methodology, the region of study, and a historical analog of climate change. *Agricultural and Forest Meteorology* 59, 3-15.

Eckert, J.B., B.B. Baker, and J.D. Hanson. 1995. The impact of global warming on local incomes from range livestock systems. *Agricultural Systems* 48, 87-100.

Gonzàlez-Meler, M.A., B.G. Drake, and J. Azcón-Bieto. 1996. Rising atmospheric carbon dioxide and plant respiration. In *Global Change: Effects on Coniferous Forests and Grasslands*, A.I. Breymeyer, D.O. Hall, J.M. Mellilo, and G.I. Ågren (eds), Scientific Committee on Problems of the Environment 56, John Wiley & Sons, Chichester, United Kingdom, pp. 161-181.

Hall, D.O., D.S. Ojima, W.J. Parton, and J.M.O. Scurlock. 1995. Response of temperate and tropical grasslands to CO_2 and climate change. *Journal of Biogeography* 22, 537-547.

Hammond, A., A. Adriaanse, E. Rodenberg, D. Bryant, and R. Woodward. 1995. *Environmental Indications: A Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development.* World Resources Institute, New York.

Hanson, J.D., B.B. Baker, and R.M. Bourdon. 1992. *SPUR2 Documentation and User's Guide*. U.S. Department of Agriculture, ARS, Great Plains Systems Research Technical Report-1, Fort Collins, Colorado, USA.

Hassan, H.M. and C. Hutchinson (eds). 1992. *Natural Resource and Environmental Information for Decision Making.* The World Bank, New York.

Holdridge, L.R. 1967. *Life Zone Ecology.* Tropical Science Centre, San Jose, California, USA.

Howden, S.M., D.H. White, G.M. McKeon, J.C. Scanlan, and J.O. Carter. 1994. Methods for exploring management options to reduce greenhouse gas emissions from tropical systems. *Climatic Change* 27, 49-70.

Hulme, M. (ed). 1996. *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region.* Climate Research Unit,

University of East Anglia, Norwich, United Kingdom, and WWF International, Gland, Switzerland.

Hunt, H.W., M.J. Trlica, E.F. Redente, J.C. Moore, J.K. Detling, T.G.F. Kittle, D.E. Walter, M.C. Fowler, D.A. Klein, and E.T. Elliot. 1991. Simulation model for the effects of climate change on temperature grassland ecosystems. *Ecological Modelling* 53, 205-246.

IGBP. 1992. *Global Change. Reducing the Uncertainties.* International Geosphere-Biosphere Programme, Stockholm, Sweden.

IGBP. 1995. *The IGBP Terrestrial Transects: Science Plan*. Global Change Report No. 36. International Geosphere-Biosphere Programme, Stockholm, Sweden.

IPCC. 1996. *Climate Change 1995. Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution f Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* R.T. Watson, M.C. Zinyowera, R.H. Moss (eds). Cambridge University Press, Cambridge.

Kenny, G.J., R.A. Warrick, N.D. Mitchell, A.B. Mullan, and M.J. Salinger. 1995. CLIMPACTS: an integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography* 22, 883-895.

Kittel, T.G.F., N.A. Rosenbloom, T.H. Painter, D.S. Schimel, and VEMAP Modelling Participants. 1995. The VEMAP integrated database for modelling United States ecosystem/vegetation sensitivity to climate change. *Journal of Biogeography* 22, 857-862.

Li Xia. 1995. Modelling the response of vegetation in North-East China transect to global change. *Journal of Biogeography* 22, 515-522.

Linstone, H. and M. Turoff (eds). 1975. *The Delphi Method: Techniques and Applications.* Addison-Wesley Publishing Company, Reading, Massachusetts, USA.

Long, S.P., C.P. Osborne, and S.W. Humphries. 1996. Photosynthesis, rising atmospheric carbon dioxide concentration and climate change. In *Global Change: Effects on Coniferous Forests and Grasslands,* A.I. Breymeyer, D.O. Hall, J.M. Mellilo, and G.I. Ågren (eds), Scientific Committee on Problems of the Environment 56, John Wiley & Sons, Chichester, United Kingdom, pp. 122-159.

McKeon, G.M., S.M. Howden, N.O.J. Able, and J.M. King. 1993. Climate change: adapting tropical and sub-tropical grasslands. In *Proceeding of the XVIIth International Grassland Congress,* Palmerston North, New Zealand, pp. 1181-1190.

Melillo, J.M. 1996. Elevated carbon dioxide, litter quality, and decomposition. In *Global Change: Effects on Coniferous Forests and Grasslands,* A.I. Breymeyer, D.O. Hall, J.M. Mellilo, and G.I. Ågren (eds), Scientific Committee on Problems of the Environment 56, John Wiley & Sons, Chichester, pp. 199-206.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore, III, C.J. Vörösmarty, and A.L. Schloss. 1993. Global climate change and terrestrial net primary production. *Nature* 363, 234-240.

Norton-Griffiths, M. 1988. Aerial point sampling for landuse surveys. *Journal of Biogeography* 15, 149-156.

Ojima, D.S., T.G.F. Kittel, T. Rosswall, and B.H. Walker. 1991. Critical issues for understanding global change effects on terrestrial ecosystems. *Ecological Applications* 3, 316-325.

Parry, M.L., and T.R. Carter. 1989. An assessment of the effects of climate change on agriculture. *Climatic Change* 15, 95-116.

Parry, M.L., T.R. Carter, and N.T. Konijn (eds). 1988. *The Impact of Climatic Variations on Agriculture Volume 2: Assessments in Semi-Arid Regions.* Kluwer, Dordrecht, The Netherlands.

Parry, M.L., J.H. Porter, and T.R. Carter. 1990. Agriculture: Climate change and its implications. *TREE* 5(9), 318-322.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science American Journal* 51, 1173-1179.

Paustian, K., E.T. Elliot, H.P. Collins, C.V. Cole, and E.A. Paul. 1995. Use of a network of long-term experiments for analysis of soil carbon dynamics and global change: The North American model. *Australian Journal of Experimental Agriculture* 35, 929-39.

Prendergast, B.J. and P.W. Hattersley. 1985. Distribution and cytology of Australian Neurachne and its allies (Poaceae), a group containing C3, C4, and C3-C4 intermediate species. *Australian Journal of Botany* 33, 317-336.

Rizzo, B. and E. Wiken. 1992. Assessing the sensitivity of Canada's ecosystems to climate change. *Climatic Change* 21, 37-55.

Rosenberg, N.J. (ed). 1993. Towards an integrated impact assessment of climate change: The MINK study. *Climatic Change* (Special Issue) 24, 1-173.

Scanlan, J.C. and G.M. McKeon. 1990. *GRASSMAN*. Queensland Department of Primary Industries, Brisbane, Queensland, Australia.

Shaver, G.R. and J.D. Aber. 1996. Carbon and nutrient allocation in terrestrial ecosystems. In *Global Change: Effects on Coniferous Forests and Grasslands,* A.I. Breymeyer, D.O. Hall, J.M. Mellilo, and G.I. Ågren (eds). Scientific Committee on Problems of the Environment 56, John Wiley & Sons, Chichester, United Kingdom, pp. 183-198.

Smit, B.D. 1993. *Adaptation to Climatic Variability and Change: Report of the Task Force on Climatic Adaptation.* Canadian Climate Program Board Department of Geography, University of Guelph, Occasional Paper No. 19. Environment Canada, Downsview, Ontario.

Smit, B., D. McNabb, and J. Smithers. 1996. Agricultural adaptations to climatic variation. *Climatic Change* 33, 7-29.

Smithers, J. and B. Smit. 1997. Human adaptation to climatic variability and change. *Global Environmental Change* 7(2), 129-146.

Steffen, W.L. and J.S. Ingram. 1995. Global change and terrestrial ecosystems: an initial integration. *Journal of Biogeography* 22, 165-174.

Stem, E., G.A. Mertz, J.D. Stryker, and M. Huppi. 1989. Changing animal disease patterns induced by the greenhouse effect. In *The Potential Effects of Global Change on the*

United States: Appendix C — Agriculture, Volume 2. J. Smith and D.A. Tirpack (eds). US Environmental Protection Agency, Washington, D.C., pp. 11-1 to 11-38.

Tate, K.R., A. Parshotam, and D.J. Ross. 1995. Soil carbon storage and turnover in temperate forests and grasslands — a New Zealand perspective. *Journal of Biogeography* 22, 695-700.

Thornley, J.H.M. and M.G.R. Cannell. 1997. Temperate grassland responses to climatic change: An analysis using the Hurley Pasture Model. *Annals of Botany* 80, 205-221.

Topp, C.F.E. and C.J. Doyle. 1996a. Simulating the impact of global warming on milk and forage production in Scotland: 1. The effects on dry matter yield of grass and grass-white clover stands. *Agricultural Systems* 52 (2/3), 213-242.

Topp, C.F.E. and C.J. Doyle. 1996b. Simulating the impact of global warming on milk and forage production in Scotland: 2. The effects on milk yields and grazing management of dairy herds. *Agricultural Systems* 52 (2/3), 243-270.

Van den Pol van Dasselaar, A. and E.A. Lantinga. 1995. Modelling the carbon cycle of grassland in the Netherlands under various management strategies and environmental conditions. *Netherlands Journal of Agricultural Science* 43, 183-194.

Viglizzo, E.F., Z.E. Roberto, M.C. Filippín, and A.J. Pordomingo. 1995. Climatic variability and agroecological change in the Central Pampas of Argentina. *Agriculture, Ecosystems, and Environment* 55, 7-16.

Viglizzo, E.F., Z.E. Roberto, F. Lértora, E. López Gay, and J. Bernardos. In press. Climate and land-use change in field-crop ecosystems of Argentina. *Agriculture, Ecosystems, and Environment.*

Walker, B. 1994. Global change strategy options in the extensive agricultural regions of the world. *Climatic Change* 27, 39-47.

Wang Futang and Zhao Zong-Ci. 1995. Impact of climate change on natural vegetation in China and its implication for agriculture. *Journal of Biogeography* 22, 657-664.

WRI. 1996. *World Resources, 1996-1997.* World Resources Institute, Oxford University Press, New York and Oxford.

10 Human Health

Lead Author
John M. Balbus [1]

Contributing Authors
Menno Bouma, UK
Sari Kovats, UK
David LeSueur, South Africa
W.C. Martens, The Netherlands
Jonathan Patz, USA

10.1 Nature of the problem

Health is defined by the constitution of the World Health Organization as "a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity" (WHO, 1946). The sustainable health of human populations is an integrating measure of our long-term environmental and ecological stewardship. Environmental degradation, whether from chemical contamination or other forms of ecosystem disruption, can affect both acute and chronic human health problems. Thus, human health should be considered one essential criterion of the "dangerous interference" with the climate system that is described in Article 2 of the UNFCCC. The ability to assess the human health impacts of climate change, however, is still at a very early stage of development.

There are a number of reasons for this relative scarcity of well-developed methods for the assessment of health impacts from climate change. Since the germ theory of medicine acquired dominance in Western thought in the nineteenth century, the focus of health research has been on specific agents of disease and methods of combating them. Understanding the relations between environmental factors such as climate and human diseases has received less emphasis than understanding in exquisite detail the biochemical workings of pathogens and the drugs created to control them. As a

1 George Washington University, Washington, D.C., USA.

consequence, our ability to describe and simulate the interactions between climate and other environmental factors and human diseases is very limited.

Research methods in human health differ from those in the physical sciences. Much of the data required for other sectors are measurements of physical states such as water flow rates or chemical composition. Even where data types are similar, significant differences remain: one example is that acquisition of data in health research depends on human behaviours and co-operation. Consider the following: determining the level of disease in an agricultural product or in a human population involves sampling. In a human population, however, that sampling requires extensive co-operation of many individuals, whether they are subjects who must co-operate with an interview or medical test, or health providers who must accumulate and submit measurements of diseases during their work day. Sampling an agricultural product either in the field or during production is comparatively simpler. This makes the acquisition of similar types of data much more expensive, difficult to do, and inherently uncertain for health as compared to the other sectors. This barrier alone impedes the progress of high quality research in health-environment interactions.

Lastly, human health is arguably more complex than most of the outcomes of other sectors. In most cases, health outcomes cannot be simply correlated with climate factors. Numerous other factors such as the level of economic development, state of sanitation and public health systems, and group and individual behaviour have a significant effect on human health. Understanding the interactions among these factors, climate variables, and human health in the present day is a difficult task. Being able to predict how these interrelated factors will change in the future and then analysing their effects on future climate changes and human health is a daunting task. This difficulty is compounded by the fact that anticipated climate changes are beyond the range of observable events for most areas (McMichael, 1993)

As a result, this chapter differs from other sectoral chapters. It is not possible to place before the reader an array of methods that have already been developed and applied for predicting impacts. Rather, a suggested approach to performing a comprehensive impact assessment for human health is offered and some general principles of climate impacts on health are explained. Next, methods that are being used to gain insight into relations between climate and human health are described. These methods should not be considered capable of providing predictions of human health under conditions of climate change. This chapter is intended to assist the handbook user in two different tasks: first, to provide a short-term answer to what the health impacts of climate change might be for a particular country or region, and second, to begin laying the foundation for greater understanding of climate-health interactions through acquisition of relevant data and development of research capability.

At the outset, two points must be emphasised. Because of the uncertainty regarding predictions of human health, resources should be devoted to understanding current serious human health problems and how they may be affected by climate change. Similarly, adaptation measures should be relevant to the current situation, and not be based solely on predictions of future events. Second, the past two decades have demonstrated the suddenness with which health problems may emerge. Diseases such as

AIDS, the Central and South American cholera outbreak, and the hantavirus pulmonary syndrome could not have been predicted prior to their emergence. While it is essential to ensure that public health measures for climate change have relevance for current problems, it is equally essential that countries enhance their ability to detect and react to unforeseen health problems. Public health and biological surveillance and monitoring will be a critical element of any national plan for human health impacts of climate change (see Levins et al., 1994).

Recent articles and monographs have described the range of human health problems that may be affected by climate change (McMichael et al, 1996a; McMichael et al., 1996b; Patz et al., 1996) and these effects are summarised in Table 10.1. Some countries have also undertaken national reviews of potential health impacts (e.g., Longstreth, 1989; NHMRC, 1991; CCIRG, 1996). One of the major impacts of climate change on health may be changes in the transmission of vector-borne diseases. A comparison of the public health impact and likely climate sensitivity of the major vector-borne diseases appears in Table 10.2.

Table 10.1 Summary of anticipated direct and ecosystem-mediated effects of global climate change.

Environmental alteration	Direct health effects	Ecosystem-mediated health effects
Higher temperatures and altered precipitation patterns	Increased heat -related mortality and morbidity.	Changes in distribution and seasonal transmission of vector-borne diseases.
	Increase in photochemical and possibly other forms of air pollution, with resulting increase in respiratory illness.	Increase in toxic algal blooms and possibly in transmission of water-borne diseases.
	Increased frequency of floods, storms, and natural disasters.	Decreased agricultural production and food shortages.
Sea level rise	Loss of habitable land, contaminated freshwater supplies, damage to public health infrastructure.	Decreased fish stocks due to loss of coastal wetlands.

Tables 10.1 and 10.2 do not represent all possible climate-related health problems. For example, moulds producing food spoilage or direct toxicity may become more prevalent, and respiratory illness caused by plant pollens may shift in geographic distribution or seasonality because of climate change. Country teams should rely on their internal expertise, and consider Tables 10.1 and 10.2 to be guidelines in assessing the possible health impacts of climate change.

Table 10.2 Estimated impacts of climate change on major vector-borne diseases around the world (after McMichael et al., 1996b).

Disease	Population at risk (millions)	Number infected or new cases per year	Present distribution	Possible change of distribution as a result of climate change
Malaria	2400	300-500 million	tropics/subtropics	+++
Schistosomiasis	600	200 million	tropics/subtropics	++
Lymphatic filiariases	1094	117 million	tropics/subtropics	+
African trypanosomiasis	55	250-300 000 cases/year	tropical Africa	+
Dracunculiasis	100	100 000 cases/year	tropics (Africa/Asia)	?
Leishmaniasis	350	12 million infected, 500,000 new cases/year	Asia/Southern Europe/ Africa/ South America	+
Onchocerciasis	123	17.5 million	Africa/Latin America	++
American trypanosomiasis	100	18-20 million	Central and South America	+
Dengue	2500	50 million	tropics/subtropics	+
Yellow fever	450	<5000 cases/year	Africa/Latin America East/Southeast Asia	+

10.2 Selection of health impacts

The WHO definition emphasises that assessing health impacts requires more than merely predicting future incidence of specific diseases. Deleterious effects of altered climate on the foundations of public health (i.e., nourishing food, safe and adequate drinking water, and secure shelter) need to be considered in addition to changes in specific diseases. This will require input from other sectors performing parallel impact analyses, such as agriculture (Chapter 8), coastal zones (Chapter 7), and water resources (Chapter 6). Changes in these fundamental public health factors may drastically alter a population's susceptibility to a number of diseases, both climate sensitive and climate insensitive. While such comprehensiveness of analysis makes the process more difficult, it is essential to integrate these fundamental health factors into the overall assessment to be able to formulate relevant responses.

The following is a possible sequence of initial steps in a comprehensive health impact assessment.

1. Review major national or regional causes of morbidity and mortality, especially infectious diseases. For infectious diseases, any geographic boundaries (such as those between areas of endemic and epidemic transmission, or between areas of epidemic transmission and no known disease) should be noted. National experts in public health should be consulted for opinions on reasons for such boundaries (i.e.,

is disease transmission limited by climate factors such as temperature or precipitation?).

2. Identify populations at risk. This would include refugee and migrant populations, populations with marginal nutritional reserves or safe water supplies, populations with poor sanitation infrastructure, populations in low-lying coastal areas, and non-immune populations bordering zones of infectious diseases.

3. Review results of other sectoral climate change impact assessments. Specifically, results from water resources, agriculture, forestry, coastal zones, and economic assessments should be assessed for impacts on:
   a. supplies of food and water;
   b. habitability of low-lying areas; and
   c. economic future of currently vulnerable or impoverished regions and populations.

4. Integrate the information gathered thus far. From this information, the existence of critical areas can be proposed. Similarly, the potential for populations fleeing uninhabitable or economically non-viable areas, with attendant health problems, can be assessed. Conversely, positive impacts on health (such as might be seen because of a decrease in seasonal rainfall in an area in which malaria is dependent on such rainfall) may also be assessed at this point.

10.2.1 Selection of health impacts, populations, and regions

Once the initial assessment is completed, the need for further study should be addressed. The direction of further study will be determined by the types of health problems identified in the initial assessment and the current status of understanding and data collection for a specific disease system and a specific area. For example, further study of health problems related to heat mortality and morbidity, if this is identified as an area of concern, may involve the application of existing models to region-specific data in a relatively straightforward way. Further study to quantify impacts on malaria or dengue fever, however, should be directed by the level of analysis already performed on those diseases in a specific area. For example, the ability to apply quantitative models to malaria in Africa has been limited by the lack of geographically referenced (georeferenced) data on disease incidence or even vector density (see Box 10.1). Before accurate quantitative estimates of the future can be made, accurate quantitation of historical and current disease dynamics is essential. Therefore, collection of such data may be the most useful form of further study for those regions. Where baseline data and validated models of the current situation exist, further study may involve extrapolation of the existing models or application of integrated models. Because of the time, money, and expertise required for such studies, decision makers should consider alternatives carefully before embarking on a specific direction for further study.

Box 10.1 Example: Building a georeferenced data base for Africa: The MARA/ARMA Collaborative

One of the greatest weaknesses with the current status of climate change research is that the building blocks are not in place for it to move beyond the scenario stage. The lack of adequate, spatially georeferenced, disease data sets means that existing models attempting to define current distribution remain invalidated. Following on from this is the conclusion that climate change impacts in the future will not be assessed because no baseline of existing conditions against which to quantify impacts is available. Similarly, the resolution and temporal detail of spatial climate data sets suitable for accurately defining existing conditions remain a limitation.

To overcome the limitations of adequate surveillance systems for malaria in Africa, the Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique (MARA/ARMA) collaboration has used the parasite ratio (percent infected) in surveys of children as a marker of intensity of transmission. The entire initiative has to date been operating on only 50 percent of the originally proposed budget. Only $235 000 has been secured (International Development and Research Centre, Canada; South African Medical Research Council; and Wellcome Trust). Thus activities have restricted country visits by regional data co-ordinators. Visit are essential as initial activities indicate that up to 71 percent of data is unpublished (Le Sueur, 1997; Omumbo et al., in press,).

To establish MARA/ARMA, the continent was sub-divided to establish five regional centres. A number of steps were taken to ensure uniformity of activities of the geographically dispersed centres:

A standardised 11 page pro forma and a set of operating procedures were compiled to guide the data co-ordinators.

Different regional centres were using different database applications (Dbase, MSAccess, Foxpro); thus, to ensure standardisation, a stand-alone application conforming to the pro forma was created with MSAccess/Visual Basic. A users guide was also developed.

Central to MARA/ARMA is the ability to geo-reference collected data within a completed pro forma. To facilitate this, two steps had to be carried out:

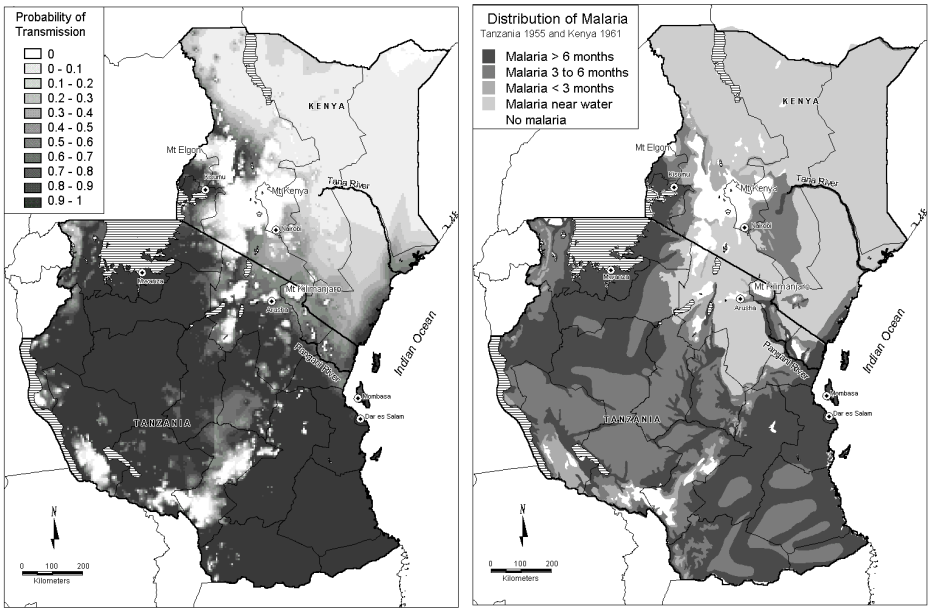
The data co-ordinators were brought to Durban and trained in the use of a vector GIS package (Mapinfo). This was done using a customised manual compiled by the co-ordinating centre in Durban, which uses local malaria data sets for the training exercises.

Continental digital data sets which were capable of supporting the geo-referencing procedures within Mapinfo were acquired. These then were converted into Mapinfo format for use by the data co-ordinators. These include data sets such as the African Data Sampler, which includes administrative boundaries, populated centres, rivers, roads, etc., and GeoName, an electronic gazetteer of place names.

A copy of all completed pro formas and a digital copy were then forwarded to the co-ordinating centre in Durban.

To date, over 2000 independent parasite surveys in children aged 1-9 have been collated. In addition, incidence data and other associated data (drug resistance, vector distribution, agricultural practice, etc.) have been collected. These data as well as data defining historical distribution are being used to define the boundaries of malaria transmission within Africa. Current models are based upon long-term mean interpolations (Hutchinson, 1995) and use the raster GIS package IDRISI. However, recently, new annual surfaces have been commissioned by MARA/ARMA which allow the periphery of distribution to be more accurately defined in terms of spatio-temporal (inter-annual) variation (New and Hulme, 1997). Inherent in the above is the fact that the numerical-eco-physiological models defining the limits of distribution are validated. The figure illustrates the validation of such a model derived from climatic data (Craig et al, in preparation) and in terms of existing country level maps of distribution.

Thus the MARA/ARMA collaboration has demonstrated that despite geographic dispersion, a methodology for creating a database can be successfully instituted; in the future, this will allow the issue of the impact of climate change on malaria in Africa to be moved beyond the scenario level. The MARA/ARMA collaboration with its existing skills and methodology also has the potential to serve as a vehicle for collecting data important to other African diseases.



Box 10.1, Figure 1 Comparison of climate based numeric distribution model and existing country specific malaria maps.

Further study of other health problems such as water-borne diseases or diseases related to environmental refugeeism may be limited by complexity or lack of current understanding. Additional analysis may be limited to comparison with historical and geographical analogues. In general, it is suggested that the decision to perform further analysis be guided by an estimation of the overall public health impact of the problem to be studied as well as the usefulness of the additional information obtained by quantitative study over and above the initial qualitative assessment.

The selection of populations and areas to be studied further will be driven by two factors: the vulnerability of that population or area to climate change and the availability of relevant data. Ideally, data will be available for the population or area determined in the initial assessment to be most at risk from specific impacts of climate change. If not, a decision must be made of whether to invest resources in developing data for the most vulnerable population or area or in conducting the analysis on a population or other health problem that may not be the most critical.

An example of a critical geographic area would be the land at the edge of an endemic zone for vector-borne diseases. In this area, small changes in temperature or rainfall may promote disease transmission to the extent that the disease becomes endemic. For example, in East Africa, there are regions where malaria is endemic in the lowlands.

The highlands surrounding these endemic zones experience unstable epidemic malaria when small local environmental or climate changes allow disease transmission within vulnerable, non-immune populations. These highlands are thus critical areas, where further studies (as well as surveillance and monitoring efforts) will need to be focused.

10.2.2 Selection of time scales

It is unlikely that one time frame will be appropriate for the entire health impact assessment. Rather, a variety of time frames may be more useful. Because of the increasing uncertainty inherent in long time frames (i.e., 2050 scenarios), short-term, incremental analyses (i.e., 5 year steps) may be of more use to policy makers.

For many human disease systems, a threshold exists, such that once a given mean or minimum temperature is reached, a significant change in disease transmission occurs. Thresholds may exist for precipitation levels as well. The time it takes to reach a threshold will depend on a number of factors, including the inertia of the climate system and the response times of different levels of ecosystems. In some cases, it may be more appropriate to determine the threshold for changes in disease transmission, and then determine a range of time frames for that threshold to be reached.

Health impacts may occur rapidly with small climate changes if the relevant climate factor is the only limitation on the range of disease transmission. For example, the transmission of dengue at higher altitudes with increases in temperature is an effect seen within months of extreme climate variability (Herrera-Basto et al., 1992). Alternatively, changes in the incidence of diseases related to sea water temperature (toxic algal blooms, shellfish poisoning) may lag changes in air temperatures by years because of slower warming of the oceans.

The time scale of data collected for the analysis of regional sensitivity of diseases to climate change will also vary depending on the data available and the health impact studied. For example, assessment of heat mortality requires daily data. The study of infectious diseases, however, will usually require weekly or monthly incidence and climate data.

10.3 Methods

This section describes the variety of methods by which climate-health interactions have been studied. For certain health problems such as weather-related mortality (whether due to heat or extreme weather events), these methods may be useful to estimate impacts of future climate changes. For other health problems, especially the vector-borne diseases, these methods may be more useful to understand relations between climate and health in a specific region in the present day. An attempt is made to discuss the general advantages and disadvantages of the different methods in this section, and a summary appears in Table 10.3. Section 10.5 discusses the details of these various methods in the context of specific health problems.

Table 10.3 Summary of approaches to assess human health impacts of global climate change.

Method	Personnel required	Time required	Data needs	Advantages	Disadvantages	Applications
Expert judgement	Interdisciplinary team including public health experts	Minimal	Current morbidity and mortality data, region-specific climate projections	Inexpensive, rapid, able to integrate multiple factors	Imprecise, may be subjective	Initial assessment; all problems
Simple mapping	Cartographers, GIS specialists	Minimal to moderate	Current areas of endemicity and sporadic disease, case or outbreak data. Georeferenced climate projections. GIS requires spatially indexed data, layers need compatible resolution	Inexpensive, rapid, able to visually represent important information for policy makers	Unable to integrate numerous factors and model dynamic interactions.	Vector-borne diseases; health problems due to sea level rise
Conceptual modelling Ecologically based risk assessment						
Regression modelling historical analogues Geographical analogues	Epidemiologists, biostatisticians	Minimal to moderate	Must have appropriate historical data to validate models.	Simpler computation than numeric models; may be able to apply published methods.	Limited applications, decreasing validity out of range of observations.	Heat stress, extreme event-related health problems; vector-borne diseases; respiratory disease due to air pollution
Numerical modelling	Generally requires services of model author, computer specialists	Requires greater time and money	Baseline disease, vector ecology and socio-economic data. Must have appropriate historical data to validate models.	Able to integrate multiple factors, explore interactions among factors.	More expensive, time consuming, large uncertainties.	Vector-borne diseases, water-borne diseases; heat stress

10.3.1 Conceptual model

For the major current health problems, especially infectious diseases, a conceptual model should be developed that describes the interactions among the various factors contributing to the severity of the problem. Such a model assists in three processes: 1) the initial qualitative assessment of climate impacts on health, 2) the quantitative analysis of regional relations between climate factors and disease, and 3) the identification of possible intermediate endpoints (for example, changes in critical host species for vector-borne diseases) that can be used for monitoring and surveillance. One possible paradigm for approaching the development of such conceptual models has been described by the USEPA in a 1992 report entitled "Framework for Ecological Risk Assessment" (Risk Assessment Forum, 1992). This framework emphasises the importance of integrating input from multiple scientific disciplines, including health professionals, biologists, entomologists, and agriculture and forestry experts, in the development of conceptual models of disease systems.

The process of ecologically-based risk assessment is divided into three phases: problem formulation, analysis, and impact characterisation. The initial phase requires a multidisciplinary team to identify critical interactions among climate factors and ecosystem mediators of the disease system as well as specific human health endpoints. Following the identification of these critical interactions, intermediate ecosystem indicators which will aid in both the monitoring of ecosystems for climate change effects and further quantitative analysis can be selected. For example, dengue fever outbreaks are thought to be dependent on high temperatures and moisture availability (influencing mosquito and viral life cycles), human behaviour (regarding water storage practices), human migration, demographics and urbanisation patterns, and human habitation (i.e., screened windows). Thus, analysis of climate impacts on dengue will need to include not only mosquito survival and viral replication rates, but also forecasts of human settlements and water provision systems. Key indicators to be monitored could include mosquito larval populations in selected water storage utensils.

Along with the development of conceptual disease system models, the initial phase involves characterising the essential elements of the system stressors. For climate stressors, care must be given to account for the complexity of climate-ecosystem interactions. Rate of change, frequency of events, and climate variability may be more detrimental to ecosystems than magnitude of change (Mearns, 1993). This introduces a level of complexity to the analysis which is beyond the capacity of current GCM models, which agree on average temperature projections but differ greatly on estimates of regional precipitation and extreme weather events. For now, addressing issues of variability will require simplifying assumptions and use of fixed estimates of certain parameters.

Intermediate ecosystem changes due to climatic stress may also be conceived of as stressors in a human disease system, since many of the human health impacts from climate change are anticipated to be ecologically mediated. Thus, changes in insect vector habitats or marine vegetation may be considered both an outcome of climate change and an intermediate stressor for human disease.

The analysis phase applies the conceptual model developed in the problem formulation phase to the particular area and time frame being analysed. The first stage, ecosystem characterisation, builds on the ecosystem description of the first phase, and involves choosing specific geographic borders and time scales. Because elements within an ecosystem can be both responders and stressors, it is essential in ecosystem characterisation to identify potential areas where this bi-directional dynamic interaction may occur. For example, land use changes may affect micro-climates, which in turn may alter the effects of climate change on mosquitoes, or irrigation of agricultural land may alter a drought's impact on crops (while simultaneously providing potential breeding sites for insect or snail vectors). Exposure analysis then superimposes the spatial and temporal distribution of stressors developed in the first phase on relevant ecological components identified in the ecosystem characterisation to determine points of contact between stressors and responding species (or abiotic elements such as water levels) within an ecosystem.

The responsiveness of ecosystem indicators to climate stressors is assessed in the stressor-response analysis. For each of the endpoints identified in the first phase, the magnitude and nature of the response to the aggregate stresses are estimated. By the end of this stage in the analysis, those human health endpoints that are likely to be affected by climate change should be apparent, and the final stage of risk characterisation will begin actual impact assessment. Understanding of climate-related sensitivity and the existence of threshold values for each given endpoint are critical in this central step. The term sensitivity as used here refers to the amount a given endpoint is affected by a given amount of change in a climate variable. This is analogous to the slope of the dose-response curve in conventional risk assessment. In an ecological risk assessment, the ultimate "sensitivity" of a human disease to climate change may reside in the life cycle of an organism in the disease system which displays marked alterations in reproductive or other types of behaviour in response to changes in climate variables. For example, cold-blooded insect vectors are quite sensitive to small changes in temperature and moisture. Diseases whose infectious agents (viral or protozoal) must reproduce within insect vectors are thus susceptible to subtle climate variations (Dobson and Carper, 1993) .

A concept related to sensitivity is that of threshold. For relatively simple systems, a threshold refers to a sudden change in the slope of the dose-response curve. For example, human sensitivity to temperature extremes varies on a physiologic basis. Heat-related mortality occurs at different temperatures, depending on the latitude and typical temperatures for that area. For example, data from Montreal, Canada, show an exponential increase in heat-related mortality at 29°C, whereas data from Dallas, Texas, USA, do not show a similar increase until 39°C (Kalkstein and Smoyer, 1993). Thus, Montreal may be said to have a temperature threshold at 29°C, and Dallas exhibits a threshold at 39°C.

When considering ecological risk assessment, the threshold may be better conceptualised as a point of non-linear behaviour of an ecosystem endpoint in response to a combination of stressors. Multiple effects of different aspects of climate make it difficult to think of thresholds in relation to a single parameter. For example, elevated temperatures decrease the survival of dengue-carrying mosquitoes. At the same time,

other parameters in the dengue disease system include biting rates (related to adult insect size) and infectivity of mosquitoes (related to maturation time of the virus in the mosquito), both of which increase with temperature. Thus, at temperatures increasing within the range of mosquito viability, the effect of a decreasing survival rate may be more than offset by the combined effects of increased biting rates and infectivity, resulting in an exponential rise in disease transmission (Focks, 1995). Further increases in temperature outside of the range of mosquito viability would then be expected to result in decreased disease activity. Thresholds may occur temporally, as changing climate within a given geographic area alters the behaviour of an already-present human disease. They may also manifest geographically, as changing climate conditions allow migration of human disease into a previously unaffected area.

The final stage, impact characterisation, attempts to translate changes in disease intensity or distribution into terms useful for decision makers, such as demand for health care services or loss of productivity. The result may be qualitative or quantitative. Essential parts of this final phase are assessments of the uncertainty of the results and integration of the results for a given disease system with other analyses.

10.3.2 Empirical studies

10.3.2.1 Historical analogues

Analysis of damage produced, societal responses, and attendant health problems from past events and trends can allow some prediction of impacts of similar severe weather events and trends in the future. Similarly, analysis of anomalous historical climate periods can give considerable insight into the relations between climate and infectious disease. For example, Leovinsohn (1994) found that malaria incidence increased during an atypically warm and wet period in Rwanda in 1987. Several studies have also examined the relationship between malaria outbreaks and temperature and precipitation changes due to the El Niño-Southern Oscillation (ENSO) (e.g., Bouma et al., 1994; Bouma and van der Kaay, 1996). Boxes 10.2 and 10.3 give details on two examples of empirical studies of historical analogues.

An advantage of the use of historical analogues is the regional specificity that comes from analysing the area of interest. The difficulty of accounting for the complexity of confounding factors, as would be required of a free-standing mathematical model, can be avoided to some degree in the creation of empirical models. A disadvantage of models based on historical analogues includes their limited ability to be extrapolated to other regions or to climate changes out of the range of observed data. It should be emphasised, however, that understanding historical climate-disease relations is a prerequisite for being able to develop models that can address changes out of the range of historical data. Moreover, empirical models which have been developed and validated based on historical data should have relevance for short-term changes. Box 10.1 describes the development of a georeferenced historical data base to support future climate predictions.

Box 10.2 Example: Heat-related mortality in US cities (Kalkstein and Greene, 1997).

Daily mortality associated with heat episodes can be assessed with several different approaches to characterising climate. For example, in a study by Kalkstein and Smoyer (1993), six meteorological variables were entered into a stepwise regression procedure to select those with the most explanatory power. In addition, variables relating to the number of days of heat and the timing of a given heat wave during the summer season were included to consider the impact of acclimatisation. Other studies have used standard composite meteorological indices such as the temperature-humidity index (e.g., Karacostas and Downing, 1996). The most sophisticated approach, developed by Kalkstein and colleagues, is the characterisation of air masses for a given locality (Kalkstein, 1991; Kalkstein et al., 1996a). This "synoptic" approach uses statistical methods to separate air masses into area-specific categories based on a large number of meteorological parameters, and is believed to provide a more meaningful tool to assess the health impacts of the specific climatic conditions on a given day. Daily mortality in 44 US cities with populations greater than 1 million were analysed in relation to the frequency of particular air masses. Two air masses associated with particularly high mortality were identified. This method has also been used to develop a weather watch/warning system in Philadelphia to prevent heat-related deaths (Kalkstein et al., 1996b).

Box 10.3 Example: Climate and malaria incidence in Rwanda (Loevinsohn, 1994).

Monthly malaria incidence in catchment centres in Rwanda was modelled with monthly precipitation and mean, minimum, and maximum monthly temperatures. A least-squares technique was used to select the best fitting model, and separate models were also developed for each of three altitude zones. The best-fitting equation for the study area as a whole was:

$$\ln I_m = -4.32 + 1.64\, Tn_{m-1} + 0.83 Tn_{m-2} + 5.34 \times 10^{-4} R_{m-2} + 7.7 \times 10^{-4} R_{m-3}$$

where I_m is the monthly incidence, Tn_m the minimum monthly temperature, and R_m the monthly rainfall. This equation demonstrates the importance of lagging the climate variables, as the rainfall from three months previous was more highly associated with incidence than more recent rainfall. This study also demonstrated that at low altitudes, the amount of rainfall was the most important predictor of disease incidence, whereas at high altitudes, minimum temperature was the most important independent variable.

10.3.2.2 Spatial analogues

In establishing empirical relations between climate and disease, areas which display more interannual climate variability are more likely to yield results than areas with less variability. Areas affected by meso-scale climate systems are particularly useful. One such meso-scale system, the ENSO, affects rainfall and temperature every 4 to 5 years in certain areas around the world. The ENSO may be seen as a valuable natural experiment (Bradley, 1997): variations in excess of 1°C have been associated with ENSO, providing a temperature signal comparable with decades of anticipated global warming. These areas (such as western South America or South Asia) where ENSO strongly affects local climate are therefore promising study locations (Bouma et al., 1994).

Reeves et al. (1994) used a geographical analogue situation to assess the potential impact of climate change on arbovirus transmission. Field and laboratory studies have shown that temperature is an important factor in determining the transmission of a viral agent by its mosquito vector. Reeves took advantage of a 5°C temperature differential between two nearby valleys to compare seasonal transmission and vector abundance in the two areas.

10.3.2.2 Techniques and tools for empirical studies

Geographical analysis/mapping

Health problems which have special associations to local geography, such as those associated with coastal flooding and especially vector-borne disease, can be effectively analysed through mapping techniques. In simplest form, these techniques start by plotting the current boundaries of a health problem (e.g., flood areas, intensities of disease transmission or incidence). The factors responsible for the geographic boundaries (e.g., altitude in the case of flooding, or temperature or rainfall in the case of vector-borne diseases) are similarly plotted. Projected changes in those factors, either from fixed projections or predictive models (e.g., GCMs), are then plotted, and the changes in the boundary of the health problem are noted with respect to population centres. An example of such an approach to malaria in Sri Lanka is shown in Box 10.4.

Geographic information systems

Box 10.1 describes the use of GIS for both current and future analysis of malaria in Africa. A discussion of GIS is given in Chapter 1, Getting Started. Other GIS-based studies include changes in vector distributions mapped by Rogers and colleagues in southern Africa (Hulme, 1996). The use of GIS systems as data platforms to assist in predicting disease incidence is still under development, but especially in combination with satellite remote sensing (see below), there appears to be promise in using ecosystem parameters such as vegetation types to help predict locations of disease outbreaks or changes in disease vector distribution (Washino and Wood, 1994).

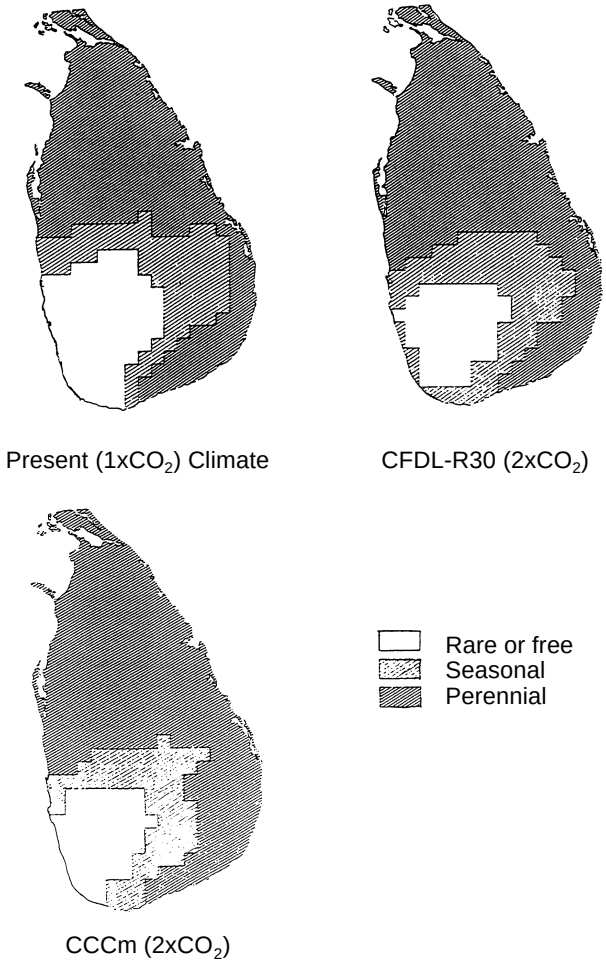
Use of remotely-sensed images

For many parts of the world, it is very difficult to acquire high quality, geographically referenced data on ecological factors related to disease transmission (such as types of vegetation or temperature and composition of surface waters). Political or geographic obstacles may impede the collection of such data through traditional field methods. Technological advances have enabled the use of remote sensing devices to assist in providing these data. Using low-flying aircraft or satellites, these devices are able to measure either directly or indirectly water and air temperatures, vegetative cover, and even water flows. Those entities measured indirectly often require significant initial field work to establish the relations between factors which can be measured directly, such as light absorption, and the desired entity, such as vegetative cover.

Box 10.4 Example: Malaria transmission in Sri Lanka.

Dhanapala (1998) used mapping used to study potential malaria transmission in Sri Lanka. Zones of perennial and seasonal malaria transmission and malaria-free zones were defined under present climate conditions. These zones were then correlated with a moisture index using historical temperature and precipitation data, and the threshold moisture indices which defined the three zones were determined. Temperature outputs from two global circulation models were combined with assumptions of either increased or decreased total precipitation (due to uncertainty) and moisture indices were calculated for each pixel of GCM output. The IDRISI GIS was used to store and display this geographically-based data. Threshold moisture indices between current malaria transmission zones were applied to the new map and new borders of malaria transmission zones were estimated. It was estimated that the area of malaria-free zone might decrease by 45.6% to 55.1% and the area of the perennial transmission zone would increase by 45.1% to 65.1%. Further analyses could assess the implications of the shifts in transmission zones for specific population centres, and begin to formulate possible adaptive strategies.

Clear limitations to this method include the fact that other geographic and anthropogenic factors affect malaria transmission, for example, pesticide use. It is not possible to account for these other factors either in the present situation or in the projections. Nonetheless, this exercise provides a number of benefits. First, the relation between areas potentially vulnerable to increases in malaria transmission can be estimated and compared to existing population centres. Second, areas which may have decreases in malaria transmission can be noted as well.



Box 10.3, Figure 1 Annual malaria potential transmission.

An example of the use of remote sensing for vector-borne disease is the study on human African trypanosomiasis by Rogers and colleagues. Vegetation indices (specifically the NDVI, normalised vegetation index) obtained from satellite images and tsetse fly abundance have been correlated for regions in Central and East Africa (Rogers and Randolph, 1991; Hay et al., 1996). Two important points are evident. First, the ability to use remote sensing for a given area is dependent on sufficient ground-based study in that area. The linkage of remotely sensed vegetation indices and vector populations was made possible by previous studies associating climate factors such as saturation deficit with vector survival. By associating both vector survival and vegetation indices to the same climate variables, the remotely sensed data could then be applied to human disease prediction. The second point is that different local species of vector may have very different responses to changes in climate. In this study, it was shown that the population of the species *Glossina palpalis* increased with increasing vegetation index (indicative of greater moisture), while the species *G. tachinoides* decreased in number with increasing vegetation index. This emphasises the need for regional models developed along with expert judgement.

10.3.3 Numerical models

Although numerical modelling is often used by epidemiologists – to gain insights into the observed dynamics of infectious disease epidemics, for example, or to estimate future time trends in diseases – the complex task of estimating future trends and outcomes in relation to global climate change and human health may ultimately require the use of integrated, systems-based numerical models (Rotmans et al., 1990; McMichael and Martens, 1995). Once empirical studies have clarified current relations between climate factors and human diseases, numerical models can be used to highlight the effects of a wide variety of scenarios on those relations. For example, the impacts of changes in demographics, health care investment, immunisations, and nutrition can be better assessed with numerical models than with standard empirical models. The information gathered from such analysis can be of great importance to policy makers.

One example of numerical modelling is MIASMA (Modelling framework for the health Impact Assessment of Man-induced Atmospheric changes), developed by Maastricht University (Martens, 1997). MIASMA is an acronym devised to refer to several models: a vector-borne disease model, a thermal stress model, and a skin cancer model. This modelling framework is designed to describe the major cause and effect relationships between atmospheric changes and human population health. The models are driven by scenarios of population figures and atmospheric changes, superimposed on baseline data regarding disease incidence, climatic conditions, and ozone-layer thickness. Global atmospheric changes directly influence the exposure to health risks via changes in ambient temperature and received UV-B radiation, as well as indirectly, in influencing the dynamics and distribution of vector-borne diseases. Changes in the pattern of health risks demarcate the changes in the levels of incidence of the diseases influenced by the determinants. The mortality rates associated with cardiovascular diseases are directly influenced by thermal stress, mainly in urban areas.

The modelling approach is orientated toward a vertical integration of global atmospheric disturbances and their respective health effects. The models try to cover as much as possible of the cause-effect relationship with respect to global atmospheric changes and human health. In the vector-borne disease model, the dynamics of malaria, schistosomiasis, and dengue are simulated in relation to climate changes. Relationships between temperature, precipitation, and vector characteristics are based on a variety of field and laboratory data. Changes in transmission dynamics of malaria and schistosomiasis are modelled using the basic infectious disease models described in Anderson and May (1991); for dengue a well-validated, dynamic life-history model of dengue transmission (Focks et al., 1993a,b) is used. Recognising the need for continuing cross-validation of large-scale and small-scale studies (Root and Schneider, 1995), simulations have been performed of the transmission potential of malaria in Zimbabwe and dengue in five cities (Bangkok, San Juan, Mexico City, Athens, and Philadelphia) (Focks, 1993 a and b; Jetten and Focks, 1997; Patz et al., 1998). The historical data available for these locations are used for validation, i.e., testing the performance of the model.

To represent a wide range of climatic conditions and levels of socio-economic developments, effects of thermal stress on cardiovascular, respiratory, and total mortality have been simulated for 20 cities throughout the world. The association between winter and summer temperatures and mortality rates has been estimated by means of a metanalysis, aggregating the results of several epidemiological studies on the subject. Projections of future risks are then simulated by simple extrapolation of this calculated relationship. Effects of acclimatisation to increasing temperatures, physiological as well as technological, are simulated.

10.4 Selecting scenarios

Chapters 2 and 3 describe in detail the use and development of socio-economic and climate change scenarios.

Scenarios specific to health impact studies include demographic and socio-economic projections. In the study of vector-borne diseases, vector resistance to pesticides and parasite resistance to drugs are also included in numerical models. In general, baseline data are obtainable from WHO and World Bank sources (e.g., WHO, 1992; World Bank, 1993).

10.5 Impact assessment

10.5.1 General considerations

This section is meant to provide more specific information on impact assessment for particular human health problems. Because the best method of assessing impacts will differ for different health problems, this section cites examples of analysis and discuss some of the issues particular to specific health problems.

The optimal method of expressing human health impacts is not clear. In addition to the traditional public health parameters of disease incidence and prevalence, there has been increasing use of terms that express the economic burden of human diseases. Because different countries may have different costs associated with addressing the same incidence or prevalence of disease, and because analysis of human health impacts will be reported next to analyses of sectors with clearer economic ties, the use of economic terms may be desirable. Measuring the economic impact of climate-related changes in human health, however, is clearly a complex task. Unlike other sectors whose products are inherently economic in nature, such as agriculture and water resources, human health is historically difficult to quantify and associate with economic value. Changes in disease incidence for different diseases can be compared by attempting to measure lost productivity due to the disease. This requires knowing the average age of onset of the disease, case fatality rates, and the average extent and duration of disability due to the disease. These data are likely to be very difficult to obtain, and the levels and types of studies from which the data come need to be examined and found comparable (Aron and Davis, 1993). Should these data be obtainable, an estimate of healthy years of economically productive life lost can be made. The further valuation of this measure in economic terms is quite problematic. Regional differences in wages, employment, and even gender roles will complicate the comparison of disease impacts.

Uncertainty analysis must accompany the overall integrated assessment. Uncertainty will be present at all levels of the risk assessment (McMichael and Martens, 1995). During the conceptual model phase, incorrect assumptions may prove difficult to resolve. The inevitability of incomplete data must be addressed throughout the analysis, and errors in measurement and sampling will need to be transparent throughout the assessment process. Finally, the natural variability, or "stochasticity", within climate and ecological systems must be adequately represented (Risk Assessment Forum, 1992). Communication regarding uncertainties must take place between scientists and policy makers early on in the process to ensure that the results of the risk assessment are accurately represented to constituencies at risk.

10.5.2 Impact assessment of public health infrastructure damage

Although it is not currently possible to predict the frequency and severity of extreme weather events for a given region, historical data on the impact of severe storms for a given region can be used to extrapolate the impact of climate change on public health infrastructure damage. Until severe weather predictions are available, a range of possible conditions based on expert judgement can be used, and infrastructure damage extrapolated from past experience. Local experts will also need to consider the range and extent of possible adaptive responses. An additional important element for assessing the impact of climate change on infrastructure damage will be the quality of socio-economic and demographic predictions of vulnerable populations.

Projections of future water supply are available for many countries (e.g., World Bank, 1992). These projections in general do not account for alterations in demand due to climate change, and can therefore serve as the baseline for impact assessments. Esti-

mates of alterations in water supply and demand should be either obtained from or co-ordinated with results from the water resources sector assessment (Chapter 6).

Impaired agricultural food production and distribution could have substantial adverse health effects, through mortality from starvation and through increased susceptibility to infectious diseases from malnutrition. One study examining this issue on an international scale estimated 40 to 300 million additional people at risk from hunger because of climate-related decreases in food production (Parry and Rosenzweig, 1993). This study accounted for projected improvements in world-wide food distribution as a result of decreased trade barriers as well as potential beneficial effects of increased carbon dioxide on food crops. Smaller scale impact assessments should account for these effects as well.

10.5.3 Impact assessment of vector-borne diseases

The assessment of the impacts of climate change on vector-borne diseases can be performed with a variety of methods, including mapping and integrated modelling. Some vector-borne diseases have been well-characterised in terms of the effects of temperature and precipitation on the life cycles of the vector and disease agent based on laboratory studies. Data from field studies are less common. Establishing current geographic boundaries on the basis of current climate conditions, applying climate projections, and estimating changes in geographic boundaries and transmission rates are the essential steps in the assessment.

The eradication campaigns of malaria in the mid-1950s resulted in dramatic changes in the ecology of many vector-borne diseases. Variations in the quantity and type of insecticide used and the level of resistance in the vectors are difficult to estimate and incorporate into models. These factors, however, may have a greater local impact on disease transmission than climate factors. Therefore, historical disease data from before the mid-1950s, where available, may allow the study of climate-disease relations with fewer potentially confounding variables (Bouma and Van der Kaay, 1996).

Sometimes data are limited to the distribution of the vector rather than human case data, and often this means merely presence or absence of the vector. More rarely, historical information about vector density is available. However, this would have to be specifically collected and therefore is less likely to available, or less likely to be freely accessible. Since presence of the vector is not sufficient for disease activity, the additional factors either facilitating or preventing disease transmission will have to be analysed. Factors important for the transmission of many vector-borne diseases include geographic and climatic features such as altitude. If possible, other relevant information such as pesticide use, surface water distribution, and vegetative cover should be included in the analysis as these are related to vector habitats.

Integrated models offer the additional feature of exploring the effects of changes in other diseases and socio-economic parameters on a given vector-borne disease. Examples of the use of integrated models for malaria on a global scale can be found in Martens et al. (1995, 1997) and Martens (1995) and for dengue in Focks et al.

(1993a,b). To date, there have been no published quantitative assessments of vector-borne diseases on a local or regional basis using integrated models.

10.5.4 Impact assessment of heat mortality and pollution-related respiratory disease

Current studies of heat mortality indicate that acclimatisation plays a critical role in determining the level and extent of sensitivity to temperature. It is not clear how long populations would take to acclimatise to an increased frequency and severity of extreme heat events, if at all (McMichael et al., 1996b). In addition, GCMs cannot predict the frequency of extreme events with accuracy, so quantitative assessment must rely on the superposition of assumed variability parameters on average temperature projections.

In extrapolating historical data to future predictions, attention should be paid to the characterisation of climate as well as the case definition of heat-related illness and mortality. Synoptic analysis (Kalkstein, 1991; Kalkstein et al., 1996), which characterises air masses on the basis of multiple parameters such as maximum temperature, humidity, and wind speed, is one method for organising climate model outputs. The frequency and severity of certain offensive air masses, specifically those appearing early in the summer season, can then be used to extrapolate future mortality from heat waves.

Usually urban populations are studied for heat-related mortality and morbidity, largely because a dense population is required to be able to observe a significant number of heat-related deaths (e.g., Kalkstein and Greene, 1997). Urban areas also tend to absorb and retain heat more than rural areas. Studies show that within the urban population (as with most health problems), the most vulnerable are the elderly, the very young, and the poorly housed.

There are no published estimations of health impacts of air pollution in the setting of climate change; studies are under way to attempt to model the interactions between climate and air pollution. Because increased air temperatures will accelerate the formation of tropospheric ozone from increased reactions between ultraviolet radiation and primary pollutants (i.e., NO_x), potential worsening of urban air pollution in association with climate change should be considered. Current impact assessment will need to be qualitative until these interactions are better understood.

10.5.5 Impact assessment for water-related diseases

Climate change may affect water-borne diseases via several mechanisms. One mechanism will be alterations in precipitation leading to flooding and biological contamination of water supplies, or leading to possibly drought and a shortage of safe drinking water. Linking climate prediction models with water budget or runoff models can provide an assessment of potential changes in precipitation effects from climate change. Both bacterial water-borne illnesses such as cholera and parasitic diseases such as cryptosporidiosis may be approached in these ways.

The relation between algal blooms in nutrient-rich warming coastal water and cholera outbreaks is still under investigation. There is growing evidence that in areas of endemic cholera, coastal waters provide an aquatic reservoir for *Vibrio cholerae* bacteria (Islam et al., 1993). What is not understood is exactly how the bacteria reproduce in the environment, and what factors cause the return to an infectious state. Thus, the presence of Vibrio bacteria in nutrient-rich coastal waters and sporadic cholera outbreaks may indicate a sensitivity to climate change, but the quantitative prediction of impacts would be very difficult. Some quantitative estimates of algal blooms and densities may be available to assist with projections, but the linkage between that data and actual cholera incidence remains to be determined. One study has shown a link between sea surface temperatures and cholera cases in Bangladesh (Colwell, 1996).

10.6 Autonomous adaptation

Given the complexity of most human disease systems, attempts to account for autonomous adaptation within the impact analysis will be prohibitively difficult in many cases.

For problems related to direct physiological stress, such as heat-related mortality, physiological acclimatisation may already be accounted for in the use of historical human data to project future mortality, although this is not clear from all studies. Non-physiological adaptations, e.g., building design, behaviour, and use of air conditioning, need to be addressed.

For infectious diseases, the development of immunity can be considered an inbuilt autonomous adaptation. Malaria is an important example because the loss of immunity in a population (i.e., when a population shifts from stable to unstable malaria) can lead to significantly higher morbidity and mortality rates (e.g., Martin and Lefebvre, 1995). Repeated infection with dengue, however, may lead to the serious complication of dengue haemorrhagic fever rather than immunity if the infections are with different serotypes of the dengue virus.

In the methods discussed above, autonomous adaptation is not considered because of the lack of data. However, changes in population immunity have been considered in malaria integrated models (Martens, 1997). For simpler assessment exercises, however, the range of uncertainty of future estimates will most likely be far greater than the potential impact of immunity or other autonomous adaptation within the population.

Many autonomous adaptations are behavioural, such as wearing protective clothing, reducing exertion levels, or obtaining drinking water from different sources. Because of the difficulty of predicting human behaviour, it may be reasonable to use a set of scenarios with different levels of behavioural changes in the impact assessment stage, and thereby investigate the possible impact of such autonomous adaptations.

For certain problems, what might be considered autonomous adaptations may have considerable public health or societal consequences of their own. For example, migration in response to local changes in climatic and environmental conditions could be considered an autonomous adaptation, but will by itself cause considerable societal strain and possibly lead to outbreaks of disease due to crowding, malnutrition, etc.

Similarly, widespread use of pesticides to combat new vector-borne disease outbreaks may contribute to both pesticide-related toxicity and further ecosystem disruption. If such adaptations are considered in an impact assessment, both the positive and negative implications need to be included.

10.7 Planned adaptation

10.7.1 General considerations

Just as the differing conditions among countries necessitate different approaches to health sensitivity and impact assessments, so too will the approaches to adaptation differ by region. For many developing countries, the health problems that are likely to be exacerbated by climate change are significant current problems. Thus, adaptive strategies developed in anticipation of future climate conditions may have substantial utility for the present situation. Many of the adaptations discussed here are not specific to climate change and, in fact, should not be viewed in isolation from the more generalised problem of global environmental degradation and compromised public health infrastructure in much of the developing and developed world.

10.7.1.1 Levels of prevention and hierarchy of controls

While cost and feasibility are clearly important considerations in evaluating adaptation options, two sets of concepts borrowed from preventive medicine and occupational health can also be applied to prioritise different adaptation options (Patz, 1995). The first set of concepts involves levels of prevention. Primary prevention consists of those measures that reduce or prevent the risk of developing a disease. This may involve protection from an infectious or harmful agent (e.g., immunisation or use of bed nets) or the removal of the harmful agent or exposure from the environment (e.g., eradication of disease vectors or replacement of a dangerous chemical in an industrial process). Secondary prevention involves the detection and treatment of a disease at a stage early enough to prevent serious clinical illness. Examples would be screening for malnutrition or asymptomatic parasitic infections. Tertiary prevention involves limiting long-term health deterioration from disease. Examples would include treatment of infectious diseases and rehydration therapy for diarrhoea. Primary prevention measures are often more cost-effective than higher level interventions, and clearly reduce the burden of human disease and suffering. There may, however, be instances where primary prevention measures are either unfeasible or have unacceptable financial or ecological costs (e.g., pesticide use in large areas), and secondary prevention measures will need to be considered. It should be noted that greenhouse gas mitigation represents an even earlier level of prevention. Mitigating the process of global warming might be viewed, therefore, as "pre-primary" public health prevention. Clearly, the discussion in this chapter addresses the results of the failure to adequately mitigate the ecosystem and human health effects of greenhouse gas emissions, and does not in any way intend to distract attention from the need to address the root cause of the problem.

The second set of concepts, called the hierarchy of controls, is derived from occupational health. Among primary prevention options, some may involve individual motivation and behaviour to a greater extent than others. For example, asking people to wear long sleeves and apply insect repellent requires significant individual co-operation, unlike using measures to decrease the insect vector population. In general, measures that require less individual behavioural change will be more efficacious than those that require significant individual co-operation. Because individual responses to health threats are highly variable and misperceptions of relative health risks are common in the public, only selected groups within a population are likely to take appropriate preventive steps. Among measures that do not involve personal behaviour, those that reduce or eliminate the potential for exposure to harmful situations are preferable to measures that merely reduce the duration or intensity of exposure.

Thus, in the hierarchy of controls, the first level of attention is given to measures that eliminate the harmful exposure, either by eliminating the agent (e.g., killing of insect vectors or substitution of less harmful chemicals) or by constructing a mechanism to protect the individual from exposure (e.g., engineering controls such as enclosure of industrial exposures or construction of architecturally heat-resistant housing). The second level of attention is given to administrative controls which reduce the amount of exposure, such as limiting work hours for outdoor workers in a situation of potential heat stress. It should be noted that in applying these industrial concepts to country-wide adaptation strategies, measures that correspond to engineering controls, such as housing or infrastructure construction, may require administrative action such as local or national legislation. The third level of attention is given to the individual use of protective measures, such as respirators for harmful air-borne chemicals or insect repellent for vector-borne diseases. Again, first level adaptation options may not always be available or feasible. These concepts can be used, however, along with considerations of cost, to help prioritise among a list of available options.

10.7.1.2 Expecting the unexpected

As stated above, it is likely that there will be unforeseen consequences of climate change for human health. It is essential that adaptation policies reflect this uncertainty and do not focus only on the specific anticipated changes in existing human diseases. Thus, in addition to disease-specific measures, improving surveillance and monitoring systems will be highly valuable. Furthermore, since our understanding of the linkages between climate and health is poorly developed, the commitment to fund and facilitate ongoing research is an essential part of adaptation.

10.7.1.3 Surveillance and monitoring

Ongoing monitoring, both of human diseases and of critical ecosystem indicators, will be essential to the timely institution of interventions as disease systems change. To the extent possible, the early indicators that have been identified during the development of conceptual models should be used rather than the incidence of actual diseases. Because of the inertia of large ecosystems, and the fact that changes in human diseases due to

climate factors generally represent the end result of ecosystem changes, substantial ecosystem changes will have occurred by the time an increase in disease incidence is detected, and intervention will be far more difficult. Where feasible, monitoring efforts should be integrated with existing surveillance systems established for certain infectious disease categories.

Long-term field data gathering and surveillance of vector-borne disease are essential. Such data not only allow the study of seasonal and inter-annual variations in disease associated with climate variability but also provide information of early climate-related changes in incidence (Haines et al., 1994). Unfortunately, institutional changes and the apparent success of vector control methods (before widespread resistance emerged) led to a decline in the long-term prospective observations necessary to understand the mechanisms by which environmental impacts influence infectious disease risk. For example, local surveillance of vector species has been employed in the United States to try to predict outbreaks of St. Louis encephalitis and eastern equine encephalitis (MMWR, 1990). Domestic chickens and wild sparrows have been tried as sentinel indicators of increased viral transmission, but the focal nature of arboviral outbreaks and the inability to survey a broad enough area have limited the usefulness of this application for certain arboviral diseases (Monath and Tsai, 1987).

A strategy for global monitoring of health effects of climate change has been proposed involving remote sensing and extensive telecommunications networks of environmental and health professionals (Haines et al., 1994). Such an effort is strongly needed on a global scale, but smaller efforts on a regional scale, targeted at the critical geographic areas identified in the sensitivity analysis, will be important for regional adaptation strategies as well. An example of large-scale physical and ecological monitoring is the new United Nations interagency Global Observing System. This consists of the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS), and the Global Oceans Observing System (GOOS) (Patz, 1995). While such an effort is beyond the capacity of a single country, participation in such international efforts will have benefits not only on a global scale but also on a regional scale.

10.7.1.4 Infrastructure development

Water treatment facilities and shelter, already in short supply in many areas, may be further threatened by severe storms and sea level rise. For these threatened areas, investment in expanded facilities may have substantial current benefit, and attention paid to safe location of the facilities with respect to sea level rise and extreme weather events will be of use in adapting to future conditions. Consideration should also be given to improving the efficiency of existing water systems as well as reducing demand for water where possible. The involvement of local communities in planning and developing water systems is essential (World Bank, 1992). This is another area in which present-day investment will have public health benefits with or without impacts of climate change.

10.7.1.5 Public education

Human behaviour has a considerable influence on disease incidence. Some behaviours such as the storage of open water containers or the improper disposal of human wastes create favourable environmental conditions for disease-causing agents to reproduce. Other behaviours such as the type of clothing worn and the filtering of drinking water affect exposure to disease-causing agents. Public education efforts will be needed, both to inform about the causes of disease and human impacts on disease and to instruct on ways to minimise the health impacts of climate change. The need may be greatest in the critical areas where experience with disease is limited but the risk of the spread of disease is high.

Educating diverse groups of people in a way that does not conflict or negate present belief systems can be quite difficult. Experience with public education efforts in Tanzania on malaria has shown that educational methods need to be adapted to the local ethnic belief systems. Without the education and involvement of local communities, regional adaptation efforts will not succeed (C. Schiff, Johns Hopkins School of Hygiene and Public Health, personal communication, 1996). Conversely, when public education is presented in a culturally appropriate and creative manner, the effort can be far more successful. An example of such an effort resulting in widespread behavioural change is the “slip, slap, slop” campaign in Australia to convince the population of the need to use clothing, hats, and sunscreen lotion to protect against ultraviolet radiation.

10.7.1.6 Technological or engineering strategies

In certain cases, technological controls such as genetic or biological pest management systems may be useful. For certain diseases such as dengue and malaria, modification of the environment by engineering methods may reduce breeding sites and therefore reduce vector populations. In all cases, consideration must be given to potential negative consequences of the use of technological adaptation methods. For example, increased use of air conditioning to combat heat stress may have unacceptable costs in terms of increased energy use, and draining of wetlands may reduce fish production.

10.7.1.7 Medical interventions

Where possible, primary preventive medical interventions such as vaccinations should be used. Unfortunately, at present, the only disease anticipated to be sensitive to climate change for which a vaccine is available is yellow fever. It has not been possible to develop a vaccine for dengue. Work is continuing on the development of a malaria vaccine; however, it is recognised that an integrated approach is needed to combat the disease, involving local initiatives for vector surveillance and control.

Medical interventions for water-borne diseases or respiratory diseases may play a role as further research determines the potential for increases in those diseases from climate change.

10.7.2 Specific adaptation strategies

In addition to the general adaptive strategies discussed above, a variety of impact-specific options are available (Table 10.4). In general, these are measures that have been employed for present-day problems. The list of options in Table 10.4 is not intended to be complete, but rather to initiate discussion and evaluation of a variety of options that will be decided upon by local and regional health experts and policy makers. Furthermore, it should be emphasised that many of these measures will only be temporary in their effects; this list should not be viewed as an alternative to addressing the root causes of global warming through policy initiatives.

10.8 Summary and implications

As an integrator of ecosystem changes, human health is influenced by many of the factors that will be analysed in other sectors of global climate change impact assessments. Assessments of nutritional health will depend on the outputs of the following sectors: agriculture, fisheries, water resources, coastal zones, and biodiversity. Projections of the adequacy of shelter and water supplies will require the outputs of coastal zones and water resources. Since disruption of ecosystems through deforestation, water re-distribution, and other land uses can be associated with alterations in human disease systems, particularly vector-borne diseases, the future projections of these factors should be provided to those performing human health assessments by the forestry, agriculture, and water resources sector assessments. It should be noted that impacts on primary factors in public health, i.e., food, water and shelter, will have secondary impacts on sensitive disease systems for both vector- and water-borne diseases.

Impaired or improved human health will affect most other sectors via changes in productivity and resource allocation. As discussed in the section on impact assessment, however, the quantification of changes in productivity is very problematic, as is the prediction of medical and public health resource allocation into the future. Qualitative changes in diseases (e.g., the appearance or spread of diseases to new areas) may be of primary importance to trade and tourism.

As has been demonstrated, the health impacts of global climate change are likely to be multiple for any given region and highly variable between different regions. A country by country approach is warranted to ensure applicability of any health impact assessment. While there is likely to be difficulty obtaining the data, resources, and time necessary for a fully comprehensive quantitative impact assessment, a qualitative initial approach, as outlined in this chapter, may be of significant benefit to policy makers. Continuing surveillance and research activities will enable more accurate assessments in the future.

Table 10.4 Matrix of possible adaptation strategies for specific health impacts of climate change.

Adaptation measures	Heat-related mortality	Extreme weather events	Vector-borne diseases	Water-borne diseases
Public education	Publicise precautions to take during heat waves		Educate public to encourage elimination of artificial breeding sites	Educate public on sources of infection
Surveillance and monitoring	Establish new weather watch/warning systems that focus on health-related adverse conditions such as oppressive air masses	Maintain disaster preparedness programs, including tools for local public health facilities to conduct rapid health needs assessments	Institute surveillance for both disease incidence and vector populations or other intermediate hosts	Create early warning systems based on algal blooms to predict cholera
Ecosystem intervention	Plant trees within cities to reduce the urban heat-island effect	Adopt land-use planning to minimise erosion, flash-flooding, precarious residential placements; restore wetlands	Release sterilised male insects to reduce reproductive capacity of vector populations	
Infrastructure development		Site intakes for water facilities far enough upstream to tolerate saline intrusion from storm surges and sea level rise	Anticipate effects of irrigation projects on vector breeding sites	Construct water treatment facilities, waste treatment measures (privies, sewers, etc.)
Technological/engineering	Design buildings to be more heat resistant	Strengthen sea-walls; require building contractors to follow hurricane standards in coastal areas	Promote the use of pyrethroid impregnated mosquito bed-nets; install window screens in areas endemic to insect-borne diseases	Distribute low-technology water filtration systems (e.g., nylon mesh, cloths)
Medical interventions	Schedule work to avoid peak daytime temperatures for outdoor labourers		Sensitise health care givers in geographically vulnerable regions	

References

Aron, J.L. and P. Davis. 1993. *A Comparative Review Of The Economic Impact Of Selected Infectious Diseases In Africa.* Johns Hopkins University, Baltimore, Maryland, USA

Bouma, M.J., H.E. Sondorp and H.J. van der Kaay. 1994. Climate changes and periodic epidemic malaria. *Lancet* 343, 1440.

Bouma, M.J. and H.J. van der Kaay. 1996. The El Niño Southern Oscillation and the historic malaria epidemics on the Indian subcontinent and Sri Lanka: An early warning system for future epidemics? *Tropical Medicine and International Health* 1, 86-96.

Bradley, D.J 1997. From chilly summer afternoon to global warming. Climate as a determinant of human disease (editorial). *Tropical Medicine and International Health* 2 (9), 823.

CCIRG. 1996. *The Potential Effects of Climate Change in the United Kingdom*. Second Report prepared at the request of the Department of the Environment. HMSO, London.

Colwell, R.R. 1996. Global climate and infectious disease: The cholera paradigm. *Science* 274, 2025-2031.

Craig M. and D. Le Sueur (in preparation). A climate-based, numeric distribution model of malaria transmission in Africa.

Dhanapala, A.H. 1998. Impact on incidence and distribution of malaria. *In Final Report of the Sri Lanka Climate Change Country Study*, J. Ratnasiri (ed). Ministry of Forestry and Environment, Colombo, Sri Lanka, pp. 28-32.

Dobson, A. and R. Carper. 1993. Health and climate change: Biodiversity. *Lancet* 342, 1096-1099.

Focks, D.A., D.G. Haile, E. Daniels, and G.A. Mount. 1993a. Dynamic life table model for *Aedes Aegypti* (Diptera: Culicidae): Analysis of the literature and model development. *Journal of Medical Entomology* 30(6), 1003-1017.

Focks, D.A., D.G. Haile, E. Daniels, and G.A. Mount. 1993b. Dynamic life table model for *Aedes Aegypti* (Diptera: Culicidae): Simulation results and validation. *Journal of Medical Entomology* 30(6), 1018-1028.

Focks, D.A., E. Daniels, D.G. Haile, and J.E. Keesling. 1995. A simulation model of the epidemiology of urban dengue fever: Literature analysis, model development, preliminary validation, and samples of simulation results. *American Journal of Tropical Medicine and Hygiene* 53, 489-506.

Haines, A., P.R. Epstein, A.J. McMichael, et al. 1994. Global health watch: Monitoring the impacts of environmental change. *Lancet* 342, 1464-1469.

Hay, S. I., C. J. Tucker, D. J. Rogers, and M. J. Packer. 1996. Remotely sensed surrogates of meteorological data for the study of the distribution and abundance of arthropod vectors of disease. *Annals of Tropical Medicine and Parasitology* 90, 1-19.

Herrera-Basto, E., D. R. Prevots, et al. 1992. First reported outbreak of classical dengue fever at 1,700 meters above sea level in Guerrero State, Mexico, June 1988. *American Journal of Tropical Medicine and Hygiene* 46, 649-653.

Hulme, M. (ed). 1996. *Climate Change and Southern Africa: Exploration of Some Potential Impacts. Implications for the SADC Region.* Report commissioned by WWF International. Climatic Research Unit, University of East Anglia, Norwich, England.

Hutchinson M.F., H.A. Nix, J.P. McMahan, and K.D. Ord. 1995. *Africa - A Topographic and Climatic Database, version 1.0*. Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Islam, M.S., B.S. Drasar and R.B. Sack. 1993. The aquatic environment as a reservoir of *Vibrio cholerae*: A review. *Journal of Diarrhoeal Disease Research* 11, 197-206.

Jetten, T.H. and D.A. Focks.1997. Potential changes in the distribution of dengue transmission under climate warming. *American Journal of Tropical Medicine and Hygiene* 57(3), 285-297.

Karacostas T.S. and T.E. Downing. 1996. Heatwaves in a changing climate. In *Climate Change and Extreme Events: Altered Risk, Socio-Economic Impacts and Policy,* T.E. Downing, A.A. Olsthoorn, and R.S.J. Tol (eds). Institute for Environmental Studies, Amsterdam, pp. 139-156.

Kalkstein, L.S. 1991. A new approach to evaluate the impact of climate upon human mortality. *Environmental Health Perspectives* 96,145-150.

Kalkstein, L.S. and J.S. Greene.1997. An evaluation of climate/mortality relationships in large US cities and the possible impacts of climate change. *Environmental Health Perspectives* 105, 84-91.

Kalkstein, L.S. and K.E. Smoyer. 1993. The impact of climate change on human health: Some international implications. *Experiencia* 49, 469-479

Kalkstein, L.S., C.D. Barthel and J.S. Greene.1996a. A new spatial synoptic classification: Application to air-mass analysis. *International Journal of Climatology* 16, 983-1004.

Kalkstein, L.S., P.F. Jamason, J.S. Greene. J. Libby, and L. Robinson. 1996b. The Philadelphia hot weather-health watch warning system: Development and application. *Bulletin of the American Meteorological Society* 77, 1519-1528.

Koopman, J.S., D.R. Prevots, M.A.V. Marin et al. 1991. Determinants and predictors of dengue infection in Mexico. *American Journal of Epidemiology* 133, 1168-1178.

le Sueur, D. (in press). *InterGovernmental Panel for Climate Change (IPCC) Special Report on Africa*. Lead author of health sector chapter.

le Sueur, D. 1997. Annual Report of the Mapping Malaria Risk in Africa/**)** (MARA/ARMA) Atlas du Risque de la Malaria en Afrique (ARMA) project.

Levins, R., T. Awerbuch, U. Brinkmann et al. 1994. The emergence of new diseases. *American Scientist* 82, 52-60.

Loevinsohn, M. 1994. Climatic warming and increased malaria incidence in Rwanda. *Lancet* 343, 714-718.

Longstreth, J. 1989. Human health. In *The Potential Effects of Global Climate Change on the United States,* J.B. Smith and D. Tirpak (eds). EPA-230-05-89-050.US Environmental Protection Agency, Washington DC, pp. 525-556.

Martens, W.J.M., L.W. Nissan, J. Rotmans, T.H. Jetten, and A.J. McMichael. 1995. Potential impact of global climate change on malaria risk. *Environmental Health Perspectives* 103, 458-464.

Martens, W.J.M., T.H. Jetten, and D.A. Focks. 1997. Sensitivity of malaria, schistosomiasis and dengue to global warming. *Climatic Change* 53, 145-156.

Martens W.J.M. 1995. *Modelling the Effect of Global Warming on the Prevalence of Schistosomiasis*. Global Dynamics and Sustainable Development Programme. GLOBO Report Series No. 10. RIVM Report No. 461502010. Rijksinstitut Voor Volksgezondheid en Milieu (RIVM), Bilthoven, The Netherlands.

Martens W.J.M. 1997. *Health Impacts of Climate Change and Ozone Depletion: An Eco-epidemiological Modelling Approach*. Doctoral thesis, University of Maastricht.

Martin P. and M. Lefebvre. 1995. Malaria and climate: Sensitivity of malaria potential transmission to climate. *Ambio* 24(4), 200-207.

McMichael, A.J. 1993. Global environmental change and human population health: A conceptual and scientific challenge for epidemiology. *International Journal of Epidemiology* 22(1), 1-7.

McMichael, A.J. 1997. Integrated assessment of potential health impact of global environmental change: prospects and limitations. *Environmental Modeling and Assessment*, 2, 129-137.

McMichael, A.J. and W.J.M. Martens. 1995. The health impacts of global climate change: grappling with scenarios, predictive models, and multiple uncertainties. *Ecosystem Health* 1(1), 23-33.

McMichael, A.J., et al. 1996a. Human population health. In C*limate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, R.T. Watson, M.C. Zinyowera, and R.H. Moss (eds). Cambridge University Press, Cambridge, United Kingdom, pp. 561-584.

McMichael, A.J., A. Haines, R. Slooff, S. Kovats (eds.) 1996b. *Climate Change and Human Health*. World Health Organization, Geneva, Switzerland.

Mearns, L.O. 1993. Implications of global warming for climate variability and the occurrence of extreme climate events. In *Drought Assessment, Management and Planning: Theory and Case Studies*, D.A. Wilhite (ed). Kluwer, Boston, Massachusetts, USA, pp. 109-130.

MMWR. 1990. Arboviral surveillance - United States, 1990. *MMWR* 39(5),593-597

Monath, T.P. and T.F. Tsai. 1987. St. Louis encephalitis: Lessons from the past decade. *American Journal of Tropical Medicine and Hygiene* 37(3) suppl., 40S-59S.

New, M. and M. Hulme, 1997. Construction of 3 minute latitude/longitude monthly climatic surfaces over Africa for the period 1951-1995. New annual digital surfaces, commissioned by the Highland Malaria Supplement to the MARA/ARMA collaboration.

NHMRC. 1991. *Health Implications of Long-Term Climatic Change*. Australian Government Publishing Service, Canberra, Australia.

Omumbo J, J. Ouma, B. Rapouda, M. Craig, D. le Sueur, and R.W. Snow (1998). Mapping malaria transmission intensity using information systems (GIS): An example from Kenya. *Annals of Tropical Medicine and Parasitology* 92, 7-21.

Parry, M.L. and C. Rosenzweig. 1993. Food supply and the risk of hunger. *Lancet* 342, 1345-1347.

Patz, J.A. 1995. Assessing the public health effects of global warming: New and ongoing international efforts. *World Resource Review* 7(1), 104-112.

Patz, J.A., P.R. Epstein, T.A. Burke, and J.M. Balbus. 1996. Global climate change and emerging infectious diseases. *Journal of the American Medical Association* 275, 217-223.

Patz, J.A. W.J.M. Martens, D.A. Focks, and T.H. Jetten. 1998. Dengue fever epidemic potential as projected by general circulation models of global climate change. *Environmental Health Perspectives* 106(3), 147-153.

Reeves, W.C. et al. 1994. Potential effect of global warming on mosquito-borne arboviruses. *Journal of Medical Entomology* 31, 323-332.

Risk Assessment Forum. 1992. *Framework for Ecological Risk Assessment.* EPA/630/R-92-001. US Environmental Protection Agency, Washington, DC.

Rogers, D.J. and S.E. Randolph. 1991. Mortality rates and population density of tsetse flies correlated with satellite imagery. *Nature* 351,739-741.

Root, T.L. and S.H. Schneider. 1995. Ecology and climate: Research strategies and implications. *Science* 269, 334.

Rotmans, J. 1990. *IMAGE: an Integrated Model to Assess the Greenhouse Effect*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Washino R.K., and B.L. Wood. 1994. Application of remote sensing to arthropod vector surveillance and control. *American Journal of Tropical Medicine and Hygiene* 50 (6 Suppl.), 134-144

Watts D.M., D.S. Burke, B.A. Harrison et al. 1987. Effect of temperature on the vector efficiency of *Aedes aegypti* for dengue 2 virus. *American Journal of Tropical Medicine and Hygiene* 36, 143-152.

WHO. 1992. *Vector Resistance to Pesticides.* Fifteenth Report of the WHO Expert Committee on Vector Biology and Control, WHO Technical Report Series, 818 World Health Organization, Geneva.

WHO. 1946. Constitution of the World Health Organization. Taken from Final Acts of the International Health Conference, held in New York from 19 June to 22 July, 116p

World Bank. 1992. *World Development Report 1992: Development and the Environment.* Oxford University Press, New York.

World Bank. 1993. *World Development Report 1993: Investing in Health.* Oxford University Press, New York.

World Resources Institute. 1995. Africa Data Sampler. Digital database and documentation. World Resources Institute, Washington, DC, USA.

11 Energy

Lead Author
Frank Stern [1]

11.1 Nature and scope of the problem

Climate change could have significant effects on the energy sector in many countries. Rising temperatures, changes the amount of precipitation, and variation in humidity, wind patterns, and the number of sunny days per year could affect both consumption and production of energy. In some countries, these impacts could be profound. The nature and magnitude of impacts may not be easy to predict, owing to counteracting effects and uncertainty surrounding both climate change and baseline projections of energy use.

While substantial work has been conducted to link changes in the global climate to the use of energy, specifically fossil fuels, less work (particularly related to developing countries) has been conducted on the reverse effect — that of climate change on the energy sector. The several studies that have been conducted provide some indication of the types of impacts that can be expected. For example, in the United Kingdom, which currently has a cool climate, projected higher temperatures would decrease overall energy demand, since demand for space heating would decline with global warming. This effect would outweigh the higher demand for air conditioning and the net increase in the amount of electricity demanded (United Kingdom Climate Changes Impacts

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[1] Hagler Bailly Consulting, Inc., Boulder, Colorado, USA.

Review Group, 1991). Yet, according to Linder and Inglis (1989), global warming could increase annual electricity generation and generation fuel use in the United States by 4 to 6 percent by 2055.

Because many components of the energy sector are capital intensive and require long-term planning, there could be significant financial implications stemming from climate-induced changes to the consumption and production of energy. Estimates of changes in energy use to climate change are needed to help ensure energy demand is met, and to allow the development of adaptation policies that may prevent, reduce, or more equitably share losses brought about by climate change.

One of the most significant impacts of climate change on the energy sector could be any policies developed to ameliorate climate change, particularly in the next few decades. The proposed targets for greenhouse gas emissions, and the policies proposed to bring about those limitations, will profoundly affect the consumption and production of energy. The topic of climate change policy and its effects on the energy sector is discussed in detail elsewhere (e.g., IPCC, 1995).

11.1.1 Effects on energy consumption

The most significant impacts of climate change on energy consumption are likely to be the effects of higher temperatures on the use of electricity and on the direct use of fossil fuels for heating. Increases in extreme weather might result in some regional changes in consumption if such weather changes result in population shifts.

11.1.1.1 Effects on electricity consumption

Climate change is likely to affect the following major electric end uses:

- air conditioning;
- space heating;
- water pumping;
- refrigeration;
- water heating.

Of these end uses, air conditioning and space heating are those most likely to be significantly affected by climate change, since both are functions of the indoor-outdoor temperature difference. A temperature increase would increase air conditioning use and saturation (the fraction of buildings having air-conditioning equipment). In countries in low latitudes, which generally already have warmer climates, such an increase could significantly affect overall energy demand. Linden and Inglis (1989) found that in the southern United States, electricity demand would increase by 10 to 15 percent. In high

latitude areas, which generally have cooler climates, the increase in the demand for air conditioning would be relatively small. Linden and Inglis found that electricity demand in the northern United States would change slightly in a positive or negative direction. Further, electric space heating use would decrease with increased temperatures, but this impact would probably not be significant in low latitudes. This could be a significant effect in those high latitude areas where electric space heating is used.

Looking briefly at the other end uses, water pumping requirements can be significant if the climate becomes warmer but not wetter, because of increased water needs for irrigation and residential, commercial, and municipal watering. Refrigeration requirements would increase and water heating requirements would decrease, although the direct effects are likely to be significantly less than the effects on space conditioning. Refrigeration and water-heating equipment is often located in conditioned spaces (i.e., spaces that are heated or cooled to a relatively constant level), and thus are not affected by outdoor temperature changes. Refrigeration equipment evaporator coil temperatures (which are in contact with the air inside the cooled space) are significantly lower than those of air conditioning equipment, and water heaters heat to temperatures significantly hotter than room temperatures. Consequently, the temperature differences that these types of equipment operate with are greater than those with which space heating equipment operates. So these uses would be less sensitive to changes in outdoor temperature even when the equipment is in unconditioned spaces.

The impacts on an electricity system also depend on the mix of resources used for heating and cooling. For example, if air conditioning is produced using electricity, but space heating is provided by gas furnaces or boilers, then global warming will increase the use of electricity, even in a cool climate. Total energy demand, however, could be reduced even though demand for electricity increases.

The magnitude of the impacts depends on the electricity usage patterns in the absence of climate change (i.e., baseline demand). Increases in electricity demand caused by economic development and increased standards of living are likely to occur along with climate change. For example, air conditioning is more prevalent in developed countries. As developing countries increase their standard of living, their use of air conditioning increases, as will their sensitivity to climate change. An accurate determination of the baseline demand for electricity, or the demand before global warming, is important in reliably estimating the effects of climate change. Any estimates of baseline demand should take into account substantial uncertainty over long periods.

11.1.1.2 Direct use of fossil fuels

The use of natural gas, oil, and fuel wood to provide space heat in residences and buildings will be the type of direct use of fossil fuels most affected by climate change. Natural gas is used to a limited extent for cooling and this use is likely to increase, but this use is substantially smaller than the use for heating. If climate change shortens the cold season and reduces the severity of cold weather events, energy demand for heating

will be less. Consequently, the direction of effects of climate change on the direct use of fossil fuels is easier to identify — this use is likely to decrease.

11.1.2 Effects on energy production

Changes in energy consumption as a result of climate change will lead to changes in energy production. Climate change itself could also have direct effects on the production of energy. These effects may be seen primarily in electric generation, including hydropower, thermal electric generation, solar and wind power.

11.1.2.1 Hydroelectric generation

The effects of climate change on river flows are uncertain, but any significant changes would have implications for hydroelectric generation. Climate change could affect the amount and seasonality of flow in most rivers (see Chapter 6, Water Resources), which could affect the amount of electricity produced annually by hydroelectric and the timing of power production.

Hydroelectric generation may be much more sensitive to changes in river flows than other types of water systems. This would be the case when the water rights of irrigation and municipal water systems are senior to those of hydroelectric generation. In a low water year, water may be drawn off upriver from the turbines to meet these needs. Consequently the reduction in hydroelectric generation may be substantially greater than the reduction in river flow. If river flows increase, the increase in electric generation may be greater than the river flow increase, if upriver senior water rights are relatively fixed. Such an increase in generation would be constrained by reservoir and turbine capacity. Hydroelectric generation in the Colorado River Basin has been found to be extremely sensitive to changes in climate (Nash and Gleick, 1993). A 20% reduction in natural water runoff was projected to cause a reduction in power generation of 60%, whereas a 20% increase was projected to cause an increase in generation of 40%. This study was not able to say with certainty whether runoff would increase or decrease.

In areas dominated by snow melt, flow and consequently hydroelectric generation could increase in the winter and decrease in the summer (e.g., see Lettenmaier et al., 1992). In a region with a summer peak demand for electricity, the net effect could be substantially increased costs for electricity. This has been projected for Pacific Gas & Electric, a California utility that owns 3,903 MW of hydroelectric generation (Hanemann and McCann, 1993). Its variable cost would increase by 12-32 percent, or US$145-370 million.

In areas where it becomes hotter and drier, hydroelectric power generation could be reduced virtually year-round. A reduction in hydropower generation would have to be made up by more thermal electric generation.

An example of the potential effects of climate change in a hot and dry climate is provided by the recent drought in Ghana (French, 1998). Ghana is heavily reliant on hydropower for electricity production and has no other indigenous sources of power. While hydropower is inexpensive, it is also vulnerable to climate variability. A severe drought in the spring of 1998 resulted in hydropower dams producing less electricity. Total power production in the country has fallen by 40%, threatening the economy. Businesses from tuna canneries to clothing manufacturers are reducing output and shortening the work week. Thus, a heavy reliance on hydropower may be good for reducing greenhouse gas emissions and improving air quality, but can increase vulnerability to climate change.

11.1.2.2 Thermal electric generation

Thermal electric generation from fossil fuels and nuclear power could also be affected by climate change. Higher ambient air temperatures will decrease the efficiency and capacity ratings of natural gas or oil fired combustion turbines. Increases in ambient temperatures and humidity will also be detrimental to electricity generation from gas, oil, or nuclear steam cycles, which rely on cooling towers for the condensing process. The overall effect of global warming on thermal electric power production is likely to be small, however. The efficiency of a plant is a function of the ratio of the high and low temperatures in the power cycle. Since the difference in high and low temperatures is typically over 500□C, the temperatures changes projected from climate change are likely to have an impact of significantly less than 1 percent. One US utility estimated that the maximum impacts of climate change on both efficiency and capacity are between 0.1 and 0.2 percent (Linder et al., 1987).

Nuclear power plants are designed for operation within certain temperature ranges. Some plants have been forced to close down on extremely hot days. Climate change might require modifications to allow such plants to continue to operate in warmer temperatures.

Plants located along a river or in a coastal zone could be at risk. Increased river flows could lead to flooding problems, and decreases could require a plant to shut down if inadequate water is available for cooling purposes. Power plants in coastal zones could be at risk of inundation from sea level rise. An increase in severe storms such as cyclones and monsoons could damage plants in coastal zones.

Thermal electric generation may also be affected indirectly by shifts in consumption patterns. In cool climates, the use of natural gas for heating is likely to be reduced, making gas less expensive and more available for power generation. This could result in gas being substituted for coal, which would result in the emission of less carbon dioxide. Reduced emissions of this greenhouse gas would tend to help prevent climate change.

In warm climates, increased demand for cooling resulting from climate change may require significant increases in new generation capacity. Reduced hydroelectric gener-

ation would exacerbate this problem. Additional US investments in new capacity by 2055 have been estimated as between US$170 billion and US$330 billion (Linder and Inglis, 1989).[2] In cooler regions, climate change may defer new capacity needs.

11.1.2.3 Solar and wind power

Climate change may also affect the supply of energy from solar and wind power. Changes in the number of sunny days per year could affect a region's ability to use the sun as a source of energy. Climate change may also lead to changing wind patterns, which may increase or decrease the availability of wind as a source of energy. It is unclear whether the effects on solar and wind power will increase or decrease the potential supply from these sources.

11.1.2.4 Other energy production effects

Electric transmission lines have greater resistance in warmer temperatures, and thus climate change will result in increased line losses. Resistance of aluminium and copper wires increases by approximately 0.4 percent with every degree centigrade of temperature increase between 0°C and 100°C. For a country with 8 percent line losses, a 3°C temperature increase will cause line losses to increase to almost 9 percent, causing an increased need for generation of about 1 percent.

Fuel wood supply may also be susceptible to the impacts of climate change. The supply of this primary source of energy in large regions in Africa and south-eastern Asia may change significantly with changes in temperatures. The impacts of climate change on fuel wood supply are not conclusive; however, if woody plants cannot respond to rapid temperature changes, many regions may experience a shortage in the supply of energy (Riebsame, 1989).

Costs for oil and gas exploration, development, and transportation in polar regions may be affected. A study of the Mackenzie Basin (Cohen, 1997) found both positive and negative impacts on all aspects of production. Pipelines built on permafrost may require structural retrofitting if the permafrost melts because of climate change. This cost may be counterbalanced by reduced operation and maintenance costs. New pipeline costs are likely to be greater, because they must be designed for a range of conditions. A reduction in ice levels is likely to reduce costs of marine transportation, although higher waves and coastal erosion near ports would increase costs. Costs of offshore exploration may be reduced because of longer seasons and less need to withstand ice loads, but these effects may be counterbalanced by costs of withstanding higher waves and costs of the increased difficulty in containing spills.

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[2] This study assumed about a 3°C warming and no improvement in technology.

Any type of energy production facilities located near or in the ocean, such as power plants and oil and gas production facilities, could be subject to damage from sea level rise. Also, virtually all energy production facilities, including electric transmission lines, thermal power plants, wind and solar generating stations, and oil and gas production facilities, are subject to damage by extreme weather, which could increase in intensity and frequency under climate change. If increases in extreme weather result in population shifts, some existing production facilities may lose utility, causing a reduction in production or closure, if the demand they were designed to serve is reduced. This could result in financial losses to the owners of the plant and increased costs to remaining customers.

11.1.3 What impacts are important?

The overall impacts on the energy sector in a country are difficult to determine without analysis: they depend on the mix of types of energy uses and production. In general, however, the most significant effects are likely to be on use in the residential, commercial, and institutional sectors, because of the use of space heating and cooling, and in the electric generation sector because of changes in demand from the residential and commercial sectors and changes in hydroelectric generation. Because it is highly capital intensive and has a long planning horizon,[3] the generation sector may be most at risk in terms of financial impacts. Because of the sensitivity of hydroelectric generation to changes in precipitation, and the uncertainty associated with changes in precipitation, climate change could have dramatic effects on countries dependent on hydroelectric generation and subject to significant changes in precipitation. Increases in extreme weather events could significantly disrupt energy production (including transportation) in some countries.

If a country is large enough to have significantly different climates, it will be necessary to examine impacts within different climate zones. Generally speaking, the greatest impact is likely to be seen in the hottest and coldest climates, where the changes in use are likely to be all in the same direction (e.g., in a cold climate, there would be no significant air conditioning needs, so there would be no significant cancellation of the effects of reduction in space heating use). The fuel most affected depends on the mix of fuel used. In hot climates, the fuels used for generation of electricity will be most affected. In most cold climates, fossil fuels used directly for space heating will be the fuel use most affected, although this may not be the case in regions with abundant hydroelectric, nuclear, or geothermal resources.

The baseline energy intensity, or energy use per capita, of different regions of a country is a key factor in the relative effects of climate change. Regions with a low level of energy use are likely to see little impact on an absolute basis, although the effects could

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[3] This planning horizon has been growing shorter in recent years, as discussed in Section 11.3.2.

still have a significant impact in terms of welfare. The rate of economic development is a key factor in projecting the baseline energy intensity.

The effects of climate change on energy use could have an impact on environmental policies, including policies to prevent climate change. For example, increased combustion of fossil fuels to meet increased demand of electricity or due to direct use of fossil fuels could make compliance with existing or proposed NO_x, SO_2, O_3, CO_2, or other emission requirements more difficult.

11.2 An array of methods

Several methods can be employed to assess the potential impact of climate change on the energy sector. The methods discussed in this section delineate a selected range of options available to countries. Some of the methods will produce detailed estimates of the impacts. These methods may require greater expertise, more money, and more time. Other methods will yield simpler and rougher estimates, but they may require fewer resources.

A country in the process of selecting a method will first need to assess its priorities (e.g., the level of detail desired for outputs from the method); its available assets for estimating climate change impacts on the energy sector (e.g., time, money, expertise); the availability of other inputs (e.g., data, computers, models); its estimated vulnerability to climate change (based on existing knowledge); and its potential risks associated with inaccurately assessing the impacts of climate change on the energy sector. By doing so, countries can select the method that falls within its time and resource constraints and whose results best meets its specific needs.

This section addresses the use of the following types of methods:

- expert judgement;
- analogue approaches;
- quantitative models, including econometric/statistical, engineering, and hybrid.

For each method, the resolution of results, data needs, time requirements to use, and skill or training requirements are discussed.

11.2.1 Expert judgement

The expert judgement method is the simplest, least time consuming, and least costly method discussed in this chapter. A detailed understanding of energy use in a country and the relationship between climate and energy use may suffice to make preliminary estimates regarding the impacts of climate change on the energy sector. This method is probably best suited to determining the need and establishing hypotheses for future,

more sophisticated analysis. Expert judgement may be useful in identifying the sub-sectors in which impacts are most likely to be significant. Experts on residential and commercial building energy use and hydropower generation might be consulted to develop a preliminary understanding of where research resources should be focused.

Expert judgement should be able to indicate the direction of change in energy use that countries with the warmest and coolest climates could reasonably expect to stem from climate change. In warmer countries such as Egypt, it is likely that energy use will increase because of the lack of heating needs and the presence of air conditioning. The greater the presence of air conditioning in the baseline projection, the greater the impact is likely to be. In colder countries, detailed analysis is probably not necessary to establish that energy use is likely to decline. Care must be taken, of course, to include complicating factors such as changes in the Gulf Stream flow. Expert judgement would probably not yield reliable results for the potential magnitude of these impacts.

Expert judgement may be unreliable in establishing even the direction of overall impacts in temperate climates. Because the combined impacts from increasing energy use to cool buildings and decreasing energy use to heat buildings may be problematic, ascertaining the directional change of energy use may be impossible without a more sophisticated method.

11.2.1.1 Resolution of results

Residential and commercial building experts might be able to project whether impacts within a specific residential and commercial end uses, and within broad climate zones, are likely to be significant or not. Given an appropriate understanding of climate and energy use, an expert could provide judgement on impacts on specific cities. A hydroelectric generation expert could offer an opinion on the relative magnitude of change in generation, given a specific change in precipitation. Further resolution of results would probably not be reliable.

11.2.1.2 Data requirements

Data requirements are relatively low, although the use of expert judgement does require an understanding of the distribution of projected energy use by:

- primary fuel coal
  - oil
  - natural gas
  - nuclear
  - hydropower
  - solar
  - wind
  - geothermal
  - biomass.

- subsector
  - residential
  - commercial
  - industrial
  - electric utility
  - other.

- end use
  - space heating
  - air conditioning
  - water pumping
  - refrigeration
  - water heating
  - other.

Because energy use is likely to change substantially in developing countries in the absence of climate change, an understanding of projected energy use over the time of interest (which can be several decades for climate change assessments) is essential. A baseline estimate of increasing electricity use is not sufficient basis for developing an expert judgement on the effects of climate change. The expert must know to whether this increase is due to the increased purchase and use of air conditioners, the use of which would be strongly affected by climate change, or personal computers and refrigerators, the use of which would not be strongly affected by climate change.

The expert must also have an understanding of the likely effects of climate changes. The types of effects to be considered include the average change in temperature, changes in precipitation, and changes in stream and river flows.

11.2.1.3 Time requirements

The time requirements to use expert judgement are relatively modest — a matter of a days, assuming that an expert is available. The time required would be inversely proportional to the expert's knowledge of a country's energy use.

11.2.1.4 Skill or training requirements

Expert judgement presumes expertise. Achieving a level of expertise to make an expert judgement on the effects on energy use of climate change requires years of specialised training in physics, engineering, statistics, or economics. Little additional training or study would be required.

11.2.2 Analogue methods

When an analysis with greater detail than the expert judgement method is desired, but not enough country-specific information on energy use is available for quantitative approaches, it may be appropriate to use the analogue method. In the analogue method, climate change impact estimates for another country for which more information is available are adapted for use in another country. The basis of this approach is an assumption that the country of interest will have an energy use response to climate change which is similar to that of another country or region.

This approach can also be used to capture baseline changes in the energy sector due to a country's economic development. A country undergoing rapid growth is likely to have substantially different use patterns over the periods involved in many climate change scenarios. It may be more appropriate to assume that a developing country 50 years in the future might have usage patterns similar to those found in a developed country today, rather than attempt to project today's usage patterns. An example of this is shown in Box 11.1.

This approach is most likely to be successful if the projected energy use of a subsector (e.g., residential and commercial building energy use) is expected to be reasonably similar in the region of interest and in the analogous region.

11.2.2.1 Resolution of results

The results will, at best, be only as good as the original study, and will depend on the appropriateness of the analogy between the region or country of interest and the region or country that was the subject of the study. The spatial resolution depends on the number of analogies made — in a country with generally similar climate, one analogy may be sufficient. In a large country with many different climates, several analogies must be made. The temporal resolution depends on the resolution of the study on the analogous region.

11.2.2.2 Data requirements

Climate and energy use indices in the region of interest and the analogue region must be available to establish whether the analogy is appropriate. A typical climate index is degree days. Degree days reflect the difference between some reference temperature and outdoor ambient temperatures over a year. Both heating and cooling degree days are used. A relatively high number of heating degree days indicates a cold climate, and a high number of cooling degree days indicates a hot climate.

Energy use should also be similar between the two regions. Where energy use in a developed country is used as an analogy for future energy use in a developing country, it is not necessary to compare current use. It is important, however, to establish whether fuel availability would allow use in the developing country to become similar to use in

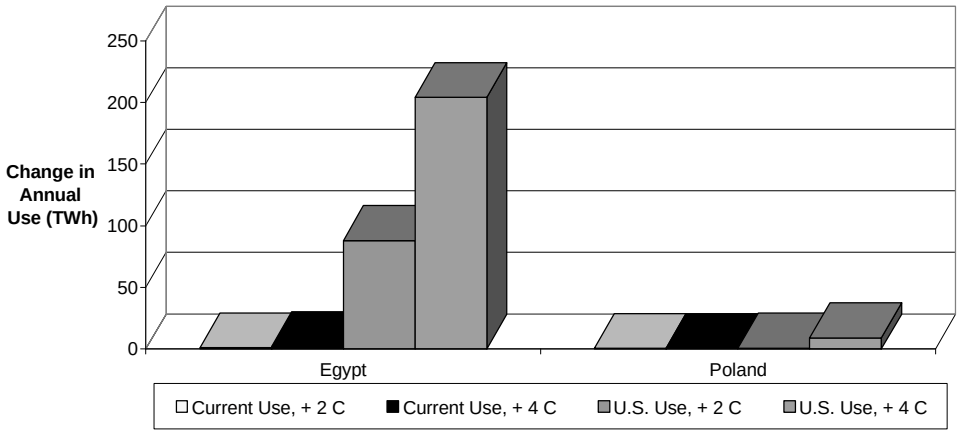
the developed country. For example, if the developed country has abundant natural gas and uses significant quantities of it, but the developing country is an island country with no indigenous gas, the two countries are probably not analogous.

Box 11.1 Example of the use of the analogue method in two countries in transition.

A study sponsored by the International Institute for Applied Systems Analysis (Smith et al., 1994) was the first analysis of climate change and its potential effects on the thermoelectric power sector in developing countries and countries with economies in transition, and in Egypt and Poland in particular. The study addressed how economic development in the two countries may affect sensitivity to climate change. The countries represent different economic situations: Poland currently has a higher standard of living than Egypt. They also represent different climatic sensitivities to thermoelectric power use and production: Poland has a high-latitude climate and Egypt has a desert climate. The goal of this study was to take a "first cut" at the sensitivities of these sectors to climate change and to develop bounds for possible impacts. Using different regions in the United States as analogues, the authors developed quantitative estimates of changes in demand for electricity in Egypt and Poland in 2060 under different assumptions of climate change and change in baseline economic conditions.

Two sets of assumptions were made about baseline electricity demand. The first assumed that the per capita standard of living in Egypt and Poland in 2060 does not change from their 1990 levels. This is unlikely over such a long period of time, but sets a lower boundary for standard of living. The second assumed the standard of living in both countries in 2060 is the same as the 1990 standard of living in the United States. This assumption is also unlikely, given projected economic growth rates, but serves as an upper boundary for standard of living. Under the second assumption, the authors used electricity consumption patterns from states in the United States with climates most similar to Egypt or Poland. They then used an engineering approach to project the effects of climate change in both countries under the two different standard of living assumptions.

The analysis found that the effects of climate change on energy use in Egypt may be pronounced, but only if significant economic development takes place, resulting in increased use of air conditioning. The effects in Poland are likely to be minor — a small increase in air conditioning electricity demand is cancelled by a decrease in space heating electricity demand. In these two countries, development and growth may actually affect thermoelectric industries and the demand for electricity to a much greater extent than will climate change. For areas most sensitive to climate change effects on the thermoelectric power sector (i.e., low latitudes), the estimated impacts on electricity demand are greatly influenced by differing assumptions about baseline demand, which are largely driven by expectations about economic growth and standards of living. For long-term planners, accurately estimating baseline energy use is integral to the reliable estimation of the change in electricity demand as a result of climate change. This study shows that long-term forecasts of electric power needs for low latitude countries should also consider the effects of climate change because it could add as much as one-seventh to potential increases in demand from population and economic growth.



Box 11.1, Figure 1 Estimates of effects on electricity demand using the analogue approach.

11.2.2.3 Time requirements

The primary reasons for using the analogue method are its expediency and economy. If a completed study for an analogue country is available, and climate data are available for the country of interest, the analogue method may be completed in a matter of weeks. The precise time requirement depends on the level of resolution required. If the analysis requires conducting a study on a analogue country for which more detailed data are available but a completed study is not, the time requirement would be much greater.

11.2.2.4 Skill or training required

Using the analogue method requires an understanding of the nature of energy use in the country of interest and the analogue country, and a good understanding of the relationship between climate change and energy use. Training in physics, engineering, statistics, or economics would be useful.

11.2.3 Quantitative methods

Quantitative methods can be broadly categorised within two basic approaches: econometric/statistical methods and engineering end-use methods. The first approach, sometimes called “top-down,” infers demand relationships using statistical models based primarily on economic theory, whereas the second approach, sometimes called “bottom-up,” relies more heavily on engineering principles. The distinction between these two approaches becomes blurred in hybrid approaches, which use both methods.

11.2.3.1 Econometric/statistical methods

Econometric and statistical approaches use statistical models to attempt to draw inferences about the relationship between energy use and climate based on historical data. Econometric models are derived using economic theories of purchasing behaviour. Simple engineering principles such as degree day variables may be incorporated in the specifications of the models.

Because the models typically use income and prices as variables, these models are well suited for analysing tax and subsidy policies. They are not well suited, however, to modelling policies that mandate efficiency levels, such as building standards (Braithwait and Gelling, 1992).

Econometric models can use data over a wide range of aggregation. At the most aggregated level, an analysis might use, as an independent variable, energy use for an entire country. At the most disaggregated level, energy use in individual buildings might be modelled. The example in Box 11.2 presents the use of a highly disaggregated data set. Linder et al. (1989) present an example of such analysis conducted at a utility level.

Box 11.2 Example of the use of econometric models.

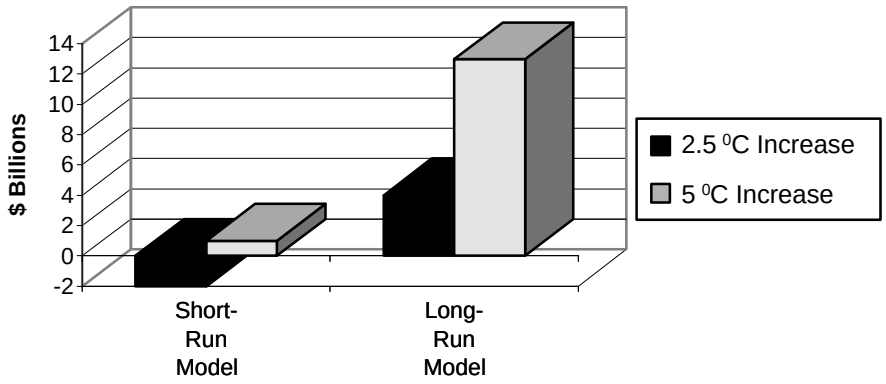
Morrison and Mendelsohn (in press) developed econometric models of US energy demand and used them to simulate the effects of climate change on US energy expenditures by the residential and commercial sectors. They used ordinary least squares regression analysis to estimate total expenditures on electricity, natural gas, fuel oil, liquid petroleum gas, district heat, and kerosene.

They developed two types of models: a long-run model and a short-run model. In the short run, people will not make significant changes to their buildings in response to climate change — they will tend to make behavioural adjustments that will reduce energy expenditures. In the long run, people will modify buildings and build new buildings to be better adapted to the climate. The short-run model included consideration of climate sensitive building characteristics, effectively holding them constant; the long-run model did not explicitly consider these variables, thereby allowing them to adjust with climate. The terms “long run” and “short run” do not reflect the period of analysis that the models consider.

Within these two types of models, they developed residential and commercial models. For their data sources, they used the results of detailed surveys of the two sectors conducted by the US government. These surveys provided detailed data on fuel consumption, climate variables, demographic and business enterprise information, and building characteristics for each building in the sample. Demographic data used for the residential model included average fuel prices, use of alternative fuels, average income range, family size, age of household head, race, and receipt of government assistance. Data on firms used for the commercial model included average fuel prices, use of alternative fuels, months open per year, and types and percentages of various building characteristics. Nonclimate sensitive building characteristics included square meters, number of floors, and building age. Climate sensitive building characteristics included building material, conservation efforts, heating and cooling equipment, and high energy-consuming appliances.

The authors analysed the effects of three climate change scenarios (1.5□, 2.5□, and 5□C increases) for a 1990 and a 2060 economy. Accounting for a 2060 economy included consideration of GDP, per capita growth, population growth, fuel price changes, and building stock age.

The results showed that the residential sector was more sensitive to climate change than the commercial sector, and that the residential sector was likely to realise a net increase in energy expenditures, while the commercial sectors were likely to see a net decrease. Results varied by climate zone — both sectors are expected to realise benefits in the colder regions and increased costs in the warmer regions. For the United States overall, the study projected a range of effects. For a 2.5□C increase, the range of effects is projected to be from a US$ 2 billion gain (short-run model) to US$ 4 billion in costs (long-run model). If temperatures increases by 5□C, the impacts are projected to be costs ranging from $ 1 billion (short-run model) to $ 13 billion (long-run model). Costs estimated by the long-run model are higher than those estimated by the short-run model because of increased saturation of cooling equipment in response to warming. Since the long-run model allows more flexibility, it may be surprising that it finds higher costs. The estimates, however, relate to energy expenditures only, ignoring comfort levels. Costs and savings of building characteristics adjustments have not been accounted for, so both total costs on the cooling side and benefits on the heating side are expected to be above the estimates produced, particularly in the long-run model.



Box 11.2, Figure 1 Estimates of damages using econometric approach. Source: Morrison and Mendelsohn, in press.

Statistical models can be used as the basis for projecting the effects of variations in river and stream flows as a result of climate change on hydroelectric generation, if flow histories and projections are available. Linder et al. (1989) used ordinary least squares regression analysis with a logistic, single variable model to project hydroelectric generation.

Resolution of results

Resolution of results depends on the level of detail and the number of observations of the dependent variables. If data are available for a large sample at the building and end-use level, across several climate zones, estimates of end-use impacts by building type and climate zone may be possible.

Data requirements

Data requirements vary. Simple, aggregated data analysis requires only historical national or regional estimates of energy use and historical and projected average temperatures. The most disaggregated analysis requires detailed data on samples of buildings and residences at a regional level, and also historical and projected average temperatures.

Time requirements to use

Time requirements are roughly proportional to the level of disaggregation of the data being analysed, but are on the order of weeks or months.

Skill or training required

A statistical or econometrics background is most useful for applying this type of method. An understanding of physics and engineering principles is essential to develop reasonable specifications.

11.2.3.2 Engineering end-use methods

Engineering models for analysis of the impacts of climate change typically involve the analysis of demand by end use (e.g., space heating, space cooling) using engineering principles. To assess climate change impacts, only a few end uses need to be addressed, which simplifies the analysis. Usually only space heating and space cooling are modelled, since the effects of climate change on other end uses are likely to be relatively small. The engineering methods used are typically either some type of degree day algorithm or a building simulation model. The degree day method is much simpler than the building simulation model approach, but offers less resolution and accuracy. Engineering methods also can encompass hydrological models of the effects on hydroelectric generation of river flows. An example of an engineering approach that modelled heating, cooling, and water pumping energy use is shown in Box 11.3.

Both the degree day approach and the building simulation approach require some type of exogenous projection, either baseline end-use energy for the degree day approach or numbers of buildings and building characteristics for the building simulation approach. Accurate projections are likely to require consideration of econometric principles.

Such models can have a greater appeal than econometric approaches because of the clear association between energy-using equipment and use. Because of this clear association and because of the detail involved, the more detailed models are well suited to modelling mandatory efficiency standards or other types of policies that involve the substitution of capital for energy.

The principal shortcoming of engineering end-use methods is their lack of consideration of price elasticity response and their dependence on exogenous projection of number of units. They are, consequently, not well suited to modelling effects of changes in energy prices and income levels. They do also not implicitly account for voluntary substitution of capital for energy, which would tend to reduce energy use. These shortcomings can be overcome through the incorporation of econometric principles into the models, the result being the hybrid approaches discussed below.

Box 11.3 Example of an engineering approach.

Baxter and Calandri (1992) used an engineering end-use approach to model the effects of climate change on annual energy use and peak demand in 2010 in California. They focused on heating and cooling of buildings, and pumping of water for farms and cities. The study used engineering simulation techniques for the baseline projection of heating and cooling use and econometric techniques for the projection of municipal pumping requirements, but relied primarily on the degree day method.

Impacts were projected by end use, using data on population and economic growth, building and appliance stocks, and the operation of appliances. Four separate models were used: a residential buildings model, a commercial buildings model, an agricultural and water pumping model, and a peak demand model. The peak demand model translated projections of energy use from the first three models into estimates of peak demand, using a response surface model derived from building simulation analysis to translate cooling impacts to each hour of the peak day.

The residential and commercial models used building simulation-derived estimates of baseline energy use for prototypical buildings. The residential model includes data on 21 residential end uses in three building types for each of the 13 climate zones modelled. The commercial model includes data on eight end uses in 11 building types for each of the climate zones. The authors modified the projections of usage rate in each building type using the ratios of degree days in the climate change and baseline scenarios.

The agricultural and water pumping model took into account both changes in water demand and changes in electricity needed to meet this demand. Changes in water demand result from changes in crop choice and increased evapotranspiration. Changes in crop choice were modelled using a linear program algorithm. Increased demand for urban water was modelled with an econometric model of water demand as function of price, income, summer temperature, and household formation rates. The modelling of electricity required to meet this demand took into account the likely changes in the source of water from surface water to groundwater, and the increased pumping requirements as groundwater levels drop.

The results showed that with their worst scenario, a 1.9□C increase in temperatures, state-wide electric energy use would increase by 2.6% and peak demand would increase by 3.7%. Peak demand increased at a higher rate than energy use because California utilities tend to be summer peaking. The increased need for water pumping contributed 34% of the increased energy requirement and 20% of the increased peak demand.

11.2.3.3 Degree day approach

The degree day approach (ASHRAE, 1997) assumes that fuel use for heating and cooling is proportional to the number of heating and cooling degree days, respectively. This assumption is generally quite accurate for modelling heating using fossil fuel combustion. It is less accurate for modelling heat pumps and air conditioners using a refrigeration cycle, because efficiency of the system is a function of outside temperature. In modelling the effects of warming, the approach tends to understate savings from heat pump heating and understate increased energy from heat pump and air conditioner cooling. The degree day approach does not consider changes in humidity — changes

that may be significant as a result of climate change. Humidity changes would be best accounted for with a building simulation model.

The key to accurate assessment with the degree day method is selecting appropriate average balance points for the base used to calculate the degree days. The balance point represents the temperature at which a building requires no space heating or cooling. A base of 18°C has been traditionally used for measuring degree days, but this base may not be appropriate for most buildings because typical balance temperatures are different. Solar heat gains and internal heat gains from lights, people, and electric equipment decrease the balance point of a building, as does thermal insulation. Balance points tend to be lower for commercial buildings than residential buildings because of the higher level of internal gains and the greater significance of core areas, which tend to require cooling at all times. Balance temperatures decline as insulation levels and internal gains increase. In the United States, a typical balance point for commercial cooling and heating is 10°C, whereas a typical balance temperature for residential heating is 15.5°C. Balance temperatures for cooling can vary considerably, depending on the use of natural ventilation, and can range from 18°C to 27°C. It is best to conduct a study of the balance points for a specific country. Examples of degree day approaches include Baxter and Calandri (1992; see Box 11.3) and Rosenthal et al. (1995).

11.2.3.4 Building simulation models

Building simulation models can offer an improvement in precision relative to degree day approaches and eliminate the need for assumptions about balance temperatures. Such models typically calculate a building's heat gains and losses on an hourly basis. Changes in humidity and the effect on cooling requirements can be accounted for by these models. Scott et al. (1994) found that the non-linear relationship of humidity and temperature is a key factor in the tendency for simple degree day approaches to underestimate cooling at higher temperatures. Sophisticated representations of building heating, ventilating, and air conditioning systems can be developed in the more detailed models. A list of such detailed models is presented in Table 11.1.

Simulation approaches use building prototypes to represent average construction characteristics for a building segment. Simulation models may also be used in combination with degree day approaches, as illustrated in Baxter and Calandri (1992).

Resolution of results

The resolution of results depends on the disaggregation of the data used. The best resolution is achieved through the use of many building segments and climate zones.

Table 11.1 Detailed building simulation models.

Model	Authoring Organisation
BLAST 3.0	US Army Construction Engineering Research Laboratory, USA
DOE-2.1d	Los Alamos National Laboratory and Lawrence Berkeley Laboratory, USA
ESP-RV8	Strathclyde University, Scotland, UK
SERIRES/SUNCODE 5.7	National Renewable Energy Laboratory and Ecotope, USA
SERIRES 1.2	National Renewable Energy Laboratory, USA Building Research Establishment, UK
S3PAS	University of Seville, Spain
TASE	Tampere University, Finland
TRYNSYS	University of Wisconsin, Madison, USA

Source: Judkoff and Neymark, 1995.

Data requirements

The degree day approach requires substantially less data than the building simulation approach. Simpler degree day approaches require only a projection of fuel use by end use and estimates of degree days. Rosenthal et al. (1995) derived this projection for US residential and commercial end uses, by building type from a nation-wide projection of space conditioning energy use. More detailed degree day and simulation models, which could be used to assess policy effects, would require more detailed data on number of buildings and equipment capacity. Simulation approaches require detailed data on construction characteristics of buildings.

The degree day approach requires estimates of degree days, using an appropriate balance temperature as the base. Thom (1966) provides a method for computing degree days as a function of average temperature and the standard deviation of temperature, which is useful if hourly data are not available.

Simulation modelling requires detailed, hourly information on temperature, solar radiation, cloud cover, and wind speed and direction. Some models use standardised formats such as Typical Meteorological Year, whereas other models use customised formats. Developing data for a climate change scenario could require significant data processing time.

Time requirements

Time requirements are relatively modest for simpler degree day approaches, if needed data are readily available. Simulation modelling approaches can be the most time intensive of any approaches.

Skill and training requirements

An understanding of the engineering principles of heating, ventilating, and air conditioning of buildings is required for degree day approaches. Modelling of water pumping requires understanding of both hydrology and agriculture, and may require econometric training for the modelling of urban water use. Use of building simulation models requires advanced engineering training.

11.2.3.5 Hybrid approaches

Hybrid approaches are combinations of econometric and structural approaches. They typically involve separate models for each end use, like structural approaches, but include econometric analysis in an effort to better incorporate behavioural response. These models are typically used for utility-specific demand forecasting. As such, they provide more resolution of results, but require more data. Hybrid models have seen limited use in the analysis of the effects of climate change

Two commonly used energy forecasting models, REEPS (EPRI, 1991), a residential energy demand model, and COMMEND (EPRI, 1986), a commercial energy demand model, are examples of hybrid econometric-engineering models that use separate submodels for each end use. Both models forecast electricity, natural gas, and fuel oil demand.

REEPS forecasts residential energy sales by end use, and models appliance purchase decisions, efficiencies, and utilisation patterns for 10 end uses. The key variables affecting purchase decisions are household and dwelling characteristics, fuel prices and availability, climate (heating and cooling degree days), and appliance attributes.

COMMEND disaggregates the commercial sector into building type, end use, and fuel type. The model uses a combination of econometrically derived elasticities, statistical and engineering simulation techniques, and life-cycle costing to address the penetration of efficient technologies and interfuel substitution.

Resolution of results

The resolution of results is high — data are available at the building and end-use levels. Separate analyses usually must be conducted if separate climate zones are involved.

Data requirements

Hybrid models are data intensive. They require the following types of data:

- end use (by building type)
  - saturation
  - energy intensity (use per unit, e.g., houses, floor area)
  - projection of number of units;
- fuel prices;
- climate data;
- personal income;
- efficiency standards;
- price response data.

Time requirements to use

Because of the intensive data requirements, the time requirements can be substantial (on the order of months), particularly if many climate zones must be modelled. Estimating price elasticities can be a significant task in and of itself.

Skill or training required

It is essential to have an understanding of both the economic and engineering principles involved in modelling of energy demand.

11.2.4 Summary of methods

A summary of methods is presented in Table 11.2. This table summarises resource requirements and selection considerations.

11.3 Autonomous adaptation

Autonomous adaptation of energy use to climate change can be divided between short-run and long-run adaptation. Short-run adaptations differ from long-run adaptations in that they involve no significant investment of capital. Most autonomous adaptations can be assessed using one or more of the methods described above.

Table 11.2 Summary of methods.

	Resource Requirements			Selection Considerations	
Method	Data	Time/Cost	Skills/Training	Advantages	Disadvantages
Expert judgement	Low, although understanding of energy use is necessary	Low	Specialised training in physics, engineering, statistics, or economics	Least time consuming and least costly technique. Useful for establishing research priorities.	Least accurate, likely to be particularly unreliable in temperate climates.
Analogue	Low	Low	Physics, engineering, statistics, or economics	Low cost and quick. Likely to be more reliable and provide greater resolution than expert judgement.	Results only as good as original study and appropriateness of analogue.
Econometric/ statistical: aggregated	Low to moderate	Low to moderate	Econometrics/ statistics	Empirical basis, relatively low cost.	Does not consider long-run adaptation, efficiency improvement policies, lack of transparency.
Econometric/ statistical: disaggregated	Moderate to high	Moderate to high	Econometrics/ statistics	Empirical basis, consideration of long-run adaptations.	Does not allow consideration of efficiency improvement policies, data intensive, lack of transparency.
Engineering end use: degree day	Low to moderate	Low to moderate	Engineering	Relatively low cost, transparency of analysis.	Inappropriate for analysis of tax and subsidy policies, requires exogenous projections.
Engineering end use: computer simulation	Moderate to high	Moderate to high	Advanced engineering	Analysis of efficiency policies, consideration of humidity effects.	Inappropriate for analysis of tax and subsidy policies, requires exogenous projections.
Hybrid	High	High	Economics/ engineering	Treatment of both behavioural and engineering principles, high resolution.	Resource intensive, limited applications in climate change analysis to date.

11.3.1 Short-run adaptation

In the short run, buildings and generation systems will remain the same. Adaptation will consist of using more or less energy for heating, cooling, and electricity generation. This type of adaptation is what is modelled by most degree day or building simulation engineering models without changes in exogenous projections and by econometric/statistical models estimated using time series data or using specifications for building characteristics. As temperatures increase, more energy will be used for heating and less for cooling.

This energy use response, usually based on the assumption that thermostat settings remain the same, may be modulated by behavioural responses. For example, if people are spending less money on heating, they may choose to maintain their homes at warmer temperatures in the heating season, reducing energy savings. If people begin spending more of their income on space cooling, they may choose to retain some of that income by maintaining their homes at warmer temperatures, reducing the increased use for cooling.

Cooling equipment capacity will also constrain short-run response. Most people in most countries do not have air conditioners and those that do have air conditioning have systems with a capacity sized for specific conditions. Although larger, central systems, particularly older units, are often oversized, smaller ones will reach their capacities in warmer climates. They may operate for longer times over the course of a year, but their operation during peak periods may not change. Detailed engineering models and econometric models based on disaggregated data may capture this effect.

Prices for energy in a deregulated environment are likely to increase in warm months and decrease in cold months relative to baseline conditions. These price changes are also likely to modulate short-run responses. Only the most sophisticated models will capture this type of feedback effect.

The dispatch of electric generation plants will change in the short run. The three factors affecting this type of change will be changes in demand, in river flows, and in natural gas prices. Change in demand will require more use of power plants during hot periods and less during cold periods. Overall, capacity factors may increase or decrease. Increases or decreases in river flows will require decreases or increases in fossil fuel generation. Natural gas prices may decline because of reduced use for heating. This may lead to a displacement of coal use by natural gas use.

11.3.2 Long-run adaptation

In the long run, people and enterprises will most likely substitute capital for energy, to the extent that energy is valued more than capital, and energy for capital to the extent that capital is valued more than energy. Substitution of capital for energy is likely to take place in warmer climates, where people will have to invest more to remain com-

fortable. Substitution of energy for capital will take place in cooler climates, where people can invest less and remain as comfortable. These substitutions will be seen in investments in heating and cooling equipment, thermal shells of buildings, and electric generation capacity.

Energy technology has been continually improving and is likely to continue to improve in the absence of climate change. Any modelling of the effects of climate change should take this type of autonomous adaptation into account to avoid overestimating adaptation costs.

11.3.2.1 Heating and cooling equipment adaptation

In warm climates, people with air conditioning will most likely invest in more efficient air conditioning systems to reduce air conditioning costs. Counteracting this effect would be capital investments to improve welfare, i.e., the purchase of air conditioners where none existed, or the purchase of higher capacity air conditioners. In cooler climates, heating systems may become less efficient as heating costs become less important. Electric heating systems may become more common, replacing natural gas heating. Electric heating systems cost more to operate than natural gas systems, but have a lower capital cost. Most residential and commercial heating and cooling equipment has lifetimes of 10 to 20 years (ASHRAE, 1995), so there will be several opportunities for adaptation over the time scale of climate change.

These adaptations may be affected by lack of information, separation of purchasing and operating parties, and government standards. Lack of information at the time of initial investment on the future costs of inefficiency may reduce the adaptation of cooling equipment in the absence of government standards. In some situations (e.g., rental properties), the party purchasing the energy using equipment is not the same as the party operating it and paying the energy bills. In such situations, the purchasing party may have little motivation to purchase more efficient cooling equipment. In the case of heating equipment, government standards may set a minimum below which efficiencies cannot fall without legislation.

Cooling equipment adaptation will take place in the context of increasing use of air conditioning in most warm climates, as standards of living increase. This change will increase the impacts of climate change. It is vitally important to consider this baseline change, particularly in developing countries.

Heating and cooling system adaptation will not be implicitly accounted for by engineering models or by time series econometric models. Econometric models using cross-sectional data that include several climates and hybrid models may account for such adaptation.

11.3.2.2 Thermal shell adaptation

People may adapt building exterior surfaces (known as the shell) in both cooler and warmer climates. In cooler climates, where heating requirements are more significant than cooling requirements, insulation, weatherisation, and glazing resistance will become less important. In warmer climates, shell improvements that reduce cooling loads will become more important. Such improvements are not necessarily the same as improvements that reduce heating loads. Common cost-effective improvements to reduce cooling loads are ceiling insulation and glass that transmits less solar radiation.

The most cost-effective time to modify residential and commercial building thermal envelopes is during design, and these buildings have long lifetimes (30 or more years), so this adaptation will take place more slowly than equipment adaptation. Further reducing the effects of this adaptation are the lack of information, separation of parties, and minimum standards issues mentioned previously.

11.3.2.3 Electricity generation adaptation

The electricity generation subsector is likely to see three types of adaptation:

1. response to changing demand for electricity;

2. response to changing fuel prices;

3. response to changing hydroelectric generation capability.

These changes will take place within the context of restructuring and technological change.

The electricity demand response to climate change will create a need for generators to modify their capacity portfolios. In cool climates, decreased use of electric heating and increased air conditioning will result in a flatter load shape. These changes in demand are likely to reduce the need for peak utilisation power plants and increase the need for base load power. In warm climates, increased air conditioning loads will create a load shape with a more pronounced peak and will increase the need for more peak and intermediate utilisation power plants. In hot climates where air conditioning is required year-round, more capacity of all utilisation levels is likely to be required.

Fuel prices are likely to change in response to changes in energy demand and also changes in generation patterns. These price changes will further modulate generation patterns. In cool climates where natural gas is used for heating, decreased heating requirements will depress prices and make natural gas a more cost-effective generation fuel. In warmer climates that rely on natural gas as a peaking and intermediate utilisation generation fuel, other fuels may become relatively more attractive.

Significant changes in the availability of hydroelectricity could have profound effects on the capacity requirements of many countries. As discussed previously, the effects could

go in either direction, depending on the changes in river and stream flow. If flows are increased, some countries may be able to defer generation expansion. If flows are decreased, major generation expansion may be necessary.

The electric generation subsector is undergoing restructuring in many countries, in part because of improvements in generation technology. These changes must be taken into account in any assessment of the effects on this subsector. Natural gas-fired systems, particularly combined cycle systems used on an intermediate and base load basis, have become substantially more efficient, less expensive, and faster to build in recent years. The optimal size has also become smaller. As a result, natural gas has become the fuel of choice for generation in most places where natural gas is available. Also, these changes have helped to erode the justification for regulated-monopoly and government-owned utilities, which developed in an era when massive coal and nuclear plants with long construction periods were perceived as the most cost-effective systems. Privatisation or deregulation is happening in many countries. This shift will result in much of the adaptation in generation being autonomous rather than planned. The time horizon for generation planning has shrunk because of both technology changes and restructuring, providing this subsector with greater flexibility in climate change adaptation.

11.3.2.4 Autonomous adaptation in the absence of climate change

Technological improvements will change energy use and production in the absence of climate change. These changes include efficiency improvements and the introduction of new technologies. Any accounting for the effects of climate change on energy must take these types of autonomous adaptations into account.

Currently, most of the energy-economy models represent technological change through an exogenous parameter commonly referred to as the Autonomous Energy Efficiency Improvement (AEEI) parameter (Edmonds and Reilly, 1983; Edmonds et al., 1991; Manne and Richels, 1992; Peck and Tiesberg, 1992; Nordhaus, 1994). This parameter is influenced by many factors such changes in the economy's product mix, shifts in consumer preferences, and true technical change (Faruqui et al., 1997). Unmodified modelling of the effects of climate change on energy will tend to overestimate changes in energy usage, since systems would be more efficient anyway. Over the periods of analysis commonly used in gauging the effects of climate change, energy production and consumption could change substantially.

Energy modellers have commonly assumed a constant rate of improvement in the energy intensity of the economy. The assumed annual rates of improvement in the AEEI have typically varied between 0.5 and 1.0 percent for the aggregate of all possible technologies (Dowlatabadi and Oravetz, 1996). This assumption may not be correct over long periods of time. One study that backcast the models over the period from 1954 through 1994 indicates that the AEEI is not constant and changes sign before and after 1974 (Dowlatabadi and Oravetz, 1996).

11.4 Planned adaptation

Governments can play a key role in preventing and reducing negative impacts from climate change in the energy sector. A country can develop adaptation measures by assessing impacts (through the methods presented in this chapter), identifying and evaluating adaptation options, and selecting and implementing options (Benioff and Warren, 1996). Adaptation policies will be most useful in those subsectors likely to incur the greatest negative impacts: space cooling and electric generation. Table 11.3 presents a list of adaptation measures. Classifications of adaptation types are as follows:

- Threat modifications would help reduce certain types of impacts.
- Effect prevention policies, if designed correctly, would eliminate certain types of impacts.
- Loss sharing would involve the spreading of impact costs across different groups.
- Use change would involve a shift in inputs or outputs of a process.

Most of the adaptation measures in the energy sector involve requiring or encouraging people and enterprises to bear additional initial capital costs. If the policies are designed properly and assumptions about climate change impacts turn out to be reasonably correct, bearing these initial capital costs will result in lower overall costs. For example, energy efficiency standards for air conditioners will result in higher initial costs for cooling. The overall life cycle costs, however, should be less than if there were no standards. Such policies are probably best assessed using engineering models, since they involve efficiency improvements.

Some adaptation measures involve a more equitable sharing of costs. For example, residential electricity subsidies would tend to hide the true costs of producing electricity. If subsidies are substantial enough, people would have no incentive to restrain their use of electricity for cooling, since other sectors of society are paying for it. Elimination or reduction of subsidies will result in the costs being borne by those responsible for incurring them. Another result of this policy is likely to be greater efficiency. Other, more efficient methods of achieving comfort, such as better building design, use of natural ventilation, and more efficient air conditioners, may be more cost-effective if prices reflect true costs. Subsidies serve to distort markets and eliminate consideration of such options. Pricing and subsidy policies are best analysed using econometric models.

Table 11.3 Energy sector adaptation measures.

Measure	Impact Addressed	Type of Adaptation	Comments
Air conditioning efficiency standards	Increased cooling electricity costs	Threat modification	Increased air conditioning efficiency will reduce electricity expenditures, but will make initial costs higher. Standards will also reduce greenhouse gas emissions.
Thermal shell standards	Increased cooling electricity costs	Threat modification	Increased ceiling insulation and reduced shading coefficient requirements are often the most cost-effective measures. Standards will also reduce greenhouse gas emissions.
River-front power plant siting regulation	Power plant flooding and cooling system problems	Effect prevention	Approval for permits for power plants along river fronts should consider effects of reduction or increase in river flow.
Coastal production facility siting regulation	Plant flooding and extreme weather damage	Effect prevention	Approval for permits for coastal power plants and oil and gas production plants should consider effects of sea level rise and increase in extreme weather.
Change approach to water management vis-à-vis hydroelectric generation	Loss of hydroelectric generation capability	Loss sharing/ use change	Reductions in or changes in patterns of river and stream flows may require changes in approach to water management. (Nash and Gleick, 1993). There is a potential for inter-regional conflicts.
Consider demand and hydroelectric generation changes in integrated resource planning	Changes in generation capacity requirements	Threat modification	Changes in electricity demand and hydro-electric generation may require a change in the generation capacity portfolio.
Information programs	Increased space cooling costs	Threat modification	Government agencies can provide information about energy efficiency measures that can reduce energy costs (e.g., appliance labelling programs).
Reduce/eliminate energy subsidies	Increased national electricity costs	Loss sharing	Subsidies to energy prices distort market signals and can result in wasteful consumption. Impacts on low-income groups can be ameliorated through targeted programs.

11.5 Summary and implications

The energy sector is sensitive to climate change. The nature and magnitude of the impacts are likely to vary widely, depending on climatic conditions and projected energy use. The subsectors most likely to be significantly affected are space heating, space cooling, and hydroelectric generation. Economic development is a key factor in projecting energy use and consequential effects of climate change, particularly the effects on space cooling.

The effects of climate change on energy use could have implications in other sectors. The effects on hydroelectric generation are likely to have implications on other aspects of water management, particularly in situations where overall stream and river flows are reduced. Increased use of electricity for space conditioning is likely to lead to an increase in various types of emissions, which may cause health problems and problems

in achieving emissions targets, including greenhouse gas emission targets. Decreased use of energy for space conditioning may ease problems associated with meeting such targets.

This chapter has presented an array of methods, ranging from judgement-based methods to data intensive quantitative methods, with different applicability and varying levels of precision. Judgement-based methods are appropriate for establishing initial research priorities, but are the least precise. They may suffice in cold climates where the effects of climate change on energy use are likely to be beneficial. Analogue methods may offer an opportunity for developing better preliminary estimates at a small increment in cost, if an appropriate analogy can be made. Econometric/statistical methods offer the best means of evaluating tax and subsidy policies. Engineering end-use methods offer the best means of evaluating energy efficiency policies. Hybrid approaches offer the best of both quantitative worlds, but have seen limited application in climate change analysis. In any quantitative approach, the better resolution can be achieved through the use of more disaggregated data.

Addressing long-run adaptation, i.e., modification of buildings and equipment, is the greatest challenge in estimating these effects. Econometric models using highly disaggregated cross-sectional data are a good means of dealing with this issue. The use of hybrid models may offer the best approach in the long run, but more applications are needed before a judgement can be made on their effectiveness.

References

ASHRAE. 1995. *Handbook of Applications*. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia, USA.

ASHRAE. 1997. *Handbook of Fundamentals*. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, Georgia, USA.

Baxter, L. and K. Calandri. 1992. Global warming and electricity demand. In: *Energy Policy*. Butterworth-Heinemann, Ltd., Oxford, UK, pp. 233-244.

Benioff, R. and J. Warren. 1996. *Steps in Preparing Climate Change Action Plans: A Handbook*. US Country Studies Program, Washington, DC, USA.

Braithwait, S. and C. Gelling. 1992. Residential forecasting. In *Demand Forecasting,* C. Gelling (ed). The Fairmont Press, Lilburn, Georgia, USA.

Cohen, S. (ed). 1997. *Mackenzie Basin Impact Study*. Environment Canada, Vancouver, British Columbia, Canada.

Crocker, T. 1976. Electricity demand in all-electric commercial buildings: The effects of climate. In *The Urban Cost of Climate Modification,* T. Ferrar (ed). John Wiley & Sons, New York.

Dowlatabadi, H. and M. Oravetz. 1996. *Understanding Trends in Energy Intensity: A Simple Model of Technical Change*. Center for Integrated Study of the Human

Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA.

EPRI. 1986. *Commercial End-Use Planning System (COMMEND)*. Electric Power Research Institute. Palo Alto, California, USA.

EPRI. 1991. *Residential End-Use Energy Planning System (REEPS), Version 2.0*. Electric Power Research Institute. Palo Alto, California, USA.

EPRI. 1995. *Potential Effects of Climate Change on Electric Utilities*. EPRI TR-105005. Research Project 2141-11. Electric Power Research Institute. Palo Alto, California, USA.

Edmonds, J.A. and J.M. Reilly. 1983. A long-term global energy-economic model of carbon dioxide release. *Energy* 52, 74-88.

Edmonds, J.A., H.M. Pitcher, D. Barns, R. Baron, and M.A. Wise. 1991. Modeling future greenhouse gas emissions: the second generation model description. In *Proceedings of the United Nations University Conference on Global Change and Modeling*, Tokyo, Japan.

Faruqui, A., B. Kick, K. Meadows, S. Burnow, I. Peters, B. Dougherty, M. Duckworth, H. Dowlatabadi, A. Smith, and M. Shealy. 1997. *Implications of Technological Change for Climate Change Modeling: Interim Draft Report*. US Environmental Protection Agency. Washington, DC, USA.

French, H.W. 1998. A drought halts Ghana on its road to success. *The New York Times*. March 15.

Hanemann, W. and R. McCann. 1993. Economic impacts on the Northern California hydropower system. In *Integrated Modeling of Drought and Global Warming: Impacts on Selected California Resources*, N. Dowling, co-ordinator. National Institute for Global Environmental Changes, University of California, Davis, USA.

IPCC. 1995. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*. Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Judkoff, R. and J. Neymark. 1995. *International Energy Agency Building Energy Simulation Test and Diagnostic*. National Renewable Energy Laboratory. Golden, Colorado, USA.

Lettenmaier, D.P., K.L. Brettman, L.W. Vail, S.B. Yabusaki, and M.J. Scott. 1992. Sensitivity of Pacific Northwest water resources to global warming. *The Northwest Environmental Journal* 8, 265-283.

Linder, K. and M. Inglis. 1989. The potential effects of climate change on regional and national demands for electricity. Appendix H: Infrastructure. In *The Potential Effects of Global Climate Change on the United States*, J. Smith and D. Tirpak (eds). US Environmental Protection Agency, Washington, DC, USA, pp. 1-1 to 1-38.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. 1987. *Potential Impacts of Climate Change on Electric Utilities*. Report 88-2. New York State Research and Development Authority, Albany, New York, USA.

Manne, A.S. and R.G. Richels. 1992. *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits.* The MIT Press, Cambridge, Massachusetts, USA.

Morrison, W. and R. Mendelsohn. (in press). The impact of global warming on U.S. energy expenditures. In *The Impacts of Climate Change on the U.S. Economy*, R. Mendelsohn and J. Neumann (eds). Cambridge University Press, Cambridge, UK.

Nash, L. and P. Gleick. 1993. *The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation*. EPA 230-R-93-009. US Environmental Protection Agency, Washington, DC, USA.

Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of Climate Change*. MIT Press, Cambridge, Massachusetts, USA.

Peck, S.C. and T.J. Tiesberg. 1992. CETA: A model for carbon emissions trajectory assessment. *The Energy Journal* 13, 55-77.

Riebsame, W.E. 1989. *Assessing the Social Implications of Climate Change Fluctuations: A Guide to Climate Impact Studies*. United Nations Environment Programme, Nairobi, Kenya.

Rosenthal, D.H., H.K. Gruenspecht, and E.A. Moran. 1995. Effects of global warming on energy use for space heating and cooling in the United States. *The Energy Journal* 16(1), 41-54.

Scott, M, L. Wrench, and D. Hadley. 1994. Effects of climate change on commercial building energy demand. *Energy Sources* 16, 317-332.

Smith, J., F. Stern, C. Yermoli, and W. Breffle. 1994. *The Impact of Climate Change on Thermoelectric Power Use in Egypt and Poland*. Report prepared by RCG/Hagler, Bailly, Boulder, Colorado, USA, for the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Stern, F., B. Neal, and J. Smith. 1993. *Air Conditioning Saturation in Selected Major Urban Areas*. Report prepared by RCG/Hagler, Bailly, Boulder, Colorado, USA, for the Center for Climatic Research, University of Delaware, Newark, USA.

Thom, H. 1966. Normal degree days above any point by the universal truncation coefficient. *Monthly Weather Review* 94(7), 461-465.

United Kingdom Climate Changes Impacts Review Group. 1991. *The Potential Impact of Climate Change in the United Kingdom*. London, UK.

12 Forest

Lead Authors
Robert J. Scholes [1]
Sune Linder [2]

Contributing Author
Khalid M. Siddiqui, Pakistan

12.1 Nature and scope of the problem

Forests and woodlands, whether intensively managed or not, are the main source of timber for construction, energy, and pulp for a large part of the world's population. They are the basis for a significant economic sector in many countries. Further, they are also a key habitat for many species and the focus of much of the world's biodiversity. Forests play a key role in either taking up and storing carbon or releasing it to the atmosphere, which adds to the greenhouse effect.

The geographical distribution, composition, and productivity of forests are controlled, overall, by climate. Within the climatic envelope, human actions and land use practices strongly determine the type and performance of forests. Since the pattern and intensity of human activity are changing all around the world, and the climate is expected to change in the next century, it is logical to expect impacts on the ability of forests to supply goods and ecosystem services.

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1 Division of Water, Environment and Forest Technology CSIR, South Africa.

2 Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, Uppsala, Sweden.

The forest sector encompasses all tree-dominated systems such as forests (Innes, 1994), woodlands, savannahs (Scholes and van der Merwe, 1996), and mangroves (Davis et al., 1994), ranging from completely unmanaged to totally managed forms such as plantation forests. It can also include trees grown on farmlands (agroforestry and woodlots) and trees in urban areas. The biodiversity and ecosystem services aspects of forests are dealt with in Chapter 13, Biodiversity. Trees which yield both timber and fruit can be dealt with in either the agriculture sector or the forest sector; it is necessary to be consistent and make clear what has been included where. Many of the methods and models used in the forest sector analysis can be applied to non-woody terrestrial ecosystems and agroecosystems as well.

Forest-based activities include the harvesting of trees for timber, pulp, other wood-based products, or fuelwood, and industries based on these primary products, such as furniture making, construction, and paper. They also include many other non-wood forest ecosystem products such as the harvesting of fruits, fungi, birds, and animals, and the use of the services that the forest ecosystem delivers, such as clean water, clean air, and recreational opportunities. Many forest-based goods and services are not reflected in the formal economy, but nevertheless have a high value.

12.1.1 The study area

The study area will typically include all the terrestrial parts of the national territory. In some cases it may be possible, right from the start, to exclude some areas as being too dry or too cold to support trees under any plausible climate change scenario. Reducing the area of the study could help reduce the amount of data to be collected. Within the study area the focus will be on those areas currently or potentially occupied by economically, biologically, or culturally important forest ecosystems. The smallest patch size (minimum mapping unit) which can be addressed will to some extent depend on the size of the national territory, the funds available for the assessment, the detail of the available data, and the importance of forests to the nation. In most countries, 1:5 million vegetation maps (or better) are available, which translates to an absolute minimum map unit of about 5x5 kilometres, which also corresponds to the minimum scale at which interpolated climate data are typically available regionally. Global vegetation and climate maps are available at 0.5° resolution (about 30x30 kilometres), which is the coarsest scale at which an assessment should be done. It should be possible to work at a more detailed scale.

12.1.2 The time frame

The period selected for the projections should satisfy the following conditions (see also Chapters 2 and 3, where socio-economic and climate scenarios are discussed).

1. Compatible with the time periods selected for assessments in other sectors.

2. Short enough to allow plausible scenarios to be constructed. It is virtually impossible to predict what might happen more than 100 years from the present.

3. Long enough to allow forest processes such as growth and species composition to be significantly affected. Most forests change quite slowly because of the longevity of the trees. Hence it is unlikely that change will be detectable in less than 20 years.

12.1.3 Expected climate impacts

A change in climate can be expected to lead to (see Table 12.1):

- a shift in the geographical area which will support forests;
- a change in the species composition of mixed-species forests;
- a change in the output of forest products per unit area of forest.

These changes will have effects on the economic and social systems which depend on forestry (loss or gain of sector turnover, export earnings, jobs, access to fuelwood, construction materials, and forest products). They will also have consequences for the species dependent on forests and for ecosystem services such as the maintenance of steady and clean water supplies.

Forests are influenced by climate and influence climate in return. The effect of forests on the climate occurs directly at the local to regional scale, through their characteristic pattern of absorption of solar radiation, evaporation of water, and surface roughness, and also indirectly at the global scale through the carbon which they store or release. An assessment needs to take note of these feedback loops, but at this stage the integrated modelling technology is not widely available to treat them explicitly in a national study.

Table 12.1 Types of climate change impacts likely in the forest sector.

• Changes in the location of optimal growing areas for given species, resulting in shifts in species composition and changes in the size of the forest estate
• Increases of decreases in the production of wood or non-timber forest products per unit area
• Changes in the type, location, or intensity of pest and disease outbreaks and fires
• Increase or decrease in the amount of carbon stored by the forest ecosystem
• Disturbances of ecosystem function – increased or decreased nutrient retention and litter decay rate – bud-break, flowering or leaf-fall out of phase with climate or pollinators
• Changes in biodiversity – due to unfavourable climates – due to changes in disturbance or disease regimes – due to breakdowns of symbioses (e.g., pollinators; see Giannini and Magnani, 1994)

- Shift in the location, type, or number of forest sector jobs
- Change in forest amenity value; for instance, the length of the winter-sport season
- Afforestation or deforestation as a result of land competition with agriculture

Forests compete with agriculture for land. When adaptation models are tested, the forest sector analysis and the agriculture sector analysis need to be co-ordinated to ensure that they are not both planning to occupy the same land in the future.

12.1.4 Impacts other than climate

Changes in forests are only partly driven by climate. In many parts of the world, socio-economic and policy factors are the main drivers of land use change. Assessment of the impacts of climate change must take place within the framework of changes in environmental and socio-economic factors which may occur at the same time, and the adaptations which they may cause. In particular, forests are likely to be affected by competition for land for other uses, changing demand for forest products, rising atmospheric CO_2, and increased deposition of pollutants such as acid rain and ozone at the same time as they are being exposed to climate change.

Forests downwind of major industrial or intensive agricultural areas are likely to be exposed to additional inputs of nitrogen from the atmosphere in the form of wet and dry deposition. Since most forest ecosystems are nitrogen limited, this leads to increased productivity, up to the point where the forests become nitrogen saturated (Dise and Wright, 1995).

12.2 An array of methods

12.2.1 Experimentation

The ideal data for assessing the impacts of climate change come from direct measurements in replicated, representative experiments (Landsberg et al., 1995). These are seldom available for forests in relation to climate change. Irrigation experiments can be used to extrapolate the possible effects of increases in precipitation (Linder, 1987). Several soil-warming experiments currently under way in forests will be useful for understanding the effects of higher temperature (Peterjohn et al., 1993, 1994).

There is a wealth of experimental data on forests which are useful for an impact assessment, although they were not collected for that purpose. For instance, any coutry with significant forest activity is likely to have handbooks of forest yield tables, which are based on experimental data. These tables estimate the amount of timber that can be extracted from given forest stands. There are also likely to be forest inventory data on the number, size, and species of trees in given forest stands. Forest inventory data can be used to quantify current biomass and species composition, and forest yield tables can be used to estimate current and future productivity (Matyas, 1994). If inventories and yield tables are not available for the study area, they probably are for similar regions

and species in neighbouring countries. Forest yield tables and inventories are for useable timber only; the numbers must be increased, often by a factor of two, to get total biomass and production.

12.2.2 Analogue methods

12.2.2.1 Historical analogues

In the absence of planned experiments, natural experiments can be used as a substitute. The climate has changed dramatically in the past, so if there is information on what the past climate was and what forest state it supported at the time, it can be used to make projections for the future. One weakness of this approach is that climate data have been recorded for a few centuries at best and a few years at worst. The climate before the period of record must be inferred from surrogate data, which introduces a further source of potential error. Second, historical analogues are a type of correlative study, and therefore are reliable only if future climates are within the range experienced in the past, and as long as all other factors remain constant (which is unlikely). Historical analogues provide a way of performing independent checks on the models. If a model constructed and calibrated with modern data is able to represent the past successfully, it can be applied to the task of projecting the future with greater confidence. Historical analogues are also the main source of information about the rate at which slow processes, for example, the migration of species, can occur (Chambers, 1993).

The two main sources of historical forest data are palynological (pollen) studies, which can tell what species occurred in a given location over long periods of time and provide coarse-resolution prehistoric climate data (Branchu et al., 1993, Servant et al., 1993), and dendrochronological (tree-ring) studies, which supply annual-resolution climate and growth-rate data stretching back several centuries (D'Arrigo et al., 1992). Both types of studies require painstaking, specialist work over many years. Palynology requires a suitable location for pollen to accumulate and be preserved, usually a quiet pond or bog. Dendrochronology is generally not possible in the tropics, since few tropical trees show clear and reliable ring structures.

12.2.2.2 Regional analogues

Regional analogues use regional variations in present-day climates as an indication of what might happen under future climates. This method assumes that if a given climate supports a particular type of forest at present, then a similar climate will support a similar forest in the future, although perhaps at a different location. It can be applied qualitatively (without sophisticated statistics) or quantitatively, in which case it is essentially the same as the empirical-statistical bioclimatic models described below and suffers the same problems (particularly the problem of not being able to describe transients). The main weakness of regional analogues is the assumption that all factors

other than climate remain constant. This is clearly violated where the location of the future has completely different soils.

12.2.3 Expert judgement

The judgement of experts, who may include people with a lifetime of experience but little formal education, may be quite accurate, but its use is hard to justify in terms of the scientific methodology since it is difficult to test. Some degree of expert opinion is involved in all methods. The guidelines for the use of expert judgement are as follows:

- use it where there is no better alternative;
- choose the expert such that he or she is operating within his or her area of expertise;
- when a finding was based on expert judgement, note it as such and acknowledge the source;
- ask the expert for a likely range of values as well as a best guess; and
- use more than one expert where possible.

12.2.4 Quantitative models

12.2.4.1 Biophysical models

Biophysical models predict the consequences of changes in their driving variables (for example, precipitation, temperature, soil type, and plant species) on ecosystem attributes such as the survival and growth of various species or the productivity of the entire ecosystem. Discussions of the use of biophysical forest models for climate change research are given in Shugart et al. (1988), Smith et al. (1992), Dale and Rauscher (1994), and Joyce (1995). Recent reviews are by Agren et al. (1991) and Ryan et al. (1996). Biophysical models fall on a continuum from those based entirely on statistical relationships to those built on detailed mathematical representations of the processes thought to be occurring in the forests.

Empirical-statistical

These models rely on statistical relationships between the input and output variables. They are relatively simple and can have a high predictive power within the range for which they are valid. Their drawback is that the existence of a correlation only suggests the possibility of a causal link, it does not prove it. It is therefore extremely risky to extrapolate these models beyond the range of data used to construct them, or to apply

them in conditions other than those under which they were derived. The further the deviation from their zone of validity, the greater the risk of error.

Most forest industry growth and yield models (or tables) are empirical. Where they include some way of varying the growth potential (often through a site index) which can be linked to climate, they can be used to estimate forest production under a moderately altered climate. They cannot be expected to estimate growth under elevated CO_2 concentrations or nitrogen deposition.

Bioclimatic models are generally empirical-statistical. They establish relationships between the presence or absence of a given species (or vegetation type) and one or more climatic variables. Typically the climatic variables include some measure of moisture (such as mean annual precipitation, or the precipitation to evaporation ratio); temperature (such as the annual minimum and maximum), and seasonality (such as the range between summer and winter or the fraction of precipitation in a given set of months). The models range from very simple (Holdridge, 1967) to complex (Box, 1980). The simple ones are easy to apply, but do not have high predictive power. The complex ones have high predictive power, but need more detailed data and should not be extrapolated to parts of the world other than where they were developed (see also Chapter 13, Biodiversity). For an application of a simple global bioclimatic model within a country, see Box 12.1.

Box 12.1 Using a simple bioclimate model to estimate forest shifts in Venezuela.

The Holdridge model is a well-known scheme for relating the equilibrium distribution of broad vegetation types to moisture and temperature conditions (Holdridge, 1967). It was applied under current and future climate scenarios to estimate the distribution of vegetation types in Venezuela. The doubled CO_2 climate scenario used was from the United Kingdom Meteorological Office (UKMO) model. The model passed the first test, which was to estimate the present distribution of vegetation types with acceptable accuracy. Under doubled CO_2, assuming a long-term equilibrium, the area covered by dry tropical and subtropical forests and thorn woodlands expanded by nearly 500 000 square kilometres, at the expense of the moist tropical and subtropical forests.

Like all equilibrium models, the Holdridge model does not project how fast the change will occur. However, it can be adapted for use in a transient scenario by making some assumptions about the feasible rates of change (Smith and Shugart, 1993). The Holdridge model is given as an example only; it is not recommended. In almost all cases more sophisticated and powerful models are available, and should be used in preference (Prentice et al., 1992; Carpenter et al., 1993).

Bioclimatic models can be thought of as a formal approach to regional analogues. They suffer from the problems inherent in all correlative models. They are likely to fail if the future climate combination has no current analogues or if the bioclimatic relationships are altered by a changing environment (for instance, if elevated CO_2 concentration changes the water requirements of plants). Bioclimatic models have two further weaknesses. First, they project the vegetation distribution under steady-state conditions

and say nothing about the rate at which the new state will be approached. For forests, this is a serious problem, since the turnover of species and the rate of dispersal are very slow. If the scenario time frame is only 100 years, then it is unlikely that a new equilibrium will have been reached by its end. Second, when they are applied to whole vegetation types (sometimes also called biomes), they assume that the type acts as a unit rather than as individual species. Despite these reservations, statistical bioclimatic models remain among the most useful tools currently available for estimating the distribution of forests under future climates, especially where they include some process-based elements (see process-based models below).

It is preferable to use a regionally-optimised and calibrated bioclimatic model rather than a general global model. Dedicated software is available for establishing the climatic relationships (e.g., BIOCLIM from the Australian National University, or DOMAIN from the Centre for International Forestry Research; see Carpenter et al., 1993), or it can be done using a combination of GIS software (such as IDRISI from Clark University) and spreadsheets. Previous studies can be used as a guide to the combination of variables which is likely to be successful in predicting species limits. Typically they will include upper and lower moisture and temperature indicators. The following steps lay out a procedure for applying bioclimatic models (Box, 1980; Woodward, 1987; Prentice et al., 1992, 1993; Carpenter et al., 1993).

1. Establish the climatic thresholds which correspond to the distribution limits of a forest type or species. This is done by constructing a data file with each row corresponding to a grid point on the gridded climate surface for the study area, and the columns to important climate variables. Add a column in which the presence (1) or absence (0) of the forest type at that grid point (from the vegetation map) can be noted. Plot the presence or absence on a graph with one climatic variable on the x-axis and another on the y-axis, and look for the thresholds which separate presence from absence. Try all pairs of climatic indices. A more sophisticated approach uses multivariate statistical techniques such as discriminant function analysis or neural networks. Clear discrimination requires that the study area include a climate range greater than the limits for the forest type. If bioclimatic relationships already exist from an appropriate study, this step can be skipped. Use half of the data to establish the climatic relationships, and keep the rest for checking them.

2. Test the model by using the other half of the data to calculate whether forest should be present or absent at a given point as predicted by the thresholds developed above. Compare the predicted distribution to the actual distribution. Chi-square tests can be used to calculate the statistical significance of the model.

3. Generate a climate surface for a given change scenario. This is usually done by adding a given amount to all the current temperature values, and adding or subtracting a given amount or proportion to the current precipitation values. The climate relationships can be used to predict the new forest distribution.

4. Overlay the current and predicted forest distribution and calculate the areas of no change, areas of forest loss, and areas of forest gain.

The principles underlying empirical bioclimatic modelling are not restricted to predicting the presence and absence of forest types. They can also be used to predict various aspects of forest structure and function, such as biomass and productivity (Kellomäki and Kolström, 1994; Peterson and Peterson, 1994). Box 12.2 presents an application of an empirical bioclimatic model in Pakistan.

Box 12.2 Example: Application of BIOME3 in Pakistan.

Pakistan has a forest area of only 4.22 million hectares (4.8% of total area) for its population of 130 million. A UNEP/GEF assisted study was carried out to determine potential impacts of climate change on natural forest ecosystems in Pakistan, especially on mountain forests in the northern regions of the country, whose altitudinal pattern of vegetation follows latitudinal patterns of vegetation found globally. The periods of the study were 1990-2020, 2020-2050, and 2050-2080, with a climatic change rate of 0.3^{o}C rise in temperature and precipitation changes of 0 %, +/-1 % per decade; 1990 was the base year. In addition, the current atmospheric CO_2 concentration of 350 ppmv was assumed to increase to 425 ppmv in 2020, 500 ppmv in 2050, and 575 ppmv in 2080. The BIOME3 model was used for computer simulation of climate change impacts. The model inputs consisted of latitude, soil texture class, and monthly climate data on a 0.5^{o} grid. Current and future potential area and net primary productivity (NPP) of nine forest types or biomes were simulated with the help of the model. Of these, three biomes (alpine tundra, grassland/arid woodlands, and deserts) showed reductions in their area and five biomes (cold conifer/mixed woodland, cold conifer /mixed forests, temperate conifer/ mixed forests, warm conifer/mixed forests, and steppe/arid shrublands) showed increases in their area as a result of climate change.

Enhanced CO_2 concentration in the atmosphere appeared to have a pronounced positive effect on the potential area of all forest biomes except xerophytic woods and scrubs. NPP was increased in all scenarios and in all biomes. However, there is a possibility of forest dieback occurring before the dominant forest types have enough time to adjust to changed climate by themselves. There would also be a time lag before forests could migrate to new sites. In the intervening period, they would be vulnerable to environmental and socio-economic disturbances, e.g., erosion, deforestation, and land-use changes, as a result of increase in human and livestock population and enhanced demand for forest goods and services.

Thus, the overall impacts of climate change on forest ecosystems of Pakistan could be negative, and a number of adaptation strategies would be needed to cope with these impacts. These include planting of more tolerant tree species, increased forest fire control, increased forest products processing efficiency, use of wood substitute materials, provision of financial assistance to forest communities affected by climate change, provision of subsidy on substitute fuels and building materials for people of hilly regions, change from productive to protective functions of forests, and establishment of forest corridors to assist in forest migration. These strategies would also improve the forest deficient situation in Pakistan even in the absence of climate change, and therefore would constitute win-win or no-regret options.

Process-based models

Process-based models are also known as mechanistic models, since they strive to represent what is known about the mechanisms which link their inputs to their outputs. They are usually more complex (and therefore more data-intensive) than empirical models, and do not necessarily give more accurate estimates for the current climate. However, they have the advantage of being more reliable when extrapolating small amounts beyond the data range for which they were developed. In most cases they are able to predict the time course of the change as well as the steady-state solution (and thus they are referred to as dynamic or transient models).

Bioclimatic models increasingly include some process-based relationships. For instance, many of the vegetation distribution models are based on the water and energy balance of plants rather than simply on annual precipitation, and use physiological limits rather than arbitrary climatological limits (Friend et al., 1993).

There are some highly detailed physiologically-based growth models for monospecific, even-aged plantation forestry stands. An example is the model developed by McMurtrie et al. (1990) for Pinus radiata in Australia.

There is an important class of forest models which simulate the establishment, growth, and death of a large number of individual trees within an area. They are typically applied to mixed-species forests, since they can project the outcome, over time, of the interaction of many different species. These are known as succession, patch, or gap models (Shugart and West, 1980; Shugart, 1984). They are based on information about the longevity, growth rate, and environmental requirements (such as shade tolerance) of individual species. This information can be obtained from forest handbooks or expert judgement in well-researched parts of the world, but may be hard to obtain for species-rich forests in less well-studied countries. Succession models are especially useful for estimating changes in species composition under altered disturbance regimes (such as more or less frequent storms or fires). Since they explicitly follow the demography of the trees, they are well-suited to transient analyses over a period of a few decades to a century.

The theory underlying succession models is so fundamental that they can in principle be applied to any forest; however, finding realistic parameter values to calibrate them for a new situation, and data sets on species composition changes over long periods of time for validating their output, is a major research task which can take several years. Therefore, unless this information is already available, it is unlikely that succession models can be used with confidence. Succession models, because they track thousands of trees in thousands of forest stands, require powerful computing resources. Running them for an entire country would require a supercomputer. In general, a stratified sub-sample of plots is simulated, which can be achieved on a desktop computer. For an example of a gap model applied in a country study, see Box 12.3.

Box 12.3 Using a gap model to estimate the rate of species composition change in the forests of Estonia.

Two study sites were chosen in central and western Estonia, representing different climate and forest types. The FORET model (Shugart, 1984) was set up for the two sites using locally-determined parameters for 13 tree species, and run to simulate 500 years of forest development under three climate scenarios. Under the current climate, the model reproduced the observed patterns of succession at the sites, and projected a long-term composition similar to that which occurred at the sites. Under warmer, drier conditions, Scots pine became dominant after a period of 50 to 100 years. Under warmer, wetter conditions, Norway spruce dominated after about 200 years. In both cases other species were prominent during the transition period.

Although succession models can predict forest productivity under current conditions, in their simplest form they are unlikely to do so reliably for conditions which differ markedly from the stands where the calibration data were collected. This is because they are based on plant demography rather than on ecosystem energetics or nutrient cycling. Biogeochemical models are probably more robust for projecting changes in production and the carbon cycle of the forest under a changed environment, especially where that change involves inadvertent fertilisation with CO_2. Most biogeochemical models simulate the water and nitrogen cycles to some degree, and use these cycles to constrain a carbon budget derived from some representation of photosynthesis.

Biogeochemical models range greatly in complexity and focus. Models such as MAESTRO (Wang and Jarvis, 1990; Jarvis, 1993) or BIOMASS (McMurtrie et al., 1990) simulate the radiation regime in the forest canopy in great detail, and use it to drive transpiration and photosynthesis. CENTURY (Parton et al., 1988) has very simple photosynthetic and transpiration routines, but models the transformation of nutrients (especially nitrogen and phosphorus) in the soil in relatively great detail. TEM (Melillo et al., 1993) treats the carbon and water cycle very simply, and as a consequence can be applied almost everywhere; but the output includes little detail on forest products. Forest-BGC (Running and Coughlan, 1988) is somewhere in between.

Most biogeochemical models include some way of varying the atmospheric CO_2 concentration and nitrogen deposition rate (Martin, 1992; McGuire et al., 1993), and so are essential for studying these aspects of global change, which occur simultaneously with climate change. They can be used as transient models, but where the main time lags are due to demographic processes rather than the slow turnover of nutrient pools, they will not capture the dynamic response very accurately. The data requirements vary in both type and amount with the complexity of the model. In general, biogeochemical models are intermediate between bioclimatic models and succession models in terms of data needs. Most require monthly precipitation and temperature and some information about plant types (initial biomass and nutrient content) and soil type (texture, carbon and nitrogen content). These data are obtainable for most sites with a modest research effort. The more sophisticated models also require details of the canopy architecture, photosynthetic parameters, and allocation patterns between leaves, wood, and roots, which can be obtained only after an intensive research effort.

There is an emerging class of hybrid model which attempts to marry the best features of the bioclimatic, succession, and biogeochemical models (Comins and McMurtrie, 1993; Friend et al., 1993). They are still under development, and consequently are not yet widely available. When they do become available they will inevitably be relatively data-intensive.

12.2.4.2 Economic models

Most economic models of the forest sector, or which include the forest sector, are known as input-output models (Arthur and van Kooten, 1989; Rosenberg, 1993). These divide the forest sector into a number of subsectors, each of which requires inputs in given ratios from other subsectors or from sources outside the model, and produces outputs for use in other subsectors or as model outputs. Examples of inputs are various raw materials, capital, and labour. Outputs include products and wastes. In transforming inputs into outputs, the subsector adds value to the product.

Dynamic economic models can also be applied to the forest sector. These models allow the price of forest products to vary according to supply and demand, given certain assumptions about the elasticity of the price curve. As a result of the changing relative prices, different subsectors or resources are favoured over others. Examples of such models are TAMM (Joyce et al., 1995) and GCTM (Peres-Garcia et al., 1995). Where the biophysical changes in the forest sector are predicted to be large, it would be advisable to use a dynamic economic model rather than an input-output model, given that the quantity of timber reaching the market is likely to alter substantially, and thus change the nature of the market.

12.2.4.3 Integrated models

Integrated models attempt to deal with biophysical processes and socio-economic processes, and their interactions, simultaneously (Rosenberg, 1993). For instance, if forest productivity goes down, the price of forest products will increase in compensation. A further meaning of integration is across sectors, preventing, for instance, the agricultural and forest sectors from both occupying the same piece of land in a future scenario. Although integrated modelling is obviously ideal, it is currently achieved by sacrificing detail within the sub-modules. The IMAGE 2.0 model is an example (Alcamo, 1994). It runs at a global scale, and therefore has little national-level resolution, but tries to capture some of the main interactions between the biological, socio-economic, climate, and ocean systems. It does not explicitly handle forests as a sector, but does model the distribution of forests.

Fully-integrated models are currently beyond the reach of most national assessments, but some of the advantages can be had by applying stand-alone models within an integrated, systematic framework where the outputs of one model become inputs to another. An overall strategy for applying models systematically to the issue of global change assessment in the forest sector is suggested:

1. Use a bioclimatic model to predict future steady-state forest distributions under a range of plausible climate change scenarios.

2. Use historical analogues and life-history information to estimate how long it might take for the forest boundary to migrate that distance, and use this information to speculate about what may happen during the transition period and to modify the steady-state prediction if it is unlikely to be reached in the assessment period.

3. Use a gap model, applied at the edge and middle of the current distribution of each forest type, to predict species composition changes and the transient biomass response under a change in the disturbance regime.

4. Use a biogeochemistry model to predict changes in productivity and carbon stocks in each forest type, with and without the effects of elevated CO_2 concentration (and, where appropriate, nitrogen deposition).

5. Use an economic and demographic model to project the demand for forest products and the land area which is likely to be available to satisfy the demand.

12.2.5 Testing the method

12.2.5.1 Feasibility studies

The first step in a feasibility study is a thorough synthesis of what is already known about forest and climate in the study area, and in related areas. A recent review of the topic will provide an entry point; this can be followed up by browsing recent editions of journals which regularly publish on this topic. A search conducted on a CD-ROM database such as the TREE-CD (Commonwealth Agricultural Bureau International) for the keywords “forest” and “climate” is an efficient way of locating recent research. An Internet search engine can be used with similar keywords to locate recent assessments. Recent review articles provide an overview of the subject (e.g., see Gates, 1993). Local or regional journals and local forest experts can provide a list of relevant work; much of it may be in unpublished reports. Government offices and research institutes often have a great deal of useful information, for example, a central statistical office, departments of forestry and agriculture, and the meteorological service.

The next step is to define the forest types which occur in the study area, and then stratify the study area by forest types and by zones of similar climate. A series of simple climate change scenarios based on the regional output of GCMs could be used, for instance, an increase in temperature of 1-4°C and an appropriate increase and decrease in precipitation (15-20 percent is a realistic order). See Chapter 3 for details on climate change scenarios. Simple bioclimatic models, regional analogies, and expert judgement can provide qualitative statements about what might happen to forest extent and productivity in each of the forest type/climate zone combinations. This is often most effectively done by convening a workshop of four to eight experts drawn from a variety

of relevant fields such as forestry, ecology, and climatology. One way of summarising the results is to record the estimated severity of impacts (rated on a scale of 1 to 3) in a matrix. Table 12.2 gives an example. The row and column sums of the matrix give an indication of which forest types and which impacts deserve most of the attention in the main study; they do not constitute reliable estimates in their own right.

Table 12.2 An example of a qualitative assessment matrix[a].

A. Forest type/climate zone	B. Area occupied or economic importance	For a scenario of X°C temperature increase and Y% change in precipitation				Row total B*(C+D+E+F)
		C. Change in extent	D. Change in species	E. Change in wood production	F. Impact on other forest products	
Type 1 Type 2 Type 3	3 large 1 small 2 medium	3 high 3 high 1 low	1 low 2 medium 1 low	3 high 2 medium 1 low	3 high 2 medium 2 medium	30 9 10
Column total of types 1+2+3		7	4	6	7	

[a] In this example Type 1 forests need the most attention, and all the major change factors other than species change are equally important.

12.2.5.2 Data acquisition and compilation

The minimum data needed are listed in Table 12.3, and Table 12.4 lists the key variables driving forest impacts. If the minimum data set is not available for the study area, then one of the coarse-resolution global data sets may be needed (for example, the Global Ecosystems Database on CD-ROM from the National Geophysical Data Center in Boulder, Colorado, USA). Sometimes the data exist, but are not in a form which can be easily used. In this case a data collation or conversion project is needed before the main assessment can begin. Where the data do not exist, and a long time series is not necessary, it may be possible to collect new data in time to satisfy the needs of the assessment.

12.2.5.3 Model testing

Once the main issues have been defined and the available data have been located, it is possible to identify the types of models than can be used. Obtain an example of the chosen models by writing to the owners of the model (a fee may be required to obtain a copy), and attempt to calibrate and test it for a few sites. This will rapidly reveal what data are needed, whether the model is appropriate or not, and the resources needed to do a full analysis. Use the model to perform a sensitivity analysis. In its simplest form, this is done by adjusting the values of the driving variables and site-specific parameters up and down by small amounts (1, 2, 5, and 10 percent) to see what impact an error in the

data or assumptions has on the conclusions reached. This will act as a guide to the quality of data needed (Frischlin et al., 1995).

Table 12.3 Minimum data needs.

Core data: needed for a basic assessment and in several advanced assessments	• A map of the current location of forests (broadly defined to include all tree-rich ecosystems), by type, at 1:5M scale, or finer. • Current climate data for the forested and non-forested area, expressed as gridded monthly surfaces of precipitation, maximum and minimum temperature and potential evaporation, at a grid scale of 0.5° or finer (a rough guide to the appropriate resolution would be the longitudinal and/or latitudinal range of the study area divided by 100). • The current output of the forest sector, in terms of the value of wood products (in both the commercial and non-commercial sectors) and other forest goods and services. These data should preferably be at the scale of less than the whole country — for instance, by district. • Projections of population growth and economic development for the study period. • Estimates of the production of the various forest types under the current climate.
Additional data: needed for advanced assessments	For biogeochemical modelling • Soil data, including at least texture, percent carbon, percent nitrogen for all sites • Time-series of production or standing crop data for a few sites for model validation For succession modelling • Demographic data (establishment rate, growth rate, longevity) for all major tree species • Stand inventories for model initialisation • Information on long-term succession patterns for model validation For economic modelling • Data on the inputs needed for every sub-component of the forest sector, the outputs generated, and the value added at each stage For integrated biophysical and socio-economic modelling • Data on the feedback between climate, human demography, and resource needs.

Table 12.4. Key variables which drive forest impacts.

1. Climate
   - 1.1 Temperature
     - 1.1.1 monthly means
     - 1.1.2 extremes of maximum and minimum temperatures
     - 1.1.3 with which temperatures fall below (or above) key biological limits such as 0° and 35°C
     - 1.1.4 accumulated degree-days in spring
     - 1.1.5 the rate at which the mean temperature changes (°C/decade)
   - 1.2 Evapotranspiration (from radiation, temperature, humidity, and wind)
     - 1.2.1 monthly means
   - 1.3 Precipitation (rain, snow and mist)
     - 1.3.1 monthly means
     - 1.3.2 frequency of droughts (water balance modelling, using 1.2.1 and 1.3.1)
     - 1.3.3 fire climate (related to 1.3.2, 1.1.1)
   - 1.4 Wind
     - 1.4.1 frequency of extreme events (hurricanes, cyclones)

2. Atmosphere
   - 2.1 mean annual CO_2 concentration
   - 2.2 duration of exceedence of phytotoxic levels of ozone
   - 2.3 duration of exceedence of phytotoxic levels of SO_2

3. Nutrients
   - 3.1 wet and dry deposition of nitrogen
   - 3.2 wet and dry deposition of sulphur

4. Land use
   - 4.1 rate of deforestation or afforestation
   - 4.2 rotation length (average period between harvests)

12.2.5.4 Indicators of change

Indicators of change which can be predicted from models and verified in the field constitute a powerful model test and are an important way of building confidence in your predictions. The problem lies in selecting indicators which are sensitive, easily defined, observed, and interpreted, and have a high signal-to-noise ratio. Early and unequivocal warning of change may be given by focusing on locations and processes which are particularly sensitive to the climate. An example is the location of the tree line, either on an altitudinal gradient or on a latitudinal gradient (Bonan and Sirois, 1992; Hogg, 1994). The same principle can be applied to looking at the location of the limit of distribution of an individual species. Tree phenology (the dates on which key physiological events occur, such as bud-break, flowering, fruit-set, and leaf-fall) is typically co-ordinated in temperate plants by a combination of temperature and light signals (Kramer, 1994; Sparks and Carey, 1995). Phenology is easily recorded, even by volunteer networks, and in some cases may be amenable to remote sensing. The point is not to use the plant as a surrogate thermometer (rather just use a thermometer), but to understand and illustrate the biologically-integrated consequences of a set of linked

changes. Litter accumulation integrates several climatic and environmental effects (Meentemeyer, 1978).

The location, spread, and intensity of tree diseases or pest outbreaks may be climate-sensitive, but they are also sensitive to many other factors, including air pollution and stand management, which complicate the interpretation of observations. Tree growth rate, as recorded by annual growth rings, is a long-term indicator of growth conditions, including climate.

12.2.6 Summary of methods

A brief overview of the methods which can be used is provided in Table 12.5.

12.3 Scenarios

The topic of scenarios in general is discussed in Chapters 2 and 3. There will typically be a team developing scenarios for use by all the sector assessments. They will need to know what the input data requirements are, in order to provide scenarios which are specific for the forest sector, such as the projected future per capita timber use or the planned growth in wood exports.

Even in the absence of climate change, the future of the forest sector is unlikely to be exactly the same as the current state, due to changes in socio-economic factors and non-climate variables such as acid deposition.

12.3.1 Climatological baseline

The dynamics of forest ecosystems are especially dependent on rare extreme events such as wind storms and droughts, which are difficult to quantify accurately using a short-term climate record. The record from which their frequency is estimated should be as long as possible.

12.3.2 Socio-economic baseline

The socio-economic baseline includes documentation of the current extent and location of the various forest types. Land cover maps are the most suitable source of this information, since vegetation maps usually depict the “potential” vegetation (that which is postulated to occur in the absence of human disturbance) rather than the “actual” vegetation. Where land cover maps are not available, high resolution satellite images and aerial photographs are the most reliable way of constructing them. Unverified land cover statistics based on district- or national-level expert judgements are often unreliable. A number of international and regional land cover exercises currently in progress may provide data for the study area. The IGBP-DIS global 1 km land cover

project (Townshend, 1992) and the European Union TREES project (JRC, 1996) are examples.

Table 12.5 Summary of methods suggested for assessing the impacts of climate change on forests.

Method	Data needs	Cost	Assumptions	Time needs	Equipment needs	Skills	Output	Validation
Experimentation	High	High	Low	High	Experiment stations	Foresters, ecologists, research scientists	Detailed but location specific	Not needed except for extrapolation
Historical analogues	Low	Medium	Many	Medium	Microscopes, labs	Palynologists, paleoecologists	Qualitative, spatially patchy	Not possible
Regional analogues	Low	Low	Many	Medium	Maps, GIS	Bio-geographers	Maps, bioclimatic models	Reserve some data
Expert judgement	Low	Low	Many	Lows	Scenarios	Mix of disciplines, experience	Broad, qualitative and general	Not possible
Empirical biophysical models	Medium	Low	Many	Low	Calculator, PC	Bioclimatologists, statisticians	Quantitative, but uncertain for large extrapolations	Reserve some data
Process-based biophysical models	High	Medium	Few	Medium	PC	Modellers, ecophysiologists	Maps, time-series. Quantitative and detailed	Essential. Try historical or regional validation
Economic models	Medium to high	Medium	Many	Medium	PC	Forest/agricultural/ resource economists	Spatially aggregated, quantitative, detailed	Necessary but difficult
Integrated models	High	High	Medium	Medium	Work station	Modelling plus other disciplines	Spatial, quantitative, moderately detailed, time series	Necessary but difficult

Many herbaria keep accurate records on the distribution of individual species. Additional information about the forest types, such as the soil (particularly the depth and texture) or topographical situations under which they occur, may be useful in interpreting their distribution and predicting where the forests may occur in the future.

Other than climate and land use, the most important changes are the effects of the steadily-increasing atmospheric CO_2 levels and the consequences of air-borne pollution in areas downwind of industrial and urban centres. Elevated CO_2 concentration is expected to increase photosynthesis and water use efficiency within forests (by up to 30 percent for doubled CO_2), which may be manifest as an increase in growth rates if sufficient nutrients are available (Wang and Polglase, 1995). Since the global atmosphere is relatively well-mixed, CO_2 data from any of the global monitoring stations can be used, as well as scenarios of increasing CO_2 from the IPCC (see Chapter 3).

The deposition of nitrogen, which results mainly from the burning of fossil fuels and the volatilisation of nitrogen from fertilised fields, also tends to increase net primary production in a large region downwind of major source areas (Townsend et al., 1995). In nitrogen-limited systems, this increase could be large. Globally, the growth-enhancing effect of nitrogen deposition is believed to be about one-half that of elevated CO_2 (Schimel, 1995). If the deposition continues at high rates for long periods, and is accompanied by the deposition of sulphur (acid rain), it may eventually lead to ecosystem degradation, tree death, and loss of carbon (Schulze et al., 1989). Nitrogen deposition rates can be obtained from acid rain measuring networks, or they can be estimated by combining knowledge of the nitrogen gas emission sources with dispersion and deposition models. There are global estimated deposition fields of this sort (Galloway et al., 1994).

High concentrations of O_3 and SO_2 can be detrimental to forest growth (McLaughlin and Downing, 1995). These usually occur close to major urban and industrial centres, especially where the regional topography and climatology allow pollutants to accumulate and be exposed to bright sunlight.

The long-term effects of nutrient depletion due to repeated wood harvest need to be considered where harvests are frequent and constitute a large fraction of the biomass. This is especially important in tropical countries, where the tree rotation is short and the soils are inherently infertile.

Trends in the spread and severity of forest pests, diseases, weeds, and fires must also be considered. Bear in mind that if such trends exist, they may be linked to subtle climate changes.

The socio-economic baseline should contain a description of how the forests are currently used and managed. How many people are currently engaged in forest enterprises, or depend on the forests for a living? Where do they live? What is the ownership pattern (communal, leasehold, or freehold)? What is the location of roads, railways, and other infrastructure which allow access to the forest resource? Information on other land uses may also be relevant where they result in the clearing of forests or the creation

of new forests. An example of the former is the clearing of forests to create pastures or croplands; an example of the latter is the set-aside policy in developed countries where land is removed from agriculture and allowed to revert to forest.

Forest management includes the harvest policy (clear-felling or selective extraction), rotation length, species planted, regulations governing where forests may be planted or harvested, and the use of fertilisers and pesticides.

The current demand for forest products must be quantified, in both the informal and formal sectors. The latter typically includes a within-country and export component. Historical data showing the trend in demand and in demand-influencing factors such as population and economic growth help to guide socio-economic scenario generation.

A socio-economic baseline study is very useful, but should not be allowed to consume a disproportionate fraction of the resources at the expense of producing well-considered, coherent scenarios.

12.3.4 Limits of predictability

The forest sector is characterised by a relatively long planning horizon, imposed by the fact that trees require many years between germination and harvest. Substantial changes in the location or species composition of natural and semi-natural forests will probably require several centuries. Changes in the location and species composition of short-rotation plantation forests, on the other hand, can take place within as little as a decade or two. It is not possible to develop reliable climate and socio-economic scenarios for a period of several centuries. Predictions of changes in these factors should not be based on a single run of a very sophisticated model, since the long-range input data are speculative. A more robust strategy would be to use a relatively simple model which allows multiple runs with a variety of scenarios. Historical analogues can provide a picture of the magnitude and type of change that can be expected.

Changes in forest productivity can occur within months or years in response to climate, environment, or management changes. The formal forest sector relies on large fixed investments such as roads, sawmills, and pulp mills, which have an investment lifetime of several decades. Scenarios spanning 20 to 100 years are reasonable for assessments of forest productivity.

12.3.5 Point-in-time or continuous scenarios

Given the relatively slow response rate of many forest processes, continuous (transient) scenarios should be used rather than point-in-time (equilibrium) scenarios wherever possible (Solomon, 1986). When continuous scenarios are used, it may nevertheless be helpful to express the results at a few discrete points in time.

12.4 Autonomous adaptation

Autonomous adaptations are the responses to climate change that will happen without policy interventions. All ecological, social, and economic systems have some degree of inherent adaptability, or they would not survive. The chances of autonomous adjustment are good if the climate change is very gradual relative to the inherent rate of change in the system and to changes which have occurred during the evolution of the system. The climate change which is anticipated to occur in the coming century is considerably more rapid than climate changes which have occurred in the past. The potential for autonomous change in the ecological aspects of the forest sector is therefore limited.

Forestry enterprises routinely adjust the species, cultivars, and areas which they plant and harvest in response to market supply and demand signals. In tropical countries, where the rotation length is short, these decisions may be able to keep up with a rapidly-changing climate. In temperate and boreal forests, where trees may take a hundred years or more to reach harvest size, the current market may not send useful information about future supply and demand.

Tactical decisions are required to follow shifts in the optimum growing areas for forests, because this requires the building of expensive infrastructure such as mills and roads. This infrastructure would be expected to have an economic life of several decades, and would not be expected to be moved as a matter of routine.

The forest assessment should examine each of the impacts resulting from climate change and pose the question of to what degree would the ecosystem, social, or economic system be able to adjust to this impact without assistance from the outside. Only impacts where the capacity for autonomous adjustment is thought to be inadequate to match the rate of change should be carried forward to the next section.

12.5 Planned adaptation

Planned adaptation is defined here as those responses which require deliberate policy decisions. Note that policy is made not only by governments, but at many other levels as well, including supra-national (such as the United Nations) and sub-national levels (such as the management teams of forest-industry corporations).

Adaptation strategies will usually be suggested by the analysis of impacts. Each adaptation strategy can be assessed by following these steps.

12.5.1 Define the objectives of adaptation

The forest sector could have a variety of objectives in undertaking an adaptation strategy. To name a few, they could be to maintain a given level or value of production, to provide a certain number of livelihoods, or to preserve a particular set of species.

The sector will frequently have several simultaneous objectives, or different sub-sectors may have different objectives. It is unlikely that all these objectives will be perfectly compatible: some degree of prioritisation of trade-off is inevitable. National objectives may override forest-sector objectives; for instance, a loss of forestry jobs may in some countries be more than compensated by an increase in agricultural employment.

For objectives to be useful it must be possible to measure their success. This is done by defining one or more evaluation criteria. For instance, if the objective is to maintain biodiversity, the criterion might be the fraction of the area contained in formally conserved areas.

12.5.2 Specify the climatic impacts and locations of greatest importance

The scope of the analysis can be reduced if it can be restricted to the climatic impacts and locations most in need of adaptation. The impact assessment will have indicated which components of the forest sector are most at risk, or where the greatest beneficial impacts are likely. For instance, it may be a particular forest type, or a particular geographical area, or an industry based on a particular forest product. The adaptation strategy should focus on these subsectors.

12.5.3 Identify adaptation options

The purpose of the climate change impacts assessment is not only to provide warning of potential threats but also to offer constructive options which will minimise the costs and maximise the benefits of change. This list of options needs to be as comprehensive and detailed as is practical. The following five general types of adaptation may act as a guide to what to look for.

1. Change the species or varieties planted and harvested.

2. Allow the size of the sector to decrease or increase, for instance by shifting land into or out of agriculture or other uses.

3. Increase the efficiency with which forest raw materials are converted to forest products.

4. Shift the geographical location of the industry to match the area of optimum potential.

5. Change the product mix to utilise new species or size classes; for instance, by producing particle boards instead of sawn timber.

Forest examples could include the planting of tree cultivars which are more tolerant to changes in temperature or drought, increased investment in fire prevention, and control of the spread of new diseases.

Small decreases in forest productivity may be tolerable to the sector, especially if there is advance warning. The industry could adapt by downsizing, by increasing its processing efficiency to compensate for the loss, or by substituting raw material inputs grown locally with those from elsewhere.

This includes all measures to share the loss beyond the sector or region where it has occurred. For instance, financial assistance from governments to assist in the relocation of forestry enterprises shares the cost across all taxpayers.

A shift in the species harvested represents a within-sector change of activity. Replacement of forest by agriculture would be a change of activities between sectors.

The location of forest sector activities may need to move to follow the areas of optimum tree production. This has implications for the location of costly fixed infrastructure such as sawmills and pulp mills. The cost of transporting timber products from the point of growth to the market is usually a significant component of forest enterprise viability.

12.5.4 Examine the constraints

Forestry is a relatively long-term activity because of the fundamental biological constraints imposed by the growth rate of the trees and the economic constraints imposed by large fixed investments. There are ecological constraints on where forests can grow, determined principally by the interaction of climate and soil. Within the area of ecological potential, it may not be feasible to establish forests everywhere because of the presence of competing land uses such as agriculture, conserved land, and urban settlement. Some forest sector workers have specialised skills which cannot be applied in other sectors without retraining. Some human communities in forested regions have a culture which is deeply embedded in their location and activity, and cannot be moved without great social disruption.

12.5.5 Quantify measures and formulate alternate strategies

Each proposed action must be measured against the objectives set for adaptation, using the evaluation criteria defined for the objective. It is important to assess the actions according to several criteria and to keep in mind the uncertainty associated with the impact scenarios. The minimum criteria should be cost, robustness, and effectiveness. The robustness of an action is its ability to remain beneficial under a wide range of scenarios, and its effectiveness is the probability of achieving the objective.

The method of evaluation will almost always involve models of some kind. Usually they will be the same models that were used in impact assessment, but now applied as simulation games to search for an optimal solution. For example, forest gap models could be run for existing forest areas using different species to estimate future productivity if the adaptation option is to change the species planted or harvested. If the

adaptation is to shift the location, forest productivity models could be run with the same species, but in new locations. Where the adaptation involves changing the land use, economic models may be needed to understand the costs and benefits as well as production models specific to the future land use.

12.6 Summary and implications

Forests and the human activities which depend on them are sensitive to climate change for two main reasons: the biological processes which underlie their distribution, composition, and productivity are under strong climatic control; and the time scale of adjustment of both the biological and socio-economic systems involved in forestry is of the order of decades. The changes imposed by rapid land use and land cover changes in forest regions, and by the rising carbon dioxide concentration of the atmosphere, are factors which act additively and interactively with climate change to increase pressure on forest resources, but make the analysis more difficult.

The state of knowledge of the response of forest ecosystems to climate change is far from perfect, but a basic toolkit of techniques can be applied anywhere in the world to get at least an indication of the direction and probable magnitude of change for a given climate scenario. At this stage the uncertainties in assessing the impacts of climate change on forests are not substantially greater than the uncertainties in the climate change scenarios themselves, and in particular in the estimates of changes in precipitation, which is critical for forestry function. At a local or regional scale, the models and information available in some parts of the world are relatively sophisticated. It is important to understand and communicate both the inherent natural variability of forests and the uncertainty of predictions, as well as the model estimates, while not unnecessarily obscuring the main issues in the mind of the reader.

The basic analytic toolkit consists of bioclimatic models for defining the climatic envelope of forest types, and thus potential shifts in distribution and composition, and productivity models for estimating their performance under different climates. Coupled to these are models of the economic dependencies within the forest sector and between the forest and other sectors. All the models can range from the purely statistical to those with a high level of process detail. As yet there are few truly integrated models of forestry within the context of global change, including its human dimensions; those that exist either are regional or have insufficient detail on forests to be helpful. Pragmatism will drive the decision on which models to use. Several different approaches to the same problem are recommended. Ancillary data and insights can be had from regional intercomparisons (i.e., look to a region which currently has a climate similar to that predicted for the target region, and see what happens there) and from paleo-ecological data.

It is a good strategy to undertake an impact study in two phases, spending a fifth to a third of the effort and resources in a “scoping” phase, based on simple models, expert

judgement, and readily-available information, which serves to define the handful of key issues which require more intensive study.

There are strong two-way links between forest impacts and several other sectors, summarised in Table 12.6. This alone necessitates a two-phase approach, to allow the feed-forward and feedback processes to be taken into account.

Table 12.6 Linkages between forest and other sector impacts.

Sector	Impact from Forest	Impact on Forest
Wildlife and biodiversity	Change in habitat area or quality	Change in non-timber products
Agriculture	Shared bioclimatic and production modelling approaches, therefore similar data and analysis needs	
Land use	Loss or gain of non-forest area	Loss or gain of forest area
Water resources	Change in the afforested area of the catchment	Water availability for saw and pulp mills and log transport
Energy	Supply of fuelwood and charcoal	Demand for biomass energy, cost of harvesting and processing timber, acid deposition

References

Agren, G.I., R.E. McMurtrie, W.J. Parton, J. Pastor, and H.H. Shugart. 1991. State of the art models of production-decomposition linkages in conifer and grassland ecosystems. *Ecological Applications* 1, 118-138.

Alcamo, J. (ed). 1994. *Image 2.0: Integrated Modelling of Global Climate Change*. Kluwer, Dordrecht, The Netherlands.

Arthur, L.M., and G.C. van Kooten. 1989. Assessing economic benefits of climate change on Canada's boreal forest. *Canadian Journal of Forest Research* 19, 463-470.

Bonan, G.B. and L. Sirois. 1992. Air temperature, tree growth and the northern and southern range limits to *Picea mariana*. *Journal of Vegetation Science* 3, 495-506.

Box, E.O. 1980. *Macroclimate and Plant Forms: An Introduction to Predictive Modeling in Phytogeography*. Junk, The Hague, The Netherlands.

Branchu, P., H. Faure, J.P. Ambrosi, E.M. van Zinderen-Bakker, and L. Faure-Denard. 1993. Africa as source and sink for atmospheric carbon dioxide. *Global and Planetary Change* 7: 41-49.

Carpenter, G., A.N. Gillison, and J. Winter. 1993. DOMAIN: A flexible modelling procedure for mapping potential distributions of plants and animals. *Biodiversity and Conservation* 2, 667-680.

Chambers, F.M. 1993. *Climate Change and Human Impact on the Landscape: Studies in Palaeoecology and Environmental Archaeology*. Chapman and Hall, London, United Kingdom.

Comins, H.N. and R.E. McMurtrie. 1993. Long-term response of nutrient-limited forest to CO_2 enrichment: Equilibrium behavior of plant-soil models. *Ecological Applications* 3, 666-681.

Dale, V.H. and H.M. Rauscher. 1994. Assessing impacts of climate change on forests: The state of biological modeling. *Climatic Change* 28, 65-90.

D'Arrigo, R.D., G.C. Jacoby, and R.M. Free. 1992. Tree-ring width and maximum latewood density at the North American tree line: Parameters of climatic change. *Canadian Journal of Forest Research* 22, 1290-1296.

Davis, W.P., K.W. Thornton, and B. Levinson. 1994. Framework for assessing effects of global climate change on mangrove ecosystems. *Bulletin of Marine Science* 54, 1045-1058.

Dise, N.B. and R.B. Wright. 1995. Nitrogen leaching from European forests in relation to nitrogen deposition. *Forest Ecology and Management* 71, 153-161.

Friend, A.D., H.H. Shugart, and S.W. Running. 1993. A physiology-based gap model of forest dynamics. *Ecology* 74, 792-797.

Frischlin, A., H. Bugmann, and D. Gyalistras. 1995. Sensitivity of a forest ecosystem model to climate parameterization schemes. *Environmental Pollution* 87, 267-282.

Galloway, J.N., H. Levy, and P.S. Kasibhatla. 1994. Year 2020: Consequences of population growth and development on deposition of oxidised nitrogen. *Ambio* 23, 120-123.

Gates, D.M. 1993. *Climate Change and its Biological Consequences*. Sinauer Associates Inc., Sunderland, Massachusetts, USA.

Giannini, R. and F. Magnani. 1994. Impact of global change on pollination processes and on the genetic diversity of forest tree populations. *Forest Genetics* 1, 97-104.

Hogg, E.H. 1994. Climate and the southern limit of the western Canadian boreal forest. *Canadian Journal of Forest Research* 24, 1835-1845.

Holdridge, L.R. 1967. *Life Zone Ecology*. Tropical Science Centre, San Jose, California.

Innes, J.L. 1994. Climatic sensitivity of temperate forests. *Environmental Pollution* 83, 237-243

Jarvis, P.G. 1993. MAESTRO: A model of CO_2 and water vapour exchange by forests in globally changing world. In *Design and Execution of Experiments on CO_2-Enrichment*, E.-D. Schulze and H.A. Mooney.. Ecosystem Research Report No. 6, Publication no. EUR 15110 EN. The Commission of the European Communities, pp. 107-116.

Joyce, L.A. (ed). 1995. *Productivity of America's Forests and Climate Change*. USDA Forest Service Technical Report RM-271. US Department of Agriculture, Fort Collins, Colorado, USA.

Joyce, L.A., J.R. Mills, L.S. Heath, A.D. McGuire, R.W. Haynes, and R.A. Birdsey. 1995. Forest sector impacts from changes in forest productivity under climate change. *Journal of Biogeography* 22, 703-713.

JRC. 1996. *TREES Project: A European Initiative for Tropical Forest Ecosystems*. Joint Research Commission, European Commission project EUR 17258 EN.

Kellomäki, S. and M. Kolström. 1994. The influence of climate change on the productivity of Scots pine, Norway spruce, pendula birch and pubescent birch in southern and northern Finland. *Forest Ecology and Management* 65, 201-217.

Kramer, K. 1994. A modelling analysis on the effects of climatic warming on the probability of spring frost damage to tree species in The Netherlands and Germany. *Plant Cell and Environment* 17, 367-377.

Landsberg, J.J., S. Linder, and R.E. McMurtrie. 1995. *Effects of Global Change on Managed Forests: A Strategic Plan for Research on Managed Forest Ecosystem in a Globally Changing Environment*. GCTE Report No 4.

Linder, S. 1987. Responses to water and nutrition in coniferous ecosystems. In *Potentials and Limitations of Ecosystem Analysis*, E.-D. Schulze and H. Zwölfer (eds). Ecological Studies 61. Springer Verlag, Berlin-Heidelberg-New York, pp. 180-202.

Martin, P. 1992. EXE: A climatically sensitive model to study climate change and CO_2 enhancement effects on forests. *Australian Journal of Botany* 40, 717-735.

Matyas, C. 1994. Modeling climate change effects with provenance test data. *Tree Physiology* 14, 797-804.

McGuire, A.D., L.A. Joyce, D.W. Kicklighter, J.M. Melillo, G. Esser, and C.J. Vorosmarty. 1993. Productivity response of climax temperate forests to elevated temperature and carbon dioxide: A North American comparison between two global models. *Climatic Change* 24, 287-310.

McLaughlin, S.B. and D.J. Downing. 1995. Interactive effects of ambient ozone and climate measured on growth of mature forest trees. *Nature* 374, 252-254.

McMurtrie, R.E., D.A. Rook, and F.M. Kelliher. 1990. Modelling the yield of *Pinus radiata* on a site limited by water and nitrogen. *Forest Ecology and Management* 30, 381-413.

Meentemeyer, V. 1978. Macroclimate and lignin control on decomposition. *Ecology* 59, 465-472.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore, III, C.J. Vorosmarty, and A.L. Schloss. 1993. Global climate change and terrestrial net primary production. *Nature* 363, 234-240.

Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry* 5, 109-113.

Peres-Garcia, J., L.A. Joyce, C.S. Binkley, and A.D. McGuire. 1995. Economic impacts of climate change on the global forest sector: An integrated ecological/economic assessment. In *Proceedings of a Meeting on Economics of Carbon Sequestration in Forestry*, Bezendal, May 15-19.

Peterjohn, W.T., J.M. Melillo, F.P. Bowles, and P.A. Steudler. 1993. Soil warming and trace gas fluxes: Experimental design and preliminary flux results. *Oecologia* 93, 18-24.

Peterjohn, W.T., J.M. Melillo, P.A. Steudler, K.M. Newkirk, F.P. Bowles, and J.D. Aber. 1994. Responses of trace gas fluxes and N availability to experimentally elevated soil temperatures. *Ecological Applications* 4, 617-625.

Peterson, D.W. and D.L. Peterson. 1994. Effects of climate on radial growth of subalpine conifers in the North Cascade Mountains. *Canadian Journal of Forest Research* 24, 1921-1932.

Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud, and A.M. Solomon. 1992. A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography* 19, 117-134.

Prentice, I.C., M.T. Sykes, and W. Cramer. 1993. A simulation model for the transient effects of climate change on forest landscapes. *Ecological Modelling* 65, 51-70.

Rosenberg, N.J. (ed). 1993. Towards an integrated impact assessment of climate change: The MINK study. *Climatic Change* (Special Issue) 24, 1-173.

Running, S.W. and J.C. Coughlan. 1988. A general model of forest ecosystem processes for regional application. I. Hydrological balance, canopy gas exchange and primary production process. *Ecological Modelling* 42, 125-154.

Ryan, M.G., E.R. Hunt, R.E. McMurtrie, G.I. Agren, J.D. Aber, A.D. Friend, E.B. Rastetter, W.M. Puliam, R.J. Raison, and S. Linder. 1996. Comparing models of ecosystem function for temperate conifer forests: I. Model description and validation. In *Global Change: Effects on Coniferous Forests and Grasslands,* A.I. Breymeyer, D.O. Hall, J.M. Melillo, and G.I. Agren (eds). SCOPE (Scientific Committee on Problems of the Environment) 56. John Wiley, Chichester, United Kingdom, pp. 313-362.

Schimel, D.S. 1995. Terrestrial ecosystems and the carbon cycle. *Global Change Biology* 1: 77-91.

Scholes, R.J. and M.R. van der Merwe. 1996. Sequestration of carbon in savannas and woodlands. *The Environmental Professional* 18, 96-103.

Schulze, E.-D., W. De Vries, M. Hauhs, K. Rosén, L. Rasmussen, C.-O. Tamm, and J. Nilsson. 1989. Critical loads for nitrogen deposition in forest ecosystems. *Water Air and Soil Pollution* 48, 451-456.

Shugart, H.H. 1984. *A Theory of Forest Dynamics.* Springer Verlag, New York.

Shugart, H.H. and D.C. West. 1980. Forest succession models. *Bioscience* 30, 308-313.

Shugart, H.H., P.J. Michaels, T.M. Smith, D.A. Weinstein, and E.B. Rastetter. 1988. Simulation models of forest succession. In *Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes,* T. Rosswall, R.G. Woodmansee, P.G. Risser (eds). SCOPE (Scientific Committee on Problems of the Environment) 35. John Wiley, Chichester, United Kingdom, pp. 125-150.

Servant, M., J. Maley, B. Turcq, M.L. Absy, P. Brenac, M. Fournier, and M.P. Ledru. 1993. Tropical forest changes during the Late Quaternary in African and South American lowlands. *Global and Planetary Change* 7, 25-40.

Smith, T.M. and H.H. Shugart. 1993. The transient response of terrestrial carbon storage to a perturbed climate. *Nature* 361, 523-526.

Smith, T.M., H.H. Shugart, G.B. Bonan, J.B. Smith, and F.I. Woodward. 1992. Modeling the potential response of vegetation to global climate change: The ecological consequences of global climate change. *Advances in Ecological Research* 22, 93-116.

Solomon, A.M. 1986. Transient responses of forests to CO_2 induced climate change: Simulation modeling experiments in eastern north America. *Oecologia* 68, 567-569.

Sparks, T.H. and P.D. Carey. 1995. The responses of species to climate over two centuries: An analysis of the Marsham phenological record, 1736-1947. *Journal of Ecology* 83, 321-329.

Townsend, A.R., B.H. Braswell, E.A. Holland, and J.E. Penner. 1995. Spatial and temporal patterns in terrestrial carbon storage due to deposition of anthropogenic nitrogen. *Ecological Applications* 6, 806-814.

Townshend, J.R.G. (ed). 1992. Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set. Report of the land cover working group of IGBP-DIS. International Geosphere-Biosphere Project, Stockholm. Also, <http://www.meteo.fr/cnrm/igbp/>.

Wang, Y.P. and P.G. Jarvis. 1990. Description and validation of an array model — MAESTRO. *Agricultural and Forest Meteorology* 51, 257-280.

Wang, Y.P. and P.J. Polglase. 1995. Carbon balance in the tundra, boreal forest and humid tropical forest during climate change: Scaling up from leaf physiology and soil carbon dynamics. *Plant Cell and Environment* 18, 1226-1244.

Woodward, F.I. 1987. *Climate and Plant Distribution.* Cambridge Studies in Ecology. Cambridge University Press, Cambridge, United Kingdom.

13 Biodiversity: Species, Communities, and Ecosystems

Lead Author
Jay R. Malcolm [1]

Contributing Authors
Antony W. Diamond, Canada
Adam Markham, USA
Francis X. Mkanda, Malawi
Anthony M. Starfield, USA

13.1 Nature of the problem

Biodiversity is short for biological diversity, the variety of life and its associated processes. As defined by Hunter (1996, p. 19), it is "the diversity of life in all of its forms, and at all levels of organisation." The term has been criticised as too all-inclusive, but it does succinctly embody the idea of the extraordinary diversity and complexity of life on earth. It includes all organisms, their genetic variation, and the diversity of ways in which they interact with each other and their physical environment

As summarised in the Convention on Biological Diversity, biodiversity has intrinsic value. It also provides many direct and indirect benefits to human populations:

- Maintenance of life-sustaining systems.
- Possibilities for future evolution of the biosphere.
- Ecological, genetic, social, economic, scientific, educational, cultural, recreational, and aesthetic services for human populations. These services range from harvesting

[1] Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada.

of individual wildlife species, to production of clean water and air, to aesthetic wilderness values, to global biogeochemical cycling.

- Genetic resources of critical importance for meeting food, health and other needs of the world population.

- Biological resources that support traditional activities of many indigenous and local communities.

13.1.1 Important climate change impacts in the biodiversity sector

Recent reviews on the impacts of a changing climate on biodiversity include Malcolm and Markham (1997) and Walker and Steffen (1997). Conclusions from these studies include the following:

- Species will respond differently to climate change because of differences in competitive abilities, migration rates, and responses to disturbance, and in other ways. Thus, new combinations of species will arise. This “reorganisation” in species composition has as yet unknown consequences for ecosystem functioning.

- Many species may be able to disperse fast enough to keep up with projected climate change provided they can disperse through continuous, relatively undisturbed, natural ecosystems. This emphasises the important consequences of fragmentation of natural ecosystems.

- Depending on the rate of climate change, other niche parameters may not change at same rate as climate, resulting in novel habitat combinations that species have not experienced before.

- Changes in the relative timing of seasonal events during the yearly cycle may have strong negative impacts for many species, especially migratory ones.

- Invasion of alien species into natural ecosystems is an increasing problem worldwide which is likely to be exacerbated by climate change. Disturbance and dieback will probably increase as more long-lived organisms (trees) are farther from their optimal environmental envelopes and subject to increasing pressure from land use change. An increase in disturbance will lead to more ecosystems in early successional states, resulting in a generally “weedier”, structurally simpler biosphere with fewer systems in a more ecologically complex, old-growth state.

- Markedly different effects of climate change on species composition will occur within individual landscapes because of local effects of soil, land use, and topographic variation.

- Reductions in the area of “cold-adapted” ecosystems such as arctic and alpine ecosystems are expected, with negative impacts for arctic and alpine species.

13.1.2 Goals of an assessment

The goal of a biodiversity assessment is to evaluate the potential impact of climate change on biodiversity attributes, including structural attributes such as species and genetic diversity, and functional attributes such as ecosystem properties and processes. The chapter outlines management options that can be used to adapt to climate change and (if possible) avoid some of its negative impacts. A comprehensive assessment will include both structural and functional approaches.

13.1.3 The study area

The study area typically consists of the lands of the national territory. However, because species and ecosystems frequently extend beyond national borders, a sub-continental, continental, or even inter-continental approach is sometimes necessary. The spatial and temporal resolution of the assessment will in many cases be determined by the resolution of the required data sets. The ultimate utility and acceptability of the results may be influenced by levels of co-operation at national, regional, and international levels.

13.2 An array of methods

Because of the diverse scope for climate change impact and adaptation assessment in the biodiversity sector, this section follows a hierarchical approach that allows the assessment to be tailored to the specific needs of the user. The classic species-community-ecosystem hierarchy is followed, and the emphasis shifts from the structural to the functional attributes of biodiversity. For some users, the impacts on a single species may be of interest, perhaps because of its special economic or ecological value. Section 13.2.1 focuses on methods that can be applied to individual species. These include techniques to assess vulnerability to environmental change in general, as well as methods that can be used to examine the implications of particular climate change scenarios. Approaches include the use of expert judgement, climate “envelope” modelling, dynamic population modelling, and analogue and monitoring studies. For other users, a group of species might form the focus of the analysis, as for example in assessing the potential impacts of climate change on wildlife species richness. Section 13.2.2 outlines methods that can be applied to groups of species, defined either according to species composition or based on community characteristics such as species richness. At the highest level in the hierarchy, the purpose of the analysis may be to examine the potential impacts of climate change on ecosystem properties and processes such as biogeochemical cycling. Section 13.2.3 describes several techniques that can be used to assess climate change impacts on ecosystems and to model possible changes in their distributions, properties, and processes.

13.2.1 Impacts on species

13.2.1.1 Vulnerability to change

The rate of climate change in the next 100 years is expected to be higher than during many periods in the past (Crowley and North, 1988; Crowley, 1990; Hinckley and Tierney, 1992; Crowley and Kim, 1995), hence a major threat to species and ecosystems may be the change itself (Peters and Darling, 1985; Peters and Lovejoy, 1992). One approach to impact assessment, therefore, is to try and determine beforehand which species are sensitive to change in the broadest sense. For example, Dennis (1993) assumed that species with narrow resource/habitat requirements and inflexible biology were most vulnerable to change and hence would be most threatened by climate change. A second approach similarly avoids uncertainty about climate change and focuses on species or ecosystems already in danger. The reasoning here is that organisms and ecosystems already threatened by human activities may be more vulnerable to the additional stress of a changing climate (Peters, 1990; Markham and Malcolm, 1996). Millsap et al. (1990) provided an example of this type of analysis. They conducted a ranking of species vulnerability based on criteria such as biological vulnerability, gaps in knowledge about population status, and current management investments. Mkanda (1996) applied the Millsap et al. (1990) technique to assess potential vulnerability to climate change of several ungulates in Lengwe National Park, Malawi.

Implementation

Dennis (1993) designed his method with butterflies in mind. If required, expert judgement can be used to the rework the categories so that they can be applied to other taxa. In both this and the Millsap et al. (1990) method, each species is assigned a score for each variable and the scores are summed across groupings of the variables. Sums can subsequently be ranked, grouped, or mapped to prioritise adaptation and management investments (e.g., Millsap et al., 1990; Figure 13.1). The scores are meaningful only in a relative sense, i.e., in comparison to scores from other species. Therefore, it is suggested that several taxa be scored simultaneously.

Data and computational requirements

Because the Dennis (1993) and Millsap et al. (1990) methods require information on geographic distributions, they are implicitly sub-continental or continental in scope. Additional requirements include information on population numbers, habitat and dietary requirements, and reproductive characteristics and seasons. In a few cases, data from manipulative or analogue experiments are desired. Ultimately, the methods are very flexible with regards to data requirements. Variables can be added or modified, and if needed, dropped from the analysis.

These techniques do not incorporate climate scenarios. Instead, they attempt to assess overall vulnerability regardless of the direction of climate change.

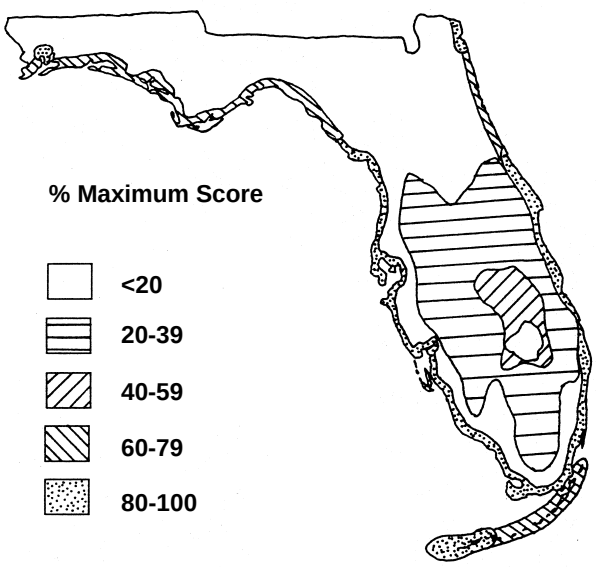


Figure 13.1. Geographic patterns in the vulnerability of bird species in Florida as determined by Millsap et al. (1990). Range maps of taxa with biological scores ≥24 were overlaid and scores were summed where ranges overlapped.

Advantages and limitations

The techniques are relatively easy to perform; they require relatively unsophisticated input information, and potential impacts can be assessed regardless of the exact nature of future climate change. However, generality is achieved at the expense of realism. All variables are assumed to be equally important and any interaction among variables is ignored. Also, the vulnerability scores are themselves relative measures and are useful only when compared with other scores. On the positive side, these screening techniques are of value irrespective of the eventual course of climate change because they help to identify species that are already in trouble, or are likely to be trouble in the face of additional negative human influences. Independent of climate change assessment, they are a useful addition to local conservation efforts.

13.2.1.2 Expert judgement

This common approach is a relatively simple way to generate ideas and discussion about potential climate change impacts. Typically, a climate change scenario is assumed, the opinion of experts as to impacts on the species of interest is solicited, and a workshop or other forum is organised to present and discuss results. Sometimes, expert judgement is collated or organised in some predetermined fashion. For example, Herman and Scott (1993) assessed the potential impacts of climate change on selected vertebrate groups in eastern Canada by adopting a specific climate change scenario, enumerating resultant changes in the physical environment that were of potential importance to the organisms, and soliciting expert judgement to score the importance of the changes.

An example of an even more quantitative setting for incorporating expert knowledge is provided by the Habitat Suitability Index (HSI) technique developed by the US Fish and Wildlife Service (1981). A software package enables an expert or group of experts to create a simple model that describes how features in the environment act together in determining overall habitat suitability for a wildlife species. Future scenarios of environmental change subsequently can be used as input to investigate changes in habitat quality (see also Chapter 14).

Implementation

Prior to soliciting expert opinion, several choices must be made: the taxa of interest, the climate change scenarios to be used, and the methods to be used to organise or present the resulting information. In the HSI system, specific steps are undertaken to create a model: (1) taxa and cover types are chosen, (2) important life requisites and other limiting factors of the species are identified, (3) single-variable models between environmental characteristics and habitat suitability are developed, and (4) relationships among the single-parameter models are established. Once an HSI model has been constructed, various types of analyses are possible: habitat conditions under baseline and future climate can be compared, sensitivity analyses can be used to identify important habitat features, impacts of management and adaptation strategies can be assessed, etc. Brody et al. (1989) gave an example of an HSI model that is integrated with forest succession models, and Laymon and Barrett (1986) provided guidelines for model development and testing.

The principal tasks for the co-ordinator of an expert judgement study are to identify and recruit the experts, specify the climate change scenarios and make them available to the experts, establish goals and directives for the experts, and decide on methods to organise the resulting information.

Data and computational requirements

From the point of view of the assessment co-ordinator, this is the least data-intensive method. Often, the most computationally-intensive task is to provide climate scenarios.

The HSI model is available as shareware written in BASIC (available from Computer Specialist, National Ecology Research Center, National Biological Service, 4512 McMurry Avenue, Fort Collins, CO 80535-3400 USA, 303-226-9263), and will run on virtually any microcomputer. Requirements for input data will vary from species to species.

In the HSI approach, climate variables may number among the environmental parameters used to model habitat suitability, hence integrating HSI simulations and quantitative climate models will be straightforward. In many cases, however, climate will determine habitat suitability indirectly through its action on other environmental parameters. For example, island area is an important measure of nesting and roosting habitat suitability for the roseate spoonbill (Lewis, 1983) and climate may indirectly influence island area through its effects on sea levels. Several approaches are available in

these cases. One is to model the relationship between climate and the parameter of interest. For example, based on sea level and shore type, island area can be estimated for different scenarios of sea level rise. Another is to use expert judgement to enumerate possible climate change effects on the environmental parameters, and use HSI sensitivity analyses to identify which of the possibilities might seriously affect habitat suitability.

Examples

Herpetofauna in eastern Canada

Herman and Scott (1992) focused on eastern Canadian vertebrates thought to be highly susceptible to climate change (salamanders, shrews, and turtles). A regional climate change scenario based on consensus from global circulation models was developed; it assumed that summer precipitation would decrease and winter temperature and precipitation (especially rainfall) would increase. To assess climatic sensitivity, a list of life history characteristics was developed and experts scored the sensitivity of each characteristic to the hypothesised climate changes. The analysis suggested that shrews would be very sensitive to changes in winter conditions, such as increased winter flooding and reduced snow and ice cover.

Ungulate populations in Malawi

Mkanda (1996) used the HSI approach to evaluate nyala (*Tragelaphus angasi*) habitat in Lengwe National Park, Malawi, under three climate change scenarios. The three general circulation models (GCMs) used were the Canadian Climate Centre (CCC) model (Boer et al., 1992), the GFD3 model from the Geophysical Fluid Dynamic Laboratory (Manabe and Wetherald, 1987), and the United Kingdom Meteorological Office UK89 model (Mitchell et al., 1989). The importance of several variables (including total annual precipitation, number of preferred browse/grass species, mean annual temperature, and distance to water) in determining habitat suitability was developed based on expert judgement, and an overall measure of habitat suitability was based on the geometric mean of the individual relationships. To estimate changes in habitat suitability under the climate change scenarios, the effects of changes in annual precipitation and mean temperature on the individual habitat variables were modelled. Habitat suitability declined under every climate change scenario, sugges-ting that climate change would further endanger populations of this rare antelope.

Advantages and limitations

The compilation of expert judgement can be very useful if the biology of the species is well known. Additionally, the mere act of bringing together specialists from diverse disciplines can stimulate new approaches and ideas. Of course, if a particular scenario is assumed from the start and it later becomes necessary to consider a different scenario, expert judgement must be solicited again. Also, the expert judgement method

suffers from a lack of objectivity: different experts will give different judgements as to climate impacts.

Although HSI model creation is very flexible, the models are descriptive of complex relationships. Interactions among habitat variables and dynamic responses to change are excluded (for example, feedback relationships between environmental variables and abundance are ruled out). The focus is on pattern instead of process. The utility of the models in predicting species-habitat relationships is thus seriously compromised, and perhaps as a result, the models are rarely tested or refined. In many cases, habitat relationships measured in one part of a species range do not hold true in other parts, and as a result HSI models may give erroneous predictions when applied to new geographic areas. From a climate change perspective, the HSI models suffer an additional drawback. Variation in climate may directly affect abundance, but in many cases the influence is indirect, through its effect on other habitat parameters. For example, a change in climate may influence habitat indirectly through its effect on browse quality and quantity. Typically, HSI models ignore these underlying indirect causes. In these cases, climate change scenarios can be incorporated only by making additional assumptions about the way in which climate interacts with the habitat parameters of interest. On the positive side, HSI assumptions are explicit and the simplicity of the software allows users to easily create models that may capture important elements of habitat suitability. As usual, simplicity is both an asset and a liability.

13.2.1.3 Climate envelopes and profiles

The use of climate envelopes and profiles capitalises on the fact that the geographic distributions of many species are highly correlated with climate. In some cases, the correlation may reflect physiological limits: the species' fundamental niche (Hutchinson, 1957). In others, climate variables may be correlates of other causative factors (MacArthur, 1972; Root, 1988a, 1988b; Sykes et al., 1996). The potential impacts of a changing climate are investigated by comparing the current geographic distribution with future distributions under one or more climate change scenarios.

Implementation

The concept is similar to the HSI approach in that environmental variables are used to model the suitability of a site for a species. In this case, however, only climate data are used. Two basic approaches can be distinguished, reflecting the distinction between a species' fundamental and realised niches (physiological limits to growth and reproduction versus observed niches). In the first approach, climate-based physiological limits are measured and modelled in the laboratory or field. Once empirical relationships have been established, potential geographic shifts in the physiological range can be compared between baseline and future climate scenarios (e.g., Johnston and Schmitz, 1997). In the second approach, a statistical model is created that estimates the geographic range based on the climate variables. Several techniques may be used to develop the model, including simple tabulation of climate statistics (Bennett et al., 1991; Morse et al., 1993), logistic regression (Price 1995), and discriminant analysis

(Rogers and Williams, 1994; Rogers, 1996; Malcolm, 1996). The statistical model is subsequently re-applied to the data to define the current climate envelope, which can then be compared with future envelopes under changed climatic conditions. A third hybrid technique has also been developed: equations that relate plant physiology to climate are defined a priori and distributional information subsequently is used to parameterise the equations (e.g., Huntley et al., 1995; Sykes et al., 1996).

In all these approaches, future distributions are after conditions have equilibrated. The species is assumed to have somehow reached its new location. Thus, the analysis does not provide information on how far or fast it can move in reality. Instead, the approach is useful in assessing the amount and potential distribution of change (Huntley et al., 1995). For example, Huntley et al. (1995) suggested that the species most affected by climate change would be those whose current and future distributions showed no overlap.

It should be kept in mind that the statistical and hybrid techniques are correlative and not causative. The usual caveat of statistical modelling applies: as more variables are included in the model, the fit of the model improves (that is, the geographic distribution is better described), but the model increasingly relies on spurious relationships. To take the extreme case, if one has as many climate variables as localities, it is possible to devise a model that perfectly distinguishes sites where a species does and does not occur, even if there is no correlation between the species' distribution and climate in the first place. A climate scenario might project extinction across the entire species range simply because of the new combination of climate values at each locality. For these reasons, models should be based on some "best" subset of the original climate variables (one of the rationales for the hybrid approach). As a rule of thumb, several statistical models should be constructed, including a simple one that uses only a few of the best predictors. The inclusion of extraneous, non-predictive variables may lead to spurious results and is not recommended. An additional refinement is to use multivariate techniques to identify discrete "climate subspecies" (should they exist) and create separate profiles for each.

Because distributional boundaries are required to derive the statistical and hybrid models, the entire geographic range of the species should be used. Thus, although analysis of final results may be at a national level, determination of the predictive model in most cases must be at a sub-continental or even continental scale.

Data and computational requirements

In the first approach, physiological relationships and current and future climate scenarios are required. In the second, in addition to the climate scenarios, the geographic distribution of the species is required. As a rule of thumb, climate information from a minimum of 30 sites within the species' range should be contrasted with data from at least as many points outside of the range. Primary data from meteorological stations within the region of interest are preferred; however, global grids of mean monthly temperature and precipitation can be used. Conveniently, baseline and GCM scenarios have been made available at the same scale of resolution for large regions (see Chapter

3). The collection and compilation of numerous climate variables and statistics is encouraged because it increases the chances of finding a strong association between climate and the geographic distribution of interest.

Because the predictive models make direct use of climate data, climate scenarios can be easily incorporated. Of course, baseline and climate change scenarios must include the same set of climate variables.

Examples

An example of the use of discriminant analysis is presented in Box 13.1.

Advantages and limitations

Provided that the required data sets and software are available, climate envelope analyses are relatively easy to perform. They can be a useful tool in several types of analysis:

- Model projections under baseline conditions can be mapped to test for correspondence with observed distributions. This technique can locate previously unknown populations of a species (e.g., Bennett et al., 1991).

- Potential distributions under climate change scenarios can be overlaid with land-use maps to identify potential areas of resource conflict.

- Models can be created for several species in a region to investigate possible changes in biodiversity (Section 13.2.2.1).

- Knowledge about climate associations can provide insight into the biology of a species and can be incorporated in habitat suitability analyses (Section 13.2.1.2).

- Historical range shifts can be used to validate models.

A key assumption of the statistical method is that the current distribution of the species is in equilibrium with climate. Thus, species that are not at equilibrium with climate must be modelled with caution (see Sykes et al., 1996). Examples include species that are currently expanding their geographic ranges, species whose distributions are critically influenced by non-ecological factors (for example, mountain ranges or other geographic barriers), and species whose geographic distributions have been significantly modified by human activities. Whenever possible, historical distributions should be used, i.e., distributions that pre-date important human impacts. Ideally, geographic distributions should be from the same period as the climate baseline scenario.

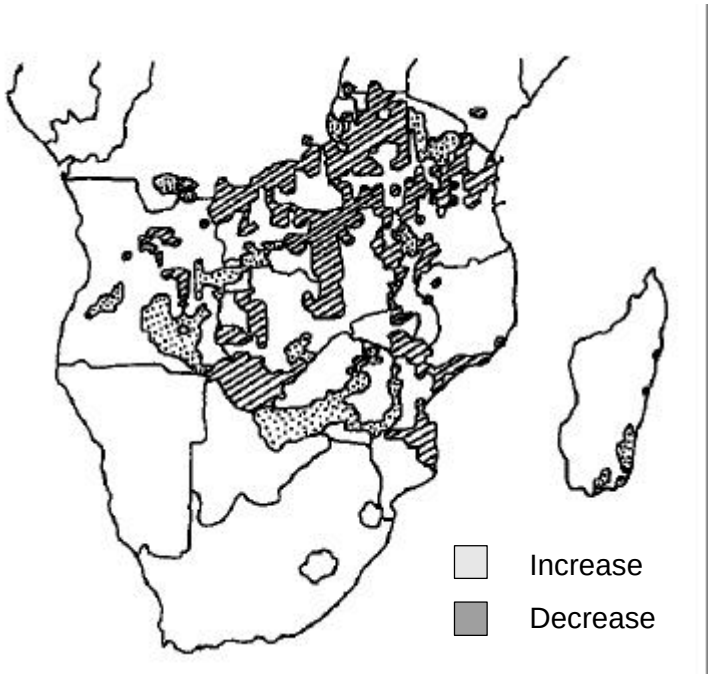
Box 13.1 Example: Use of discriminant analysis in climate envelope modelling

Rogers (1996) used discriminant analysis to model the current and potential future geographic distribution of a widespread species of tsetse fly (*Glossina morsitans*) in southern Africa. Tsetse flies transmit human and animal trypanosomiasis, causing sleeping sickness in humans and nagana in domestic animals, both of which are generally fatal unless treated. Large areas in Africa are threatened by one or other of these diseases, which drastically reduce agricultural productivity and critically influence the dynamics between human and wildlife populations.

Distributional data were digitised from published maps and climate data layers included mean, maximum, minimum, and standard deviation of monthly averages of eight variables (mean temperature, minimum temperature, maximum temperature, precipitation, potential evapotranspiration, vapour pressure, cloud cover, and windspeed). A series of reliable training sites of 200 sites of vector absence and 400 of vector presence were chosen to calculate the discriminant function. Of the full set of climate variables (i.e., 32), 10 were selected in order of importance in distinguishing between presence and absence centroids. This was decided by choosing each variable in turn on the basis of the increase it provided in Mahalanobis distance (D2) between the two centroids.

New maps were created using three climate change scenarios: UKMO (Murphy and Mitchell, 1995), OSU (Schlesinger and Zhao 1989), and CCC (McFarlene et al., 1992).

The climate change scenarios showed losses in the north-western part of the range, with fewer and more scattered gains, sometimes to the east and west (see figure). The change was attributed to the overriding importance of changes in temperature and evapotranspiration in determining the distribution of the species. Rogers (1996) noted that although the model relies on correlation instead of causation, given our weak understanding of vector population dynamics, most predictions must be based on this sort of analysis. He also noted that it is an over-simplification to conclude that the maps show future distributions, because of the lack of consideration of the relationship between the pace of climate change and the dispersal ability of the vector.



Box 13.1, Figure 1 Changes in the simulated distribution of G. morsitans in southern Africa between the 1961-90 climate baseline and the OSU (wet) climate change scenario.

The statistical techniques rely entirely on patterns of correlation and as such may not identify key processes that drive responses to climate change (Davis et al., 1998). Under both approaches, a host of potentially important limiting factors are ignored, such as species interactions (competition, predation, and parasitism) and soil parameters. Also, baseline and future climate data sets often do not include information on extreme climatic events, which can be fundamentally important in limiting distributions. Sykes et al. (1996) call for increased use of field experiments to determine physiological limits, so that hybrid models can more closely approximate physiological models, and so that differences between fundamental and realised niches can be empirically investigated.

These models are equilibrium descriptions of a very dynamic process. They do not provide information on the ability of a species to move with climate change. As a final limitation of the approach, accurate geographic distributions are available for few organisms, especially tropical ones.

13.2.1.4 Dynamic models

Several models have been developed that model tree community dynamics within forest stands (e.g., Shugart, 1984; see Chapter 12); unfortunately, they usually do not incorporate the spatial component required to model changes in species distributions. Outside of this literature, models that explicitly model the dynamics of individual species in response to climate change are rare.

There are, however, a number of dynamic models that address issues associated with climate change, such as habitat destruction, dispersal, and cycles of drought or other short-term weather patterns. These models provide an indication of both the difficulties and rewards of future modelling efforts. For example, Tilman et al. (1997) explore the effects of habitat destruction on plant communities and suggest that the most abundant species (which are also the poorest dispersers) may be among the first species to be driven extinct by habitat destruction. McKelvey et al. (1993) use the case of the northern spotted owl in North America to investigate conservation planning for species in fragmented landscapes. Dunning et al. (1995) review spatially explicit population models and their potential uses, and Ruskelshaus et al. (1997) caution how sensitive such models can be to poor data on dispersal characteristics. Starfield and Bleloch (1991) show how an animal species at the limits of its range might struggle to persist under adverse weather conditions and hypothesise that behaviours that benefit a species in prime habitat might actually be debilitating at the margin.

Forest gap models (Chapter 12) and other forest stand models can be used to model forested habitats (see Section 13.2.1.2 for an example). However, habitat quality and quantity are increasingly being determined by direct human management. Thus, future changes in habitat will be dictated in part by human responses to climate change. These responses may significantly alter existing management regimes (whether by design or not) and lead to the emergence of new zones or types of wildlife/human conflicts (Dublin et al., 1995). Therefore, in addition to the direct and indirect effects of climate change on species and their habitat, a comprehensive assessment must consider likely

human responses to climate change, and consequent changes in management regimes and conflicts.

13.2.1.5 Monitoring

Monitoring is an important research priority, both for biodiversity conservation (Article 7, United Nations Convention on Biodiversity) and because plant and animal populations serve as barometers of ecosystem integrity. Extinctions of species in many cases reduce the capacity of an ecosystem to respond to additional changes and thus may jeopardise the future ability of the system to provide useful services to human populations. In the final analysis, losses of species indicate inappropriate and, quite likely, dangerous management practices. From a climate change perspective, monitoring is required to establish current population levels and distributional limits, and to detect climate-induced change that is already under way.

Techniques for monitoring populations and their habitats vary greatly from one group of organisms to another. A few examples of the many field studies that have increased our understanding of the role of climate in natural systems are listed in Table 13.1.

Table 13.1 Examples of long-term monitoring studies and of research on responses of natural communities to spatial and temporal variation in climate.

Study	Primary taxa	Biome
Aebischer et al. (1990)	Various	Marine ecosystem
Bethke and Nudds (1995)	Waterfowl	Temperate grassland
Foster (1982)	Vertebrates	Tropical forest
Laurie and Brown (1990)	Marine iguanas	Oceanic island
Overpeck et al. (1991)	Trees	Temperate forest
Parmesan (1996)	Butterfly	Temperate ?
Pounds and Crump (1994)	Anurans	Cloud forest
Schreiber and Schreiber (1984)	Seabirds	Oceanic island
Stiles (1992)	Hummingbirds	Tropical forest

13.2.1.6 Analogue studies

Understanding the past responses of natural populations to spatial and temporal climate variability provides important insights into the possible effects of future climate change. These analogue studies provide information on the kinds of climate changes that have influenced resources of interest in the past. Our ability to detect and respond to global climate change is improved with an increased understanding of the present- day role of climate in natural systems.

Examples

Deer-caribou winter distributions in Nova Scotia

Winter snow depth affects the distribution of many mammals at both local and regional scales (Formozov, 1946; Telfer and Kelsall, 1984). Ungulates differ in their morphological and behavioural adaptations to snow, and current distributions of ungulate communities in North America correspond well with their adaptations to type and depth of snow in the regions in which they occur (Telfer and Kelsall, 1984). Changes in winter climate will likely change the suitability of winter habitat, and hence the ranges of these species. Such changes occurred between the Little Ice Age (1300-1850), when moose and caribou occupied Nova Scotia, and the period after 1850 when white-tailed deer re-colonised the province at the expense of caribou, probably because of milder winters and the associated decrease in snow depth (Telfer, 1967). Predator-prey relations also may shift with changing distributions of snow types; wolves flounder in deep snow that caribou can cross, but can follow moose, which are little better suited to travel through soft snow (Telfer and Kelsall 1984).

Tree swallows and other aerial insectivores.

Birds that feed on insects in flight — aerial insectivores — are particularly vulnerable to weather conditions in the spring and early summer. Mortality of adults from cold snaps in April and May are relatively common, and growing young are vulnerable in June when adults must spend most time catching food rather than brooding the chicks. Unusual cold and rain at this time, such as occurred in June 1993 in southern Saskatchewan, can lead to mass mortality of chicks because the adults have to spend more time trying to find food and cannot keep the young warm (Hoyt in litt.). Increased frequencies of such extreme events may cause enough mortality to lead to a shift in distribution away from regions experiencing such weather patterns. Some other aerial insectivores, particularly swifts (family Apodidae), are metabolically better adapted to cold wet summer weather: the chicks have variable growth rates and can go into torpor to conserve energy through lean periods (Lack, 1973).

African wildlife

Magadza (1994) used the impacts of previous droughts in southern Africa as an analogue for predicting the possible impacts of climatic change on wildlife. Recorded impacts of previous droughts on mammalian populations showed shifts in geographic ranges and shifts in community structure. Because the rates of response were slower than rates postulated to occur under global warming, and because the GCMs predicted higher temperatures than those found during the droughts, Magadza (1994) concluded that large mammals were likely to be threatened by climate change.

13.2.2 Impacts on communities

13.2.2.1 Species as independent entities

A common approach for assessing the impacts of climate change on communities is to conduct individual species-level assessments and subsequently combine the results. Comparisons among species can be used as a screening technique to help identify those species or species groups at greatest risk from climate change and in need of further detailed analysis. The community approach is implicit in some of the species screening techniques (Section 13.2.1.1) because vulnerability scores for one species must be interpreted relative to those for other species.

A second approach is to assess possible climate-induced changes in community characteristics such as species richness. Baseline species richness can be obtained from field studies or by overlaying species-specific distributional maps. Statistical methods can subsequently be used to model species richness as a function of climate, and changes in species richness can be mapped under current and future climate scenarios. However, an important requirement is to distinguish between alpha (site- specific) and gamma (regional) diversity.

Examples

Several of the species-level approaches outlined above have been applied across groups of species. For example, Herman and Scott (1992) applied expert judgement in assessing climate change impacts on eastern Canadian salamanders, shrews, and turtles. Dennis (1993) assessed potential impacts of climate change on butterflies of the United Kingdom. Millsap et al. (1990) analysed present-day vulnerability of vertebrate groups in Florida (e.g., Figure 13.1). Examples of climate envelope modelling as applied to species richness are in Price (1995) and Malcolm (1996). Western (1991) speculated on the potential impacts of climate change on the abundance and diversity of African savannah ungulates mammals using observed relationships between climate and biomass, productivity, diversity, and average body size.

Advantages and limitations

Climate envelope modelling of species richness can be a misleading technique because it focuses on the sheer numbers of species in an area rather than qualitative aspects of diversity, such as species composition, distribution, and relative abundance. Under climate change, species numbers may increase if species adapted to the new climate regime invade an area. Thus, even though sensitive species might be lost, and regional diversity decrease, species richness at a site may increase. It is at the largest spatial scale - the turnover in species composition across a region (gamma diversity) - that biodiversity impacts must ultimately be judged (Noss, 1983).

A simple thought experiment illustrates the danger of equating species diversity with the numbers of species at a site. Because of the increase in species richness as one proceeds

from the poles to the tropics, average annual temperature and species richness are highly correlated. Making use of this relationship, a scenario of consistent greenhouse warming might be expected to result in increased species richness in the Antarctic and Arctic (provided that southern taxa were able to move pole-ward). At the same time however, Arctic and Antarctic species would be going extinct because the cold polar conditions they require no longer exist. Thus, even though local diversity might be increasing, global biodiversity would be decreasing.

A more quantitative example of the dangers implicit in using alpha diversity to represent diversity is presented by Malcolm (1996). Based on a regression model between climate and species richness, total species richness of ungulates was consistently projected to increase throughout southern Africa. However, species richness of a subset of the community, the highland savannah community of South Africa, decreased under every scenario.

13.2.2.2 Species assemblages

With respect to overall community and ecosystem properties, not all species are equal. Some play a disproportionate role in determining community composition and functional properties of the ecosystem. Nor are all species equal from a conservation perspective: some may be good indicators of certain kinds of ecological impacts, others may have a high public profile. Given limited resources and knowledge, a valuable approach to impact assessment is to preferentially devote efforts to just a few species, perhaps because of their overall importance in the ecosystem or their value from a conservation viewpoint (Table 13.2).

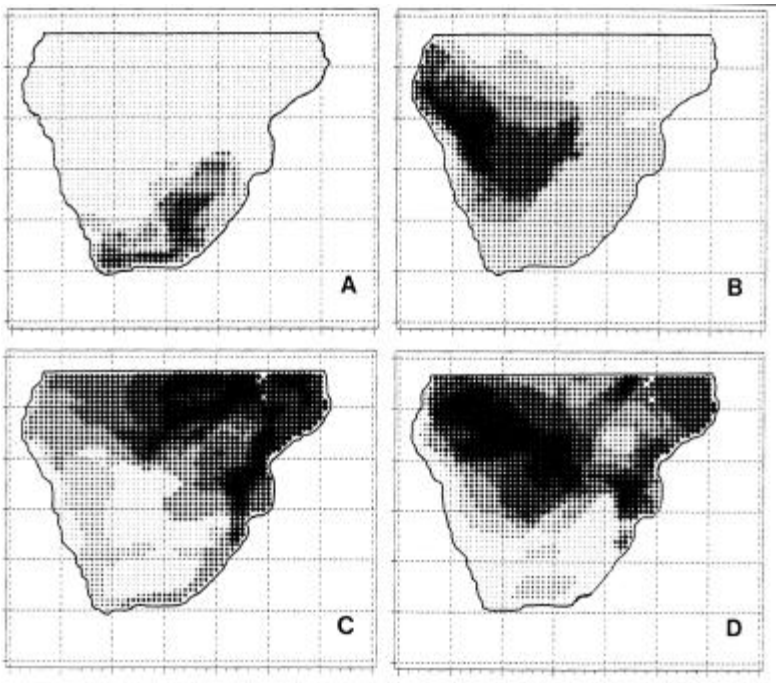
Table 13.2 Species classification from a conservation viewpoint (after Meffe et al., 1997).

Keystone species	Species that play a disproportionate role in determining major ecosystem functions/properties (trophic relationships, community structure, hydrological flow, successional patterns, disturbance cycles, etc.).
Indicator species	Species that: • have highly specific niche or narrow ecological tolerance; • are characteristic of a specific biotic community, successional stage, or substrate; • are reliably found under a certain set of circumstances, but not others.
Umbrella species	Species that require large blocks of relatively natural or unaltered habitat to maintain viable populations.
Flagship species	Species that elicit a strong and positive emotional response.
Vulnerable species	Species that: • have small populations; • exist in highly fragmented habitats and are poor dispersers; • have narrow or highly specialised niches; • are vulnerable to human activities.
Economically important species	Species that are harvested species or incur economic losses or benefits.

In an example of the use of species distributions to analyse species assemblages, Malcolm (1996) used ordination to group ungulate species according to the similarity of their geographic distributions (Box 13.2). The analysis identified four more-or-less distinct ungulate assemblages that showed contrasting responses to climate change. Presumably, species in the same assemblage have faced similar selective pressures through time, and hence will show similar responses to climate change.

Box 13.2 Example: Use of climate envelope modelling in investigating changes in ungulate diversity in southern Africa.

The climate envelope approach was used to model the potential impact of climate change on the diversity of hoofed mammals in southern Africa (Hulme et al., 1996). Distributions of 44 taxa from Smithers (1983) were digitised at 0.5° resolution, including the elephant and ungulates from two orders: Artiodactyla (even-toed animals such as pigs, hippopotamuses, giraffes, and antelopes and their kin) and Perissodactyla (odd-toed species such as zebras and rhinoceroses). Multiple regression was used to model total diversity and diversity in four zoogeographic groupings identified by ordination (see figure 1). Discriminant analysis was used to model the distributions of individual taxa.

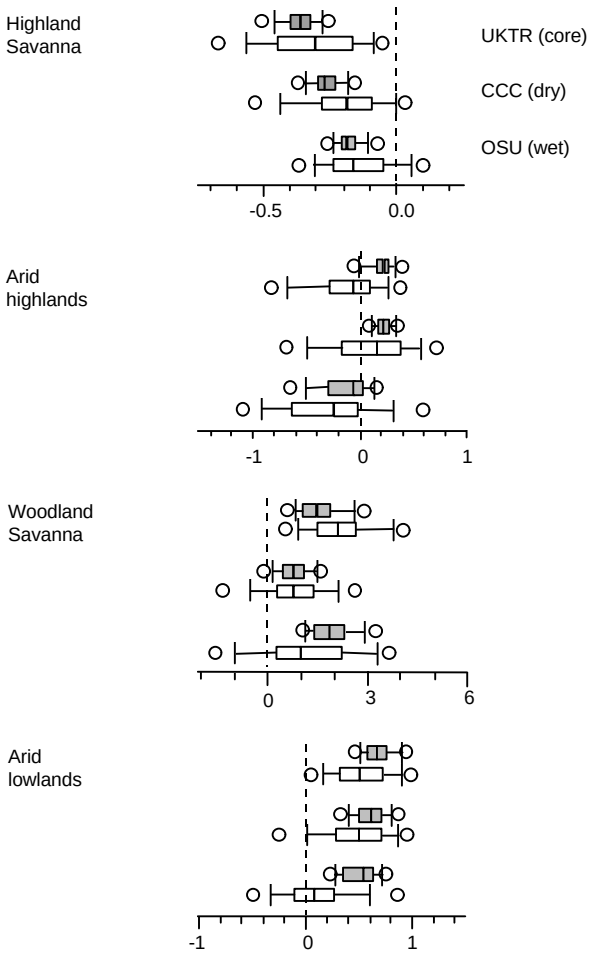


Box 13.2, Figure 1. Observed species richness in four species groups identified from a principal components analysis. A: highland savannah group (7 species); B: arid highlands group (7 species); C: woodland savannah group (25 species); D: arid lowlands group (5 species). In each part, six sizes of diamonds represent six classes of species richness. (A and D = ≤0.5, 0.5-1.5, 1.5-2.5, 2.5-3.5, 3.5-4.5, >4.5; B = ≤1.5, 1.5-2.5, 2.5-3.5, 3.5-4.5, 4.5-5.5, >5.5; C = 0.5, 0.5-1.5, 1.5-7.5, 7.5-11.5, 11.5-14.5, >14.5).

The IIASA data set (Leemans and Cramer, 1990) was used to calibrate the models. Predicted baseline values were subsequently calculated using a 1961-1990 baseline data set, and served as a reference for judging the impacts of three doubled CO_2 GCMs: a core scenario

(UKMO: Murphy and Mitchell, 1995), a wet scenario (OSU: Schlesinger and Zhao, 1989), and a dry scenario (CCC: McFarlene et al., 1992).

Diversity was predicted to increase over much of the region, but separate zoogeographic groupings showed contrasting responses. Richness in the savannah woodland and arid lowlands groups increased in most grid cells, especially under the core and dry scenarios. In contrast, species richness in the highland savannah group demonstrated a consistent pattern of regional decrease. For the arid highlands group, predicted changes in richness varied from scenario to scenario (see figure 2).



Box 13.2, Figure 2. Box plots summarising changes in species richness across grid cells for the four species groups identified in Figure 1. Boxes represent the 25th and 75th percentiles, capped bars represent the 10th and 90th percentiles, and circles represent the 5th and 95th percentiles. Upper (filled) bars are for two-variable multiple regressions; lower (open) bars are for many-variable multiple regressions. Results are shown for three climate change scenarios (UKTR, CCC, and OSU).

Success of the discriminant analysis approach in predicting individual distributions varied greatly from species to species. The analysis was least successful for species with restricted or patchy distributions. Among taxa that exhibited a consistent change in geographic distributions in response to climate change, decreases in distributions were more prevalent than increases. Such taxa included three in the savannah woodland group (elephant, buffalo, nyala) and two in the arid lowlands group (blue wildebeest, eland). Every species (black wildebeest, bontebok, blesbok, Cape mountain zebra, grey rhebok, grysbok, mountain reedbuck) in the highland savannah group showed a consistent decrease in distribution size,

as did three species in the arid highlands group (Hartmann's mountain zebra, springbok, steenbok) and one in the savannah woodland group (klipspringer).

13.2.3 Impacts on ecosystems

13.2.3.1 Ecosystem screening

As summarised in Table 13.3, research has identified several biomes and ecosystem types that are thought to be at special risk from climate change (Houghton et al., 1990; Leemans and Halpin, 1992; Peters and Lovejoy, 1992; Markham et al., 1993). These biomes can be mapped at national or regional scales to identify priority areas for research, monitoring, and management.

Table 13.3 Examples of ecosystem types sensitive to climatic change (after Markham and Malcolm, 1996).

Ecosystem/Biome	Key Climate Sensitivities	Reference
Coastal wetlands	Sea level rise, storms	Reid and Trexler (1992)
Mangrove forest	Sea level rise, storms	Ellison and Stoddart (1991)
Island ecosystems	Sea level rise, temperature, storms	Rose and Hurst (1991)
Coral reefs	Sea surface temperature, storms	Smith and Buddemeier (1992), Agardy (1994)
Arctic ecosystems	Temperature	Alexander (1990), Chapin et al. (1992)
Alpine/montane ecosystems	Temperature, precipitation	Halpin (1997), Beniston (1994)
Boreal forest	Temperature, fire regime, soil moisture	Shugart et al. (1992)
Tropical forest	Drought, seasonality, fire regime, hurricanes	Hartshorn (1992)

Data and computational requirements

Ecosystem screening requires that biomes or ecosystems be mapped at a national or regional scale. Creation of these maps will be easiest if remote-sensing information or biophysical/biogeophysical classifications are available. These data and the software required to process them are becoming increasingly available.

A priori classification of biomes according to climate change sensitivity involves implicit assumptions about the likelihood of particular climate change scenarios. Often, assumptions are also made about the way that climate interacts with organisms in a biome. Depending on current scientific understanding, certain climate change scenarios may be deemed more likely than others; hence, if desired, more attention can be devoted to subsets of the biomes listed in Table 13.3.

13.2.3.2 Biome modelling

Over the years, a number of biogeographic models have been developed that predict the dominance of various plant life forms in different environments. Biogeochemical models go another step and, based on plant life-form types, simulate cycling of carbon and other nutrients. The VEMAP project (VEMAP Members, 1995) provides a useful introduction to both types of models. The project was designed to provide spatially explicit information on the sensitivity of terrestrial ecosystems in the conterminous United States to elevated atmospheric CO_2 concentration and associated climate change. A standardised methodology was created whereby climatic, biogeographic, and biogeochemical models were linked and compared. In the Phase I analysis, three mixed-layer ocean GCMs were selected to span a range of possible equilibrium climate changes, from the relatively insensitive Oregon State University model (3.0°C average US temperature increase under doubled CO_2) to the more sensitive UKMO model (+ 6.7°C) (the GFDL model was intermediate at +4.3°C). The resulting climate scenarios, plus baseline controls and information on soils, served as input for three biogeographic models (BIOME2, DOLY, and MAPSS) that simulated major vegetation types across the lower 48 US states. In turn, these data (climate, soils, and plant life forms) served as input for three biogeochemical models, BIOME-BGC, CENTURY, and TEM (VEMAP Members, 1995).

These biogeographic models show similarities with the climate envelope modelling techniques described in Section 13.2.1.3. All three biogeographic models in VEMAP show characteristics of species-level physiological models in that they rely on ecophysiological constraints and resource limitations. DOLY additionally makes use of a statistically defined vegetation classification model. Dynamic components are also included; for example, MAPSS includes a simple fire model. The biogeochemical models incorporate general algorithms that describe plant and soil processes such as carbon capture by plants, decomposition, and waterflux.

Implementation

Typically, the models are run under baseline conditions and under one or more climate change scenarios. Useful outputs include maps and tabulations of biome distributions, properties (such as net primary productivity and carbon change), and changes in biome distributions. These analyses are especially useful when overlaid with land- use patterns and maps of protected areas and when used in concert with other species- and community-level analyses (e.g., Hulme et al., 1996; Box 13.3). For example, Malcolm and Markham (1997) used results from the VEMAP Phase I analysis to examine two aspects of potential ecosystem change. In one analysis, they overlaid the pixel (grid cell) change maps from the nine combinations of climate scenarios and vegetation models. Areas that showed consistent change among the nine combinations were judged to be particularly affected by climate change. In a second analysis (Figure 13.2), they examined change in the regions surrounding pixels, arguing that possibilities for reestablishment and movement in the surrounding landscape would critically influence species' chances of survival in a changing climate. Interestingly, this second analysis

showed more consistent change (and hence greater impacts on ecosystems) than the first.

Data and computational requirements

Because the models are complex, users must rely on data sets generated by the modelling teams. Fortunately, these are often available. For example, all the input and output data sets in the VEMAP Phase I project were made available electronically. In some cases, the data sets are large and hence considerable computer storage space and processing power are required.

Typically, the baseline and climate change scenarios are based on GCM runs, which are made available along with the vegetation outputs.

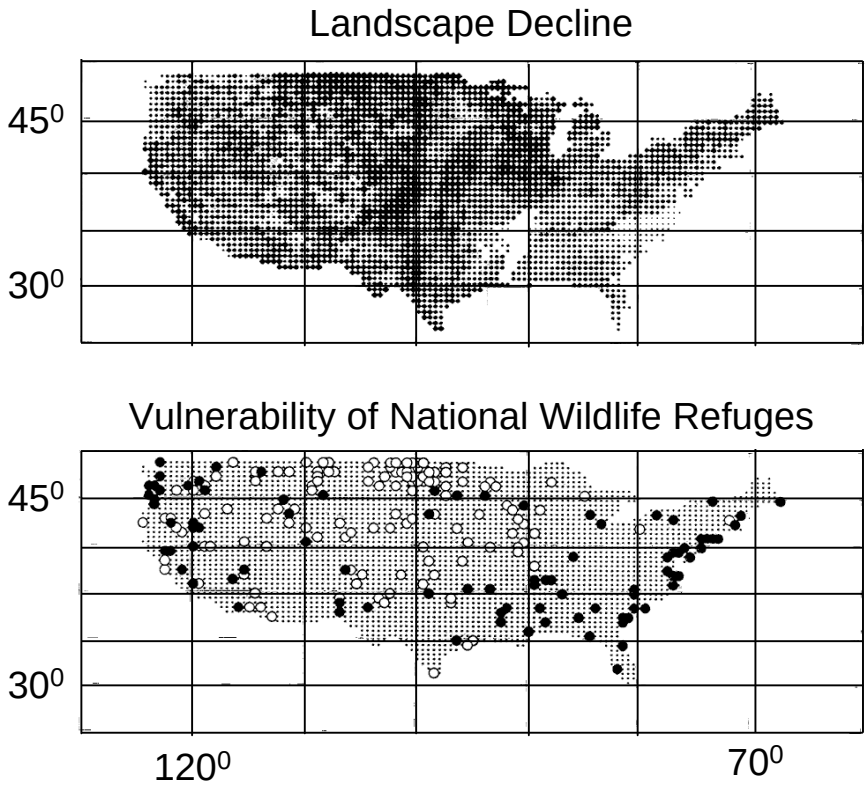


Figure 13.3 **Malcolm and Markham (1997) used results from the VEMAP experiment (VEMAP Members 1995) to examine representation of vegetation types in the regions surrounding grid cells. In part A, the number of nine models that showed declines in representation in the surrounding region is represented by the size of the diamond (largest diamond=all 9 models; smallest diamond = no models). Locations of National Wildlife Regions are shown in part B, with the most vulnerable (declines in ≥5 models) symbolised with open circles. The analysis identifies greatest vulnerability to climate change in the central grasslands.**

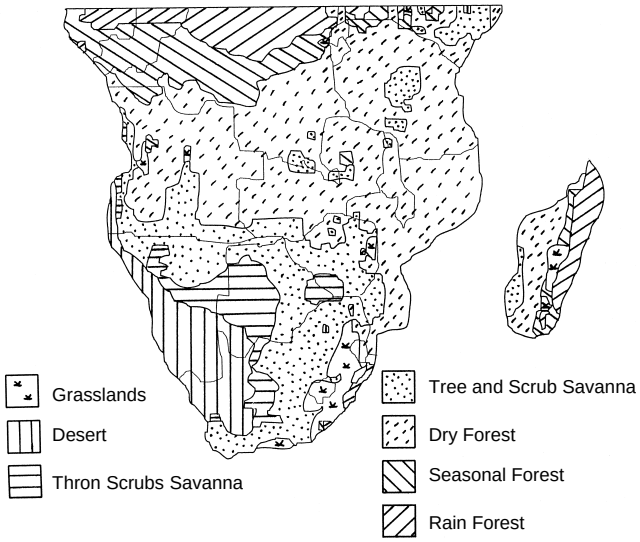
Examples

In an illustrative example (Box 13.3), the geographic distributions of biomes in southern Africa were modelled by Hulme et al. (1996). In another example, Boonpragob and Santisirisomboon (1996) used the Holdridge Life Zone Classification (Holdridge, 1947) to model potential changes of forest area in Thailand under three GCM scenarios.

Box 13.3 Example: Use of eco-climatic classification to screen the vulnerability of protected areas in southern Africa.

Hulme et al. (1996) used the BIOME model (Prentice et al., 1992) to investigate potential vegetation changes in the protected areas of southern Africa. They argued that biome shifts can indicate significant threats to the ecosystems that reserves were established to protect.

The current distribution of natural vegetation in the region was reasonably well simulated using baseline (1961-1990) climate and the BIOME model (see figure 1), although several significant differences were found. The actual border between the savannah and grassland biomes [as illustrated in White (1983)] was in poor agreement with the predicted one and modelled savannah areas were too extensive. In addition, swamplands and salt pans, which cover significant areas in the region, were not defined by the BIOME model. Recent attempts to improve the model by incorporating interannual climate variability and soil nutrients may improve performance.



Box 13.3, Figure 1. The distribution of modelled biomes for southern Africa using the 1961-1990 climate and 350 ppmv carbon dioxide concentration. After Hulme et al. (1996).

The authors ran the BIOME model for three GCMs scenarios for the region, including a core scenario (UKMO: Murphy and Mitchell, 1995), a wet scenario (OSU: Schlesinger and Zhao 1989), and a dry scenario (CCC: McFarlene et al., 1992). Recognising that plants may increase their water use efficiency (WUE) under the increased carbon dioxide concentrations, the authors ran two versions of the BIOME model: one in which only climate determined the changes in distributions of biomes, and a second in which a WUE response was simulated by setting a lower limit for the moisture index of each modelled biome (=Plant Functional Type). Under all scenarios, there were significant shifts in most biomes. Without a WUE response,

the most significant shift was a loss of grassland. About 20% of the region showed a shift in biome type. With a WUE response, grassland was much less affected, but even larger shifts in biome types were predicted.

The IUCN national reserve and national parks database compiled by the World Conservation Monitoring Centre in the United Kingdom contained 349 reserves in the southern Africa region that were larger than 1000 hectares. For each reserve, it was determined whether its current vegetation would change. Climate change alone impacted some 17 percent of reserves. Under greater WUE, some 25 to nearly 40 percent of the reserves were affected (see table). Thus, the analysis identified the importance of considering climate change in developing long-term planning strategies for protected areas. A more detailed analysis would include country-specific and reserve-specific analyses.

Box 13.3, Table 1. Percentage of the nature reserves in Southern Africa in which a biome shift occurs under the different climate change scenarios. After Hulme et al. (1996).

Scenario	Impacted nature reserves
dry without WUE	16.7
wet without WUE	15.8
core without WUE	18.7
1961-1990 climate with WUE at 560 ppmv CO_2	24.4
dry climate with WUE at 560 ppmv CO_2	25.0
wet climate with WUE at 560 ppmv CO_2	37.9
core climate with WUE at 560 ppmv CO_2	27.9

Advantages and limitations

These methods are valuable because they explicitly incorporate climate variables. Also, because species and other structural and functional system properties are often characteristic of a biome, biome distributions provide information applicable to many aspects of biodiversity assessment. In essence, the biogeographic models combine climate variables in a biologically meaningful way. For example, water availability to a plant will depend not only on precipitation, but also on the rate of water loss via evaporation, which is partly a function of ambient temperature. Thus, a map that already combines these two variables in a biologically realistic way will be of greater value to an ecologist than maps of one or the other.

It was recognised by the VEMAP members that current understanding of ecosystem structure and functioning, or for that matter of global climate, does not yet allow the identification of "best" models or acceptance of correct predictions. However, by providing information from a suite of models, the results can be used to provide preliminary information on the overall sensitivity of natural ecosystems to greenhouse warming (VEMAP Members, 1995).

Just as in the climate envelope techniques, the biogeographic models assume that vegetation is in equilibrium with climatic conditions. For the moment, the models provide no information on rates of change, although dynamic models are being created (e.g., Kirilenko and Solomon, 1998). They are thus static and non-interactive descriptions of a very dynamic process.

13.2.3.3 Dynamic ecosystem models

Process-based models of the causative agents in an ecosystem are very diverse in their approach. It is useful to distinguish two general types of models: tactical and strategic. The former are very detailed models of specific systems, and their objective is to mimic the behaviour of the system as closely as possible. These models are probably the most common type in the climate change literature and can provide very detailed predictions as to vulnerability and climate change impacts. Strategic models, on the other hand, sacrifice detail for generality, and attempt to incorporate the essences of a broader class of systems.

Tactical models face two problems. First, they may be strong in some details, but weak in others (for example, the effects of disturbances such as large fires and insect outbreaks). Second, they may be difficult to scale up from detailed patches to extensive landscapes. Starfield and Chapin (1996) attempt to overcome these problems by using a parsimonious, frame-based modelling paradigm.

It is difficult to validate the predictive powers of these models. However, investment in modelling effort can pay off in a number of ways: identifying data needs for boosting confidence in model projections, helping to sharpen hypotheses, exploring alternative scenarios, and generating new possibilities and ideas.

Examples

Some examples of dynamic models are listed in Table 13.4.

Table 13.4 Examples of processed-based models in climate change research.

Model Type	Examples
Forest gap model	Botkin and Nisbet (1992)
	Shugart and Smith (1992)
	Shugart (1990)
	Botkin et al. (1991)
	Cambell and McAndrews (1993)
Plant physiological models	Running and Coughlan (1988)
	Running and Nemani (1991)
Arctic plants	Reviewed in Reynolds and Leadley (1992)
Temperate grasslands	Hunt et al. (1991)
Bird populations	Rodenhouse (1992)
Prairie wetlands	Poiani and Johnson (1991)
Coastal ecosystems	Costanza et al. (1990)

Advantages and limitations

Tactical models are especially useful in concrete problems of resource management, but a detailed understanding of the system is required. Also, they are often so specific that it is difficult to extract general insight and the calculations are so detailed that the model

behaviour is not transparent. Of course, there is a continuum of approaches between tactical and strategic models that reflect attempts to balance thoroughness and realism on the one hand and generality and workability on the other.

13.3 Autonomous adaptation

All multicellular organisms are able to sense and respond to abiotic factors, and have evolved various mechanisms to track the set of the environmental conditions under which they are able to exist and reproduce. Thus, in response to climate change, organisms and the ecosystems in which they occur will adapt autonomously. In a sense, impact assessment is the task of identifying those species and or ecosystems that are least likely to adjust to a changing climate. Note however, that in the absence of significant evolutionary change, species are dependent on their inbuilt phenotypic plasticity and capabilities in order to respond to climate change. Thus, their ability to autonomously respond to climate change is inherently limited. If suitable habitat conditions disappear entirely, or shift in position faster than a population can react, extinctions will occur and ecosystem simplification will result.

13.4 Planned adaptation

It is possible to adopt policies and practices which assist species in adjusting to climate change, for example by designating and protecting migration corridors. However, our ability to manage ecosystems is very limited because of our inability to predict ecosystem responses. The analogy that ecosystems can be "managed" in the same way that much simpler human-designed industrial systems can is misleading and dangerous (Walker and Steffen, 1997). In a changing climate, one must expect the unexpected (and unpredictable) and keep open as many response options as possible (Walker and Steffen, 1997). In the face of these uncertainties, a key adaptation strategy is to maintain ecological structure and processes at all levels and reduce existing pressures on natural ecosystems (Markham and Malcolm, 1996). Perhaps the most significant challenge is to incorporate biodiversity conservation into adaptation strategies in other sectors, so that societal responses to climate change do not further jeopardise biodiversity.

Adaptation strategies should be developed within the context of global, regional, and national biodiversity conservation plans and according to the articles of the United Nations Convention on Biodiversity. Various strategies are available to aid efforts to conserve biodiversity in the face of climate change, including the establishment and maintenance of protected areas (in situ preservation), the active management of wild populations outside of protected areas (inter situ management), and the maintenance of captive populations (ex situ methods) (see Table 13.5). Of these, highest priority should be placed on in situ and inter situ conservation (Markham and Malcolm, 1996). A protected areas review is a logical first step in defining conservation objectives and goals and in assigning adaptation priorities.

Various habitat management and intervention techniques can be used as part of an overall adaptation strategy. Many of these are already in use in protected areas and managed reserves throughout the world, and the techniques can be adapted to respond to a change in climatic conditions (Table 13.6).

Table 13.5 Typology of biodiversity conservation strategies (after Soulé, 1991).

Strategy	Types of activity
In situ	Protected areas
Inter situ	Conservation outside protected areas. e.g., habitat conservation, development restrictions, buffer zones Extractive reserves Resource harvesting on a sustainable basis Ecological restoration Intensive management to restore degraded habitats and landscapes Zooparks Maintenance of artificial mixes of species under semi-natural conditions. e.g., game farms Agroecosystems and agroforestry High management production oriented systems. e.g., plantation forests, forest gardens.
Living ex situ	Zoos, botanical gardens, aquaria.
Suspended ex situ	Germplasm storage, e.g., seed banks

- The ability of natural habitats to withstand climatic change depends on their ability to both absorb change and bounce back from change. These abilities can be improved by:
  - conserving biological diversity;
  - reducing fragmentation and degradation of habitat;
  - increasing functional connectivity among habitat blocks and fragments; and
  - reducing anthropogenic environmental stresses. Threatened and endangered species and ecosystems already under stress from environmental degradation and human pressures are likely to be vulnerable to the added stress of climatic change.

- Reducing population and ecosystem vulnerability to climate change is likely to have strong additional benefits through the simultaneous reduction of vulnerability to other environmental and anthropogenic stresses.

Table 13.6 Intervention strategies (adapted from Markham and Malcolm, 1996).

Strategy	Examples of current use	Potential use in a changing climate
Ecosystem restoration	Restoration of water meadows and riparian habitat along the Rhine in the Netherlands	Restore degraded land to provide connectivity between existing reserves
Prescribed fire and fire exclusion	Use of fire to maintain age-suitability of jack pine habitat for Kirtlands warbler breeding in Michigan, USA	Prevent conversion of savannah to shrub-dominated communities
Species relocation	Removal of elephants from Zimbabwe to South Africa to relieve population pressure in parks	Remove species from newly unsuitable habitat and relocate them in new areas to which natural migration would be impossible
Removal of impediments to migration and colonisation	Closure of logging roads in western USA	Prepare land for colonisation of desired species - e.g., by removal of scrub to allow forest recruitment. Remove dike or road systems preventing inland migration of coastal wetlands. Remove fences or provide bridges/tunnels
Assisted migration or reintroduction	Reintroduction of wolves to Yellowstone National Park, USA.	Capture and move animal species past obstacles to migration (e.g., agriculture, industrial developments) in direction of climatically forced population migration. Plant seeds, move soil
Control of alien or invasive species	Eradication programs in native forest in Haleakala National Park, Hawaii	Monitor for new invasive species and prevent their spread. Minimise disturbance (e.g., canopy openings in tropical forest) to reduce susceptibility to invasion
Control of disease	Tsetse fly control programs in southern Africa	Monitor for changes in disease distribution and expansion of range of disease vectors. Plan disease control strategies
Irrigation or drainage	Creation of shallow, brackish coastal lakes at Minsmere Reserve (UK) to provide shorebird habitat	Use water management technologies to reduce impacts of drought or sea-level rise. Create new wetlands
Food and water provision	Provision of water in game areas during droughts in Botswana	Plan or expand programs aimed at ameliorating impacts of drought or famine
Population reduction	Culling of elephants in Kruger National Park (South Africa) and in Zimbabwe.	To relieve population pressure on habitats or competitors where relocation is impossible and where mortality due to lack of intervention could lead to even greater losses of genetic variability

In addition to these general principles, several adaptation principles apply specifically to protected areas (Markham and Malcolm 1996):

- Adaptation strategies should emphasise redundancy of populations and protected areas. Just as poorly enforced regulation or political instability can be arguments for increased number of reserves and therefore, greater redundancy (Soulé, 1991), so too can the uncertainty of climate change impacts.

- Design considerations that promote the evolutionary potential of species within protected areas include maximisation of reserve connectivity, size, and number.

- A protected areas network must balance preservation of ecological complexity with preservation of landscape diversity. Altitudinal range within reserves is important because species may be able to migrate upslope to avoid the consequences of warming (Peters and Darling, 1985; McNeely, 1990). Heterogeneity of topography, habitat, and microclimate in reserves allows for greater flexibility of organismal responses to climate change. Gap analysis (see below), based on representative ecosystem and enduring landscape features, will have to become more dynamic (Halpin, 1997). Reserve planning in a changing climate must examine future needs in areas where present-day conservation needs are few, but where migration and dispersal of valued species may make protection necessary or desirable.

- Flexible zoning of reserve boundaries, development of more effective buffer zone management, and inter situ management will play an increasing role as climate change forces changes in species distributions and migration patterns (Peters and Darling, 1985; Bennett et al., 1991; Parsons, 1991).

- Fragmentation itself may be the single biggest barrier to ecosystem adaptation in a changing climate. Even where paleoecological studies suggest that species have been able to adapt to rapid climatic changes in the past, current habitat fragmentation patterns and human barriers may prevent range shifts. Edge effects that accompany fragmentation expose complex habitats to climatic extremes in adjacent simple habitats (e.g., Malcolm, in press). Thus, reduction of fragmentation rates is a critical climate mitigation strategy and increases in connectivity are a high priority adaptation response. Because range shifts are a likely response to climate change, corridors will need to function as habitat rather than as mere transit lanes (Simberloff et al., 1992).

13.4.1 Assessing the vulnerability of protected areas

One goal of adaptation is to ensure that the existing network of protected areas will be successful in conserving biodiversity into the future. Given that existing problems will most likely only worsen under climate change, a logical first step is to identify and correct existing weaknesses in the protected areas network. A powerful tool for conducting such analyses are gap analyses that identify taxa and ecosystems which are underrepresented in the network (these are not to be confused with gap models used in forest simulation; see Chapter 12). A full discussion of these techniques is beyond the

scope of this chapter, but several components are usually involved, including 1) land cover and land use change maps, 2) species distributions, 3) predicted species distributions based on climate envelope or habitat suitability modelling, 4) land stewardship patterns, and 5) existing protected areas. These techniques can be used to assign priorities for land acquisition and to provide information that is useful for a variety of land planning exercises, quite independent of climate change per se (Scott and Csuti, 1997). A gap analysis is a useful addition to attempts to establish national or regional priorities and action plans.

13.4.1.1 Screening techniques

An additional approach is to attempt to assess the vulnerability of an existing protected areas network under a changing climate. A number of characteristics that predispose protected areas to climate change impacts have been suggested (Table 13.7) and can be used to rank protected areas. Malcolm and Markham (1997) undertook a more quantitative analysis and overlaid protected areas onto maps of pixel or landscape change as determined from the VEMAP results (Figure 13.2). Protected area vulnerability was assessed based on the consistency of change among nine vegetation models and scenarios.

Table 13.7 Some characteristics of protected areas that predispose them to climate change vulnerability.

- Presence of sensitive ecosystem types (see Table 13.3)
- Presence of species and/or ecosystems near the edges of their historical distributions
- Presence of species and ecosystems that have geographically limited distributions
- Topographic and geomorphological uniformity
- Small size and high perimeter:area ratio
- Isolation from other examples of component communities
- Human-induced fragmentation of populations and ecosystems
- Existing anthropogenic pressures within and close to borders
- Presence of natural communities that depend on one or a few key processes or species

Implementation

One procedure is to rank each protected area for each of the characteristics in Table 13.7 and sum the rankings to obtain an overall vulnerability index for each protected area. Alternatively, different characteristics can be differentially weighed to assign some higher importance.

The vulnerability characteristics listed in Table 13.7 are guidelines only and in some cases will require refinement in order to form the basis for a quantitative, or even qualitative, ranking scheme. For example, to score protected areas according to “presence of taxa with geographically limited distributions”, decisions must be made as to which floral or faunal groups are to be considered and how limited distributional will be scored. For the final analysis, additional decisions must be made as to the relative importance of each of the various characteristics.

Data and computational requirements

Various sets of information are required for each protected area and the area surrounding it, including ecosystem types, land-use patterns, and species distributions. Ultimately, the screening technique is very flexible with regards to data requirements. Variables can be added or modified, and, if needed, dropped from the analysis. A comprehensive analysis requires the amassing of considerable amounts of data. Some are already available on a global basis, albeit at low resolution. The required data sets will be of immediate use in other efforts to conserve natural resources and to achieve the goals of the United Nations Convention on Biodiversity (Articles 8(a) and 8(b)).

Some of the characteristics listed in Table 13.7 require that assumptions about future climatic conditions be made, others provide measures of vulnerability to change irrespective of the direction of change, and some measure vulnerability irrespective of change. Thus, the user can adjust the final set of characteristics to reflect knowledge about future conditions or, if desired, to make as few assumptions as possible.

Examples

An example of the use of biome-level modelling in assessing protected area vulnerability is provided in Box 13.3.

Advantages and limitations

The screening technique outlined here is easy to perform; it may require relatively unsophisticated input information, and vulnerability in some cases can be assessed regardless of the exact nature of future climate change. However, generality is sometimes achieved at the expense of realism; for example, all variables are assumed to be equally important and any interaction or feedback among variables is ignored. Also, the vulnerability scores are themselves relative measures and are useful only when compared with other scores. On the positive side, the screening techniques are of value irrespective of the eventual course of climate change because they help to identify protected areas that are already in trouble, or are likely to be because of additional negative human impacts. The use of biome models to assess protected area vulnerability is only as reliable as the biome models themselves.

13.5 Integrating the methods

The assessment involves not only the selection of an appropriate suite of techniques, but also specification of the manner in which the various inputs and outputs will be integrated. Careful integration of methods during the assessment offers many benefits: input data sets (especially climate scenarios) can be shared, results from one technique can be used to validate those from others, and comparisons among methods can provide new insights. The identification of vulnerable populations and ecosystems provides important guidance as to where adaptation efforts should be devoted.

Several general strategies are available for conducting an integrated method assessment:

- Preferentially devote research and conservation efforts to species and areas identified as being under particular threat from climate change.

- Couple preliminary screening with detailed investigation of selected taxa and communities using quantitative modelling techniques (Table 13.8).

- Use screening techniques to identify potential indicator species and subsequently use process-based models to determine which species might be affected first or most.

- Test predictions from one model against those from others. For example, sites where a species is predicted to go extinct based on climate envelopes should also show a decrease in habitat suitability using HSI.

- Achieve different levels of detail, depending on data availability. For species with poorly-known habitat requirements and geographic distributions, use qualitative screening. Build detailed models for those species or systems that are well understood and are the subject of active research.

- Preferentially devote monitoring to species where their changes in distributional limits are predicted. Use dynamic models and analogue information to estimate the time-frame of any predicted change.

- Overlay maps of overall species and ecosystem vulnerability with the geographic boundaries of reserves and protected areas to assess the strength of the reserve system in protecting threatened organisms.

- Overlay maps of distributional changes in biome distributions (e.g., Hulme et al., 1996; Malcolm and Markham, 1997), climate envelopes, or habitat suitability (e.g., Lancia et al., 1986) with the geographic boundaries of reserves and protected areas to examine the extent to which taxa and communities will be represented in protected areas in the future. Use these analyses also to identify protected areas where climate change might be manifested first.

Table 13.8 Integration of screening techniques, climate envelope analyses, and habitat suitability in assessing the vulnerability of protected areas.

Protected area 1										
	Occurrence in the Future									
	Vulnerability Scores			Based on Climate Envelopes				Future Habitat Suitability		
Species	Biological	Action	Climate	Scenario 1	Scenario 2	Scenario 3	Baseline Habitat Suitability	Scenario 1	Scenario 2	Scenario 3
A										
B										
C										
.										
.										
.										

13.6 Economic analyses

Some examples of the potential integration of the assessment with economic analyses are as follows:

- When species can be assigned direct market values, for example, based on their harvest value, the techniques can provide an estimate of the economic costs associated with climate change. A comprehensive economic analysis must consider impacts on the supply of the resource and secondary impacts on values and pricing that result from changes in supply.

- Given relationships between harvest rates, productivity, and habitat suitability, the influence of climate change on economic returns from harvests can be investigated using habitat suitability indices.

- Changes in species and habitat distributions can be overlaid with maps of regional resource utilisation to identify regions of high impact and areas of likely shifts in resource utilisation patterns.

- In the case of non-marketed environmental resources, attempts can be made to utilise non-market valuation techniques (Thresher, 1981; Smith, 1993).

Unfortunately, quantifying the value of biodiversity resources is, at best, a difficult task (Krutilla, 1967; Kellert, 1984; McNeely, 1988). These attempts need to made, however. Kellert (1984) argued that in the face of an inherent societal bias toward consideration of only those factors that can be measured and quantified, attempts need to be made to quantify all environmental values, including recreational, ecological, moralistic, scientific, aesthetic, utilitarian, and cultural ones. If natural resources are valued based solely on their contribution to monetary gain, a steady erosion in environmental quality can be expected (Krutilla, 1967).

13.7 Summary and implications

Ecosystems, with their myriad plant and animal species, are complex systems whose structure and function are intimately influenced by climate. Responses to climate change involve patterns and processes over a wide range of temporal and spatial scales, from the nearly instantaneous physiological responses of individual organisms, to shifts in species distributions from one year to the next, to large-scale shifts in biomes over decades and centuries, to shifts in the genetic makeup of populations over millennia. As yet, our understanding of the role of climate in ecosystems, or for that matter in the biology of individual species, is incomplete, and our ability to predict future responses is rudimentary. Much work remains to be done in furthering the science of climate change assessment, particularly in developing realistic dynamic models, in understanding interactions of species with their environment and with each other, in amassing baseline data on species distributions, and in making baseline and climate change scenario data sets widely available in the scientific community.

Impact assessment in the biodiversity sector has broad scope. Techniques are available at several levels of biological organisation, including populations, species, communities, ecosystems, and biomes. Depending on the resources available, many techniques are available within each level, from simple screening based on data in the literature, to the collation of expert judgement, to statistical descriptions of existing climate relationships, to the creation of dynamic simulation models. Most of these techniques are undergoing active development, and steady improvement is expected in the coming years.

Even more rudimentary than our understanding of the role of climate in natural ecosystems is our ability to manage natural ecosystems. Natural ecosystems are much more complex than human systems, and possibilities for emergent and unexpected behaviour are manifest. Our history of interactions with natural systems provides many more examples of mismanagement than of successful management.

The primary goal of adaptation in the biodiversity sector is to ensure that natural systems are able to respond to climate change to the limits of their capabilities. An effective strategy for achieving this is to reduce or remove existing pressures. Many of the same principles that are currently used to minimise negative impacts of development on natural systems find direct application in avoiding the potential negative impacts of climate change, such as the designation of interconnected and comprehensive reserve networks and the development of ecologically-benign production systems. A significant challenge is to incorporate biodiversity thinking into adaptive responses in other sectors, to ensure that future development activities do not further jeopardise the world's biological resources.

Because the potential responses of natural systems to human-induced climate change are inherently limited, the best overall strategy is to minimise the amount of change.

References

Agardy, M.T. 1994. Advances in marine conservation: The role of marine protected areas. *Trends in Ecological Evolution* 9, 267-270.

Aebischer, N.J., J.C. Coulson, and J.M. Colebrook. 1990. Parallel long-term trends across four marine trophic levels and weather. *Nature* 347, 753-755.

Alexander V. 1990. Impacts of global change on arctic marine ecosystems. *In Global Change: Proceedings of the Symposium on the Arctic and Global Change*, J. McCullock (ed). The Climate Institute, Washington, DC.

Beniston, M. (ed). 1994. *Mountain Environments in Changing Climates*. Routledge, London.

Bennett, S., R. Brereton, I. Mansergh, S. Berwick, K. Sandiford, and C. Wellington. 1991. *Enhanced Greenhouse Climate Change and its Potential Effect on Selected Victorian Fauna*. Arthur Rylah Institute Tech. Rep. No. 132, Department of Conservation & Environment, Victoria, Australia.

Bethke, R.W. and T.D. Nudds. 1995. Effects of climate change and land use on duck abundance in Canadian prairie-parklands. *Ecology Applications* 5, 588-600.

Boer G.J., N.A. McFarlane, and M. Lazaro. 1992. Greenhouse gas-induced climate change simulated with the CCC second generation general circulation model. *Bulletin of the American Meteorological Society* 5, 1045-1077.

Boonpragob K, and J. Santisirisomboon. 1996. Modeling potential changes of forest area in Thailand under climate change. *Water Air and Soil Pollution* 92, 107-117.

Botkin, D.B., and R.A. Nisbet. 1992. Projecting effects of climate change on biological diversity in forests. In *Global Warming and Biological Diversity*, R. L. Peters and T. E. Lovejoy (eds). Yale University Press, New Haven, Connecticut, USA, pp. 277-293.

Botkin, D.B., A.D. Woodby, and A.R. Nisbet. 1991. Kirtland's warbler habitats: A possible early indicator of climatic warming. *Biol. Conservation* 56, 63-78.

Brody, M.,W. Conner, L. Pearlstine, and W. Kitchens. 1989. Modeling bottomland forest and wildlife habitat changes in Louisiana's Atchafalaya Basin. In *Freshwater Wetlands and Wildlife*, R.R. Sharitz and J.W. Gibbons (eds). CONF-8603101, DOE Symposium Series No. 61. US Department of Energy, Office of Scientific and Technical Information, Oak Ridge, Tennessee, USA, pp. 991-1004.

Campbell, I.D., and J.H. McAndrews. 1993. Forest disequilibrium caused by rapid little ice age cooling. *Nature* 366, 336-338.

Chapin III, F.S., R.L. Jefferies, J.F. Reynolds, G.R. Shaver, and J. Svoboda. 1992. *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective*. Academic Press, San Diego, California, USA.

Costanza, R., F.H. Sklar, and M.L. White. 1990. Modeling coastal landscape dynamics. *Bioscience* 40, 91-107.

Crowley, T.J. 1990. Are there any satisfactory geologic analogs for a future greenhouse warming? *Journal of Climate* 3, 1282-1292.

Crowley, T.J., and K. Kim. 1995. Comparison of longterm greenhouse projections with the geological record. *Geophysical Research Letters* 22, 933-936.

Crowley, T.J., and G.R. North. 1988. Abrupt climate change and extinction events in earth history. *Science* 240, 996-1002.

Davis, A.J., L.S. Jenkinson, J.H. Lawton, B. Shorrocks, and S. Wood. 1998. Making mistakes when predicting shifts in species range in response to global warming. *Nature* 391, 783-786.

Dennis, R.L.H. 1993. *Butterflies and Climate Change*. Manchester University Press, Manchester, United Kingdom.

Dublin, H.T., T. Milliken, and R.F.W. Barnes. 1995. *Four Years after the Cites Ban: Illegal Killing of Elephants, Ivory Trade and Stocks*. IUCN/SSC African Elephant Specialist Group, Gland, Switzerland.

Dunning, J.B., Jr., D.J. Stewart, B.J. Danielson, B.R. Noon, T.L. Root, R.H. Lamberson, and E.E. Stevens. 1995. Spatially explicit population models: Current forms and future uses. *Ecology Applications* 5, 3-11.

Ellison, J.C., and D.R. Stoddart. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research* 7, 151-165.

Formozov, A.N. 1946. *Snow Cover as an Integral Factor of the Environment and its Importance in the Ecology of Mammals and Birds*. Occasional Publications 1, Boreal Institute for Northern Studies, University of Alberta, Edmonton, Alberta, Canada.

Foster, R.B. 1982. Famine on Barro Colorado Island. In *The Ecology of a Tropical Forest: Seasonal Rhythms and Long-term Changes*, E. G. Leigh, Jr., A. S. Rand, and D. M. Windsor (eds). Smithsonian Institution Press, Washington, DC, pp. 201-212.

Halpin, P.N., 1997. Global climate change and natural-area protection: Management responses and research directions. *Ecol. App.* 7, 828-843.

Hartshorn, G.S. 1992. Possible effects of global warming on the biological diversity in tropical forests. In *Global Warming and Biological Diversity*, R.L. Peters and T.E. Lovejoy (eds). Yale University Press, New Haven, Connecticut, USA, pp.137-146.

Herman, T.B., and F.W. Scott. 1992. Global change at the local level: Assessing the vulnerability of vertebrate species to climate warming. In *Science and the Management of Protected Areas: Proceedings of an International Conference*, held at Acadia University, Nova Scotia, Canada, 14-14 May 1991. J.H.M. Willison, S. Bandrup-Nielson, C.D. Drysdale, T.B. Herman, and N.W.P. Munro (eds). Elsevier, Amsterdam and New York.

Hinckley, D., and G. Tierney. 1992. Ecological effects of rapid climate change. In *Global Climate Change: Implications, Challenges, and Mitigation* Measures, K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (eds). Pennsylvania Academy of Sciences, Easton, Pennsylvania, USA, pp. 292-301.

Holdridge, L.R. 1947. Determination of world plant formation from simple climatic data. *Science* 105, 367-368.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums. 1990. *Climate Change: The IPCC Scientific Assessment*. Cambridge University Press, Cambridge, United Kingdom.

Hulme, M., et al. 1996. *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region*. Climate Research Unit, University of East Anglia, Norwich, United Kingdom, and World Wildlife Fund International, Gland, Switzerland.

Hunt, H.W. M.J. Trlica, E.F. Redente, J.C. Moore, J.K. Detling, T.G.F. Kittel, D.E. Walter, M.C. Fowler, D.A. Klein, and E.T. Elliott. 1991. Simulation model of the effects of climate change on temperate grassland ecosystems. *Ecological Modelling* 53, 205-246.

Hunter, M.L. 1996. *Fundamentals of Conservation Biology*. Blackwell Science, Cambridge, Massachusetts, USA.

Huntley, B., P.M. Berry, W. Cramer, and A.P. McDonald. 1995. Modelling present and potential future ranges of some European higher plants using climate response surfaces. *Journal of Biogeography*, 22, 967-1001.

Hutchinson, G.E. 1957. Concluding Remarks, Cold Spring Harbor Symposium. *Quantitative Biology* 22, 415-427.

Johnston, K.M, and O.J. Schmitz. 1997. Wildlife and climate change: Assessing the sensitivity of selected species to simulated doubling of atmospheric CO_2. *Global Change Biology* 3(6), 531-544.

Kellert, S.R. 1984. Assessing wildlife and environmental values in cost-benefit analysis. *Journal of Environmental Management* 18, 355-363.

Kirilenko, A.P. and A.M. Solomon. 1998. Modeling dynamic vegetation response to rapid climate change using bioclimatic classification. *Climatic Change* 38, 15-49.

Krutilla, J.V., 1967. Conservation reconsidered. *American Economic Review* 57, 777-786.

Lack, D., 1973. *Swifts in a tower*. Chapman and Hall, London.

Lancia, R., D.A. Adams, and E.M. Junk. 1986. Temporal and spatial aspects of species-habitat models. In *Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates*, J. Verner, M.L. Morrison, and C.J. Ralph (eds). University of Wisconsin Press, Madison, Wisconsin, USA, pp. 65-69.

Laurie, W.A., and D. Brown. 1990. Population biology of marine iguanas (Amblyrhynchus cristatus): III. Factors affecting survival. *Journal of Animal Ecology* 59, 545-568.

Laymon, S.A., and R.H. Barrett. 1986. Developing and testing habitat-capability models: Pitfalls and recommendations. In *Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates*, J. Verner, M.L. Morrison, and C.J. Ralph (eds). University of Wisconsin Press, Madison, Wisconsin, USA, pp. 87-91.

Leemans, R. and Cramer, W. 1990. *The IIASA Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness of a Global Terrestrial Grid*. WP-90-41. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Leemans, R., and P.N. Halpin. 1992. Biodiversity and global climate change. In *Global Biodiversity: Status of the Earth's Living Resources*, B. Groombridge (ed.). Chapman & Hall, London.

Lewis, J.C. 1983. *Habitat Suitability Index Models: Roseate Spoonbill*. FWS/OBS-82/10.50. US Department of the Interior, Fish and Wildlife Service, Washington, DC.

MacArthur R.H. 1972. *Geographical Ecology: Patterns in the Distribution of Species*. Princeton University Press, Princeton, New Jersey, USA.

Magadza, C.H.D. 1994. Climate change: Some likely multiple impacts in southern Africa. *Food Policy* 19, 165-191.

Malcolm J.R. 1996. Changes in ungulate diversity. In *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region*, M. Hulme et al. (eds). Climate Research Unit, University of East Anglia, Norwich, United Kingdom, and World Wildlife Fund International, Gland, Switzerland, pp. 55-61.

Malcolm J.R. 1998. A model of conductive heat flow in forest edges and fragmented landscapes. *Climatic Change*,39, 487-502.

Malcolm, J.R. and A. Markham. 1997. *Climate Change Threats to the National Parks and Protected Areas of the United States and Canada*. World Wildlife Fund, Washington, DC.

Manabe S, and R.T. Wetherald. 1987. Large-scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. *Journal of the Atmospheric Sciences* 44, 1211-1235.

Markham, A. and J.R. Malcolm. 1996. Biodiversity and wildlife conservation: Adaptation to climate change. In *Adapting to Climate Change: Assessments and Issues*, J.B. Smith, N. Bhatti, G. Menzhulin, R. Benioff, M. I. Budyko, M. Campos, B. Jallow, and F. Rijsberman (eds). Springer, New York, pp. 384-401.

Markham, A., N. Dudley, and S. Stolten. 1993. *Some Like it Hot: Climate Change, Biodiversity and the Survival of Species*. World Wildlife Fund International, Gland, Switzerland.

McFarlene, N.A., G.J. Boer, J.P. Blanchet, and M. Lazare. 1992. The Canadian Climate Centre second generation general circulation model and its equilibrium climate. *Journal of Climate* 5, 1013-1044.

McKelvey, K., B.R. Noon, and R.H. Lamberson. 1993. Conservation planning for species occupying fragmented landscapes: The case of the northern spotted owl. In *Biotic Interactions and Global Change*, P.M. Kareiva, J.G. Kingsolver, and R.B. Huey (eds). Sinauer Associates, Sunderland, Massachusetts, USA, pp. 424-450.

McNeely, J.A. 1988. *Economics and Biological Diversity: Developing and Using Economic Incentives to Conserve Biological Resources*. IUCN, Gland, Switzerland.

McNeely, J.A. 1990. Climate change and biological diversity: Policy implications. In *Landscape Ecological Impacts of Climate Change*, M.M. Boer and R.S. de Groot (eds). IOS Press, Amsterdam, pp. 406-428.

Meffe, G.K., C.R. Carroll, and Contributors. 1997. *Principles of Conservation Biology* (Second Edition). Sinauer Associates, Sunderland, Massachusetts, USA.

Millsap, B.A., J.A. Gore, D.E. Runde, S.I. Cerulean. 1990. Setting priorities for the conservation of fish and wildlife species in Florida. *Wildlife Monographs* 111, 1-57.

Mitchell, J.F.B., C.A. Senior, and W.J. Ingram. 1989. CO2 and climate: A missing feedback? *Nature* 341, 132-134.

Mkanda, F.X. 1996. Potential impacts of future climate change on nyala (Tragelaphus angasi) in Lengwe National Park, Malawi. *Climate Research* 6, 157-164.

Morse, L.E., L.S. Kutner, G.D. Maddox, J.T. Kartesz, L.L. Honey, C.M. Thurman, and S.J. Chaplin. 1993. *The Potential Effects of Climate Change on the Native Vascular Flora of North America North of Mexico: A Preliminary Climate-Envelopes Analysis*. Prepared by The Nature Conservancy, Arlington, Virginia, for the Electric Power Research Institute, Palo Alto, California, USA.

Murphy, J.M. and J.F.B. Mitchell. 1995. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part 2, spatial and temporal structure of the response. *Journal of Climate* 8, 57-80.

Noss, R.F. 1983. A regional landscape approach to maintain diversity. *BioScience* 33, 700-706.

Overpeck, J.T., P.J. Bartlein, and T. Webb III. 1991. Potential magnitude of future vegetation change in eastern North America: Comparisons with the past. *Science* 254, 692-695.

Parmesan, C. 1996. Climate and species' range. *Nature* 382, 765-766.

Parsons, D.J. 1991. Planning for climate change in national parks and other natural areas. *Northwest Environment Journal* 7, 255-269.

Peters, R.L. 1990. Effects of global warming on forests. *Forest Ecology Management* 35, 13-33.

Peters, R.L., and J.D.S. Darling. 1985. The greenhouse effect and nature reserves. *Bioscience* 35, 707-717.

Peters, R.L. and T.E. Lovejoy (eds). 1992. *Global Warming and Biological Diversity*. Yale University Press, New Haven, Connecticut, USA.

Poiani, K.A., and W.C. Johnson. 1991. Global warming and prairie wetlands. Potential consequences for waterfowl habitat. *Bioscience* 41, 611-618.

Pounds, J.A., and M.L. Crump. 1994. Amphibian declines and climate disturbance: The case of the golden toad and the harlequin frog. *Conservation Biology* 8, 72-85.

Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud, and A.M. Solomon. 1992. A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography* 19, 117-134.

Price, J.T. 1995. *Potential Impacts of Global Climate Change on the Summer Distributions of some North American Grassland Birds*. PhD Dissertation. Wayne State University, Detroit, Michigan.

Reid, W.V., and M.C. Trexler. 1992. Responding to potential impacts of climate change on US coastal biodiversity. *Coastal Management* 20, 117-142.

Reynolds, J.F., and P.W. Leadley. 1992. Modeling the response of arctic plants to changing climate. In *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective*, F.S. Chapin III, R.L. Jeffries, J.F. Reynolds, G.R. Shaver, and J. Svoboda (eds). Academic Press, San Diego, California, USA, pp. 413-438.

Rodenhouse, N.L. 1992. Potential effects of climatic change on a neotropical migrant landbird. *Conservation Biology* 6, 263-272.

Rogers, D.J. 1996. Changes in disease vector distributions. In *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region*, M. Hulme et al. (eds). Climate Research Unit, University of East Anglia, Norwich, United Kingdom, and World Wildlife Fund International, Gland, Switzerland, pp. 49-55.

Rogers, D.J., and B.G. Williams. 1994. Tsetse distribution in Africa: Seeing the wood and the trees. In *Large-scale Ecology and Conservation Biology*, P.J. Edwards. R. May, and N.R. Webb (eds). Blackwell Scientific Publications, Oxford, United Kingdom, pp. 247-271.

Root, T. 1988a. Energy constraints on avian distributions and abundances. *Ecology* 69, 330-339.

Root, T. 1988b. Environmental factors associated with avian distributional boundaries. *Journal of Biogeography* 15, 489-505.

Rose, C., and P. Hurst. 1991. *Can Nature Survive Global Warming?* World Wildlife Fund International, Gland, Switzerland.

Running, S.W., and J.C. Coughlan. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecol. Model*. 42, 125-154.

Running, S.W., and R.R. Nemani. 1991. Regional hydrologic and carbon balance responses of forests resulting from potential climate change. *Climatic Change* 19, 349-368.

Schlesinger, M.E. and Z.C. Zhao. 1989. Seasonal climate changes induced by doubled CO2 as simulated by the OSU atmospheric GCM mixed layer ocean model. *Journal of Climate* 2, 459-495.

Schreiber, R.W., and E.A. Schreiber. 1984. Central Pacific seabirds and the El Niño Oscillation: 1982 to 1983 perspectives. *Science* 225, 713-716.

Scott, J.M., and B. Csuti. Gap analysis: Assessing landscape trends in diversity. In *Principles of Conservation Biology* (Second Edition), G. K. Meffe, C. R. Carroll, and Contributors, Sinauer Associates, Inc., Sunderland, Massachusetts, USA, pp. 409-410..

Shugart, H.H. 1984. *A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models*. Springer-Verlag, New York.

Shugart, H.H. 1990. Using ecosystem models to assess potential consequences of global climatic change. *Trends in Ecological Evolution* 5, 303-307.

Shugart, H.H., and T.M. Smith. 1992. Using computer models to project ecosystem response, habitat change, and wildlife diversity. In *Global Warming and Biological Diversity*, R.L. Peters and T.E. Lovejoy (eds). Yale University Press, New Haven, Connecticut, USA, pp. 147-157.

Shugart, H.H., R. Leemans, and G.B. Bonan. 1992. *A Systems Analysis of the Global Boreal Forest*. Cambridge University Press, Cambridge, United Kingdom.

Simberloff, D., J.A. Farr, J. Cox, and D.W. Mehlman. 1992. Movement corridors: Conservation bargains or poor investments? *Conservation Biology* 6, 493-504.

Smith, S.V., and R.W. Buddemeier. 1992. Global change and coral reef ecosystems. *Annual Review of Ecological Systems* 23, 89-118.

Smith, V.K. 1993. Nonmarket valuation of environmental resources: An interpretive appraisal. *Land Economics* 69, 1-26.

Smithers, R.H.N. 1983. *The Mammals of the Southern African Subregion*. University of Pretoria, Pretoria, South Africa.

Soulé, M.E. 1991. Conservation: Tactics for a constant crisis. *Science* 253, 744-750.

Starfield, A.M., and A.L. Bleloch. 1991. An exploratory stochastic model. Chapter 3 in *Building Models for Conservation and Wildlife Management* (Second Edition). Burgess International Group, Edina, Minnesota, USA, pp. 38-66.

Starfield, A.M., and F.S. Chapin III. 1996. Model of transient changes in arctic and boreal vegetation in response to climate and land use change. *Ecology Applications* 6, 842-864.

Stiles, F.G. 1992. Effects of a severe drought on the population biology of a tropical hummingbird. *Ecology* 73, 1375-1390.

Sykes, M.T., I.C. Prentice, and W. Cramer. 1996. A bioclimatic model for the potential distributions of north European tree species under present and future climates. *Journal of Biogeography* 23, 203-233.

Telfer, E. S. 1967. Comparison of moose and deer winter range in Nova Scotia. *Journal of Wildlife Management* 31, 418-425.

Telfer, E. S. and J. P. Kelsall. 1984. Adaptation of some large North American mammals for survival in snow. *Ecology* 65, 1828-1834.

Thresher, P. 1981. The present value of an Amboseli lion. *World Animal Review* 40, 30-33.

Tilman, D., C.L. Lehman, and C. Yin. 1997. Habitat destruction, dispersal, and deterministic extinction in competitive communities. *American Naturalist* 149, 407-435.

US Fish and Wildlife Service. 1981. *Standards for the Development of Habitat Suitability Index Models*. 103 ESM. US Fish and Wildlife Service, Division of Ecological Services, Washington, DC.

VEMAP Members. 1995. Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling. *Global Biogeophysical Cycles* 9, 407-437.

Walker, B., and W. Steffen. 1997. An overview of the implications of global change for natural and managed terrestrial ecosystems. *Conservation Ecology*, 1(2), 2. [online] [http://www.consecol.org.Journal/vol1/iss2/art2/]

Western, D. 1991. Climatic change and biodiversity. In *A Change in the Weather*, S.H. Ominde, and C. Juma (eds). African Centre for Technology Studies, Nairobi, Kenya, pp. 87-96.

White, F. 1983. *The Vegetation of Africa*. Natural Resources Research XX, UNESCO, Paris, France.

14 Fisheries

Lead Authors
Michael Brody [1]
Ihor Hlohowskyj [2]

14.1 Problem definition and scope

Evidence has been accumulating in recent years that suggests climate change may drive changes in fish stocks, although global fisheries production may not change substantially (particularly in marine systems). Rather, the relative abundance and distribution of individual species as well as distributions of centres of fish production may be significantly altered (IPCC, 1996). There are considerable uncertainties as to how much, how fast, and where the climate will change, and this creates considerable uncertainty in predicting changes in fisheries. But as average air temperature increases and precipitation patterns change, we can expect changes in water temperature, water quality, and hydrology, which will in turn affect fish populations. Thus, the goal for a fisheries assessment will be to evaluate the impact of climate change on the fisheries of interest or concern in a particular location. Specific aspects of the fisheries of concern to be evaluated may include biodiversity, total catch (biomass), species changes in catch composition, and displacement of fishing grounds.

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[1] US Environmental Protection Agency, Washington, DC, USA.

[2] Argonne National Laboratory, Argonne, Illinois, USA.

The ways that aquatic habitats may be affected by climate change will depend in large part on the specific geographic region where the fisheries are found, the type of aquatic system potentially affected (such as marine upwelling zones and freshwater lacustrine or riverine habitats), and the nature and magnitude of the climate change. Ultimately, many species of fish could be affected. Some climate-related changes are likely to be beneficial to local or regional fish stocks, whereas other stocks may be negatively affected. There is some agreement that, at the least, significant redistribution of both marine and freshwater fisheries will occur (see Beamish, 1995). Poleward migrations may be the most likely change (IPCC, 1996) as waters generally warm, but many specific estimates will have to wait for more certainty in regional estimates of climate change.

14.1.1 Fisheries resources affected

Some of the fisheries resources that may be most affected by climate change include 1) fisheries stocks that are currently heavily or over-exploited, 2) species with narrowly defined physiological tolerances to environmental conditions such as high water temperatures or low levels of dissolved oxygen (Stefan et al., 1995; Jobling, 1997; Magnuson and DeStasio, 1997), 3) threatened and endangered anadromous species whose complex life cycles are currently affected by artificial structures such as dams, 4) coastal species dependent on nearshore wetland nursery areas that are already subsiding and likely to be vulnerable to sea level rise, 5) species that currently occur only in physically isolated habitats for which there are no emigration pathways to other habitats, 6) species dependent on coastal upwelling zones, 7) species dependent on habitats that will be lost because public infrastructure impedes or blocks migration of habitat, and 8) heavily managed high-density aquaculture stocks.

14.1.2 Climate change impacts on fisheries

Fisheries resources provide a considerable amount of protein in diets around the world, and in some countries provide the majority of the animal protein consumed by local human populations. In addition, fisheries resources may support significant recreational and tourism economies at a local or regional scale, and the export of fisheries products contributes considerably to the economies of a number of countries. Thus, maintaining healthy and sustainable fisheries resources is of major importance. Regardless of the nature of the stress (e.g., overfishing, pollution, climate change), fisheries will continue to be important to subsistence, recreational, and commercial fishers on both a local and regional scale.

Today, many of the world’s fisheries are already under considerable stress. For example, many of the world’s major marine commercial fish stocks are currently fully or over-exploited (IPCC, 1996). Most of the anadromous salmonid fish stocks in the Pacific Northwest of the United States are threatened or endangered because of barriers to upstream spawning migrations, extensive habitat alterations associated with impoundments, and water quality deterioration associated with sedimentation or urban

pollution. For marine fisheries, perhaps the greatest concern is that 70 percent of the global fish resources depend on nearshore and estuarine ecosystems (IPCC, 1996) that are being threatened by physical loss and pollution. Growing human settlement and development in the coastal zone is rapidly eliminating many important nursery habitats as these areas are converted into agricultural lands or residential or commercial development, and domestic and industrial sewage from coastal population centres is degrading water quality. In addition to the effects of human activities, native and endemic fisheries are under stress from introductions of other species. For example, the introduction of the Nile perch into Lake Victoria has been associated with a decline there in the native cichlid fish populations.

14.1.3 What fisheries impacts are important?

World-wide fisheries resources can be placed into three principal categories, marine, coastal and estuarine, and freshwater, and each of these may be affected differently by climate change (Beamish, 1995). For example, marine fisheries may be most affected by changes in the magnitude, duration, and location of upwelling zones and major ocean currents. These changes may directly affect distributions of fish stocks by shifting locations of larval, juvenile, and adult habitats; they may also have secondary effects associated with reduced food resources and altered food webs and community structure. Coastal and estuarine fisheries may be most affected by the loss of nearshore coastal wetland nursery habitats, resulting in major declines in recruitment and standing stocks. Freshwater fisheries may be affected by changes in water temperatures affecting habitat quality, and changes in precipitation could affect habitat availability, leading to isolation of some habitats, as well as timing of hydrograph-driven life-cycle events. Additionally, changes in overall water availability may affect the extent of both adult and juvenile nursery habitats. Table 14.1 identifies some categories of potential climate change impacts to fisheries resources.

14.2 An array of methods

14.2.1 Current approaches

Three general approaches have been used to evaluate potential impacts to fisheries resources from climate change: 1) estimating changes in the availability of thermal habitat by evaluating changes in the thermal structure of lakes and streams; 2) estimating impacts of changes in physical habitat features (i.e., water temperatures, flow rates, water levels, water quality, and wetland nursery areas) to important life cycle stages (such as migration periods and spawning times), to species distributions, or to overall productivity; and 3) estimating effects of temperature changes on fish physiological processes, particularly growth and feeding, using process-based bioenergetics models. Some researchers have identified these general approaches as the basic framework for evaluating climate change impacts on fisheries resources

Table 14.1 Potential climate change impacts in the fisheries resources sector.

- Potential loss of coastal wetlands and estuarine habitats due to altered currents, limnology and sea level.
- Changes in the quality and/or availability of suitable habitat.
  - Loss of thermal habitat due to increased water temperatures.
  - Change in habitat availability due to shifts in major ocean currents and disruption of areas of upwelling.
  - Reduction in habitat quality due to changes in water quality parameters such as nutrients, dissolved oxygen or pollutant levels.
  - Loss of habitat due to changes in the duration, magnitude and distribution of total precipitation affecting water availability and volume (annual or seasonal).
- Changes in the distribution of habitats for particular species, resulting in shifts in the fish community structure and function.
- Alteration of food webs resulting in shifts in species composition.
- Inflow of other species resulting in altered competition and/or predation.
- Increased habitat fragmentation due to changes in water quality and availability.
- Loss or shifts in location of fishing grounds with direct consequences on jobs.
- Loss or shifts in location of fishing grounds with direct consequences on jobs.
  - Loss of jobs due to collapse of fishery.
  - Establishment or expansion of fishery industry with development of new fishing grounds.
  - Increased expenses related to migration of fishing grounds to more distant locations.

(Regier and Meisner, 1990; Shuter and Meisner, 1992). Data needs associated with these approaches include historical environmental and biological data (including catch or yield data), species-specific physiological information, and species-specific life history data.

Studies that evaluated potential impacts of climate change on fisheries in temperate and northern latitudes (see Beamish, 1995) largely followed the first two approaches, in particular evaluating potential responses of fisheries to the thermal aspects of climate change (see Transactions of the American Fisheries Society, 1990, Volume 119). Many of these studies estimated changes in the production or distribution of fisheries resources within particular habitats such as individual lakes of the North American Great Lakes (Hill and Magnuson, 1990), or in the distribution of suitable thermal habitats across large geographic regions such as the interior of Canada (Minns and Moore, 1992) or the Pacific coast of North America (see Beamish, 1995).

In contrast, evaluations of fisheries resources in tropical latitudes focus on estimated changes in seasonal water availability rather than on estimated temperature changes. The magnitude of temperature changes in tropical areas of the world is expected to be relatively minor in comparison to the magnitude of those changes in more temperate and northern latitudes. However, water availability in tropical regions is expected to be affected to a greater extent by potential climate changes (Meisner and Shuter, 1992). Seasonal water availability affects lake levels, stage and flow in rivers, extent and timing of floodplain inundation, and sea level, and thus plays an important role in

maintaining the life history of tropical fish species (Welcomme, 1976, 1985; Lowe-McConnell, 1987; Shuter and Meisner, 1992). Because of the importance of water availability and seasonal flooding to the life history of many fish species, changes in water availability due to changes in precipitation may affect tropical fisheries resources more than will changes in temperature (Meisner and Shuter, 1992).

In addition to these approaches, a number of studies have attempted to assess potential future responses of fisheries resources by examining past fisheries' responses to historical climate changes (Beamish, 1993; Murawski, 1993; also see Beamish, 1995). These studies examined how actual changes in environmental parameters such as water temperature affected species distribution and abundance, community structure, and distribution of fishing grounds. The observed responses are considered representative of how the fishery resource will respond in the future under similar climate-related environmental changes.

In all cases, the spatial scale of the assessment is directly related to the nature of the climatic change and the fisheries resource of interest. The effects of climate change on freshwater fisheries are more likely to be associated with localised climate conditions than will be effects on marine environments. In marine systems, major shifts in productivity and species distributions can be the product of changes in currents and upwelling zones that are driven by the aggregate of climate changes (e.g., ENSO, the North Atlantic oscillation) over very broad geographic regions (Mann and Lazier, 1996). Thus, assessments for freshwater resources are typically performed at a water-shed level that may or may not extend beyond a country's boundaries (e.g., Meisner, 1990; Minns and Moore, 1992). In contrast, assessments of marine fisheries are done at geographic scales that extend well beyond that of an average country (e.g., Brander, 1997).

14.2.2 Applicability of methods to specific fisheries resources

The assessment methods described in this chapter address freshwater (riverine and lacustrine) and marine (coastal, estuarine, and pelagic) habitats and evaluate potential impacts to fisheries resources from climate-induced changes in water temperature, water quality, and hydrology. The methods focus primarily on growth, feeding, and mortality of individual taxa; fish yield or catch for entire fishery resources; species-specific habitat suitability; and habitat availability. Because of the diversity of fisheries resources and aquatic habitats that must be addressed, no single method or approach is likely to adequately evaluate potential impacts to all the resources and habitats. In many cases, the assessment for evaluating potential climate change impacts on fisheries resources may require the use of a weight-of-evidence approach (USEPA, 1992) to adequately evaluate the vulnerability of a particular fishery resource to climate change. The weight-of-evidence approach uses multiple lines of evidence to identify potential impacts and evaluate the significance of any estimated impacts. Thus, any number of the following assessment methods may be used to relate climate change to biological responses.

Four basic approaches are presented: 1) using empirical models and historical environmental and ecological data to estimate changes in catch, yield, natural mortality, and other ecological parameters; 2) evaluating historical climate, limnological, and hydrological data together with species- or fishery-specific data to estimate changes in habitat quality, availability or distribution; 3) comparing species-specific physiological parameters to projected climate conditions to identify changes in growth and biomass production and shifts in distributions; and 4) forecasting future fisheries' responses by analogy with past responses to historical climate events. These four approaches are of two major types: species-specific methods that permit evaluation of potential impacts to target species and non-species-specific methods that focus on potential impacts to entire fish communities.

Because of the importance of the fisheries resources to the diet of many nations, a number of the methods focus primarily on estimation of yield or catch, and largely do not address or consider the effects of climate change on species diversity, predator-prey relationships, or other ecological issues. Many of the methods do not directly address such factors as community structure and function, nutrient cycling, or predator-prey relationships, although some methods are amenable to evaluating these aspects of the fishery resource. No stock assessment methods are described here. Although some stock assessment models include environmental variables, most do not; they do require long time series of data on the size of the fish stock and the annual recruitment, which may not be available for the fishery of concern. Most stock assessment models do, however, include a natural mortality parameter, which can be related to changes in temperature (see Pauly, 1983) and thus may be amenable to evaluating the effects of climate change (Edwards and Megrey, 1989). For information on one computerised fish stock assessment model that includes climate variables (CLIMPROD), see Freon et al. (1993).

Many of the assessment methods were initially developed to investigate ecological problems other than climate change, such as to predict potential fish yield in planned or newly constructed reservoirs (Marshall, 1984) or to conduct general fisheries stock assessments (Sparre and Venema, 1992). However, each of these methods is based on at least some parameters that are expected to change with climate, and thus are appropriate for consideration for use for assessing climate change impacts and the responses of fisheries resources. In addition, many of the methods can also be used to assess the impacts of other human activities at the same time.

The choice of approaches to evaluate the impacts of climate change on fisheries resources in any particular place or region will depend on the habitats and fisheries present and on the availability of climate, hydrology, limnology, ecology, and fisheries data, as well as the expected nature of the change in climate. In general, the approaches focus on changes in temperature, precipitation, and sea level, and evaluate potential effects at either the species or the total fishery (yield) level. The approaches are not restricted to specific geographic regions. However, some of the specific methods discussed under the various approaches are restricted to a basic habitat type (e.g., coastal, lake, or river) or a particular geographic region (e.g., African lakes). A number

of methods recommend the use of mapped data, and the use of geographic information systems (GIS) is particularly applicable to these methods (see Chapter 1 for a fuller discussion of GIS). Some methods where expert opinion can be especially useful are mentioned. The approaches and methods are summarised in Tables 14.2, 14.3, and 14.4.

14.2.3 Description of assessment methods

14.2.3.1 Empirical modelling using historical environmental and fishery data

In this approach, models are developed by regression and correlation from historical data. The principle is to identify a sufficiently accurate quantitative relationship between yield (or abundance) and a climatological parameter (temperature or precipitation) to estimate future yields under different climate scenarios. The overall approach is similar between freshwater and marine systems, differing primarily in the species of interest (e.g., pollock, king crab, walleye) and the climate variable of interest (temperature or precipitation or both).

The largest obstacle for using this approach is the availability of sufficient historical climatological and fisheries data to permit development of acceptable models. Data needs for these models may include historical time-series precipitation, temperature, surface water area, surface water runoff, floodplain area, stream flow and discharge, and catch data, as well as water depth, dissolved solids, and estimated precipitation and temperature data. Potential impacts are assessed by comparing recorded yield or catch under historical climate conditions with the yield or catch estimated for future climate conditions. This approach also does not consider potential impacts associated with changes in water temperature, water quality, biotic interactions, or fishing effort, gear, or success.

Assessing the effects of precipitation changes on fish yields in lacustrine systems

Changes in local or regional precipitation patterns or precipitation magnitude are likely to affect inflows to lakes and reservoirs, thereby affecting surface water area or water depth. Empirical models that estimate potential annual fish yield from lakes and reservoirs as a function of the surface area of the water body may be developed which permit estimation of fish yield as a function of precipitation-related limnological or hydrological parameters. For example, Crul (1992) employed regression analysis to develop an empirical model for estimating total annual fish yield as a function of surface water area for lakes and reservoirs in Africa. If appropriate limnological and fish yield data are available, similar empirical models could be developed using regression analyses for lakes and reservoirs of interest. Regression analyses using historical and

estimated limnological and climate data can be used to develop lake- and reservoir-specific models for estimating surface water area under different

Table 14.2 Suggested approaches for evaluating impacts of climate change using empirical modelling and historical data.

Climate variable	Fishery response	Method	Output	Climate-aquatic environment linkage	Data needs	Advantages and disadvantages
Precipitation	Total annual yield in lacustrine systems	Estimate yield using regression analyses to develop empirical models relating annual yield to lake surface area	Impact assessed on differences in yield between historical and predicted precipitation scenarios	Precipitation to surface runoff inflow to lake surface area	Historical and predicted precipitation, surface water runoff, and surface water area; historical annual yield	Easy approach. Sufficient data may not be available; does not consider individual taxa, species interactions, water quality, or fishing effort, gear, or success
Precipitation	Total annual yield in riverine systems	Estimate yield using regression analyses to develop empirical models relating annual yield to areal extent of floodplain inundation or river discharge	Same as above	Precipitation to surface runoff to stream flow and floodplain inundation	Historical and predicted precipitation, surface water runoff, stream flow, areal extent of floodplain inundation; historical annual yield.	Same as above
Precipitation	Yield or abundance in marine systems	Estimate yield or abundance using regression analyses to develop empirical models relating yield or abundance to precipitation.	Same as above	Precipitation used directly	Historical and predicted precipitation; historical yield or abundance	Same as above
Temperature	Total maximum annual sustainable yield in lacustrine systems	Estimate maximum annual sustainable yield using empirical models relating sustainable yield to mean annual air temperature and morphoedaphic index	Impact assessed on differences in estimated maximum sustainable yield between historical and predicted temperature scenarios	Air temperature used directly	Mean annual air temperatures, morphoedaphic indices for lakes of concern, estimated fishing intensity; no biological data needed.	Same as above
Temperature	Yield in marine systems	Estimate yield as a function of air temperature using regression models developed from empirical data	Impact assessed on differences in yield between historical and predicted temperature scenarios	Air temperature used directly	Mean annual air temperature, yield data	Same as above

Table 14.3 Suggested approaches for evaluating impacts of climate change on habitat quality, availability, and distribution.

Climate variable to be evaluated	Habitat and parameter evaluated	Method approach	Impact assessment and method output	Climate-aquatic environment linkage	Physical and biological data needs	Advantages:disadvantages
Precipitation	Availability (as surface area) in lacustrine and riverine systems	Use map or remote sensing imagery analyses to quantify habitat availability under different water regimes; regression analyses to develop predictive models relating habitat availability to precipitation	Impact assessed on difference in habitat availability between historical and predicted precipitation scenarios	Precipitation to surface runoff to inflow lakes and rivers to surface water area	Historical and predicted precipitation, runoff, lake levels and stream flows; bathymetric and topographic maps, remote sensing imagery; no direct biological data other than knowledge of specific habitats of concern	Permits quantification of habitat availability on the basis of site-specific data. Sufficient data may not be available; collection of imagery may be expensive and difficult to process; does not consider habitat quality.
Sea level	Availability in shallow marine systems	Use map or remote sensing imagery analyses to quantify habitat availability under different sea levels; regression analyses to develop predictive models relating habitat availability to sea level; comparison of rates of change in sea level and habitat quantity	Impact assessed on difference in habitat availability between historical and predicted sea levels; also in difference between rate of sea level change and growth rates of some habitat types (e.g., coral reefs)	Sea level to water depth	Historical and predicted sea levels; bathymetric and topographic maps, remote sensing imagery; accretion rates of coastal wetlands and growth rates of corals if these represent habitats of concern	Same as above.
Temperature	Quality, availability, and distribution	Develop thermal profiles, including temperature minima, maxima, and distributions, for habitats of concern and identify changes in thermal habitat for species of concern	Impact assessed by comparing availability of thermal habitat under historical and predicted temperature scenarios	Air temperature to water temperature	Historical air and water temperatures for habitats of concern; predicted air and water temperatures; thermal biology data for species of concern	Easy approach. Thermal data for habitats and species of concern may not be available
Multiple parameters	Suitability	Develop species-specific habitat suitability models (HSI) that incorporate climate-related parameters	Impact assessed on differences in estimated habitat suitability between historical and predicted climate scenarios	Air temperature to water temperature; precipitation to water depth, stream flow	Species-specific requirements for climate related parameters; historical parameter values for habitats of concern	Easy approach; permits use of expert opinion to develop models Species data may not be available

Table 14.4 Suggested approaches for evaluating impacts of climate change through evaluations of species-specific physiology.

Climate variable to be evaluated	Fishery parameter evaluated	Method approach	Impact assessment and method output	Climate-aquatic environment linkage	Physical and biological data needs	Advantages / disadvantages
Temperature	Natural mortality rate	Use empirical models using length, weight, and water temperature to predict natural mortality as a function of mean annual water temperature; the mortality estimates can also serve as input to quantitative stock assessment models	Impact assessed by evaluating the difference in natural mortality, and standing stock or yield, between historical and predicted temperature scenarios	Air temperature to water temperature	Historical and predicted air and water temperatures; species-specific asymptotic length and weight	Easy approach requiring minimal biological data Only addresses fish; does not consider changes in water quality, biotic interactions, or changes in fishing gear, effort, or success
Temperature	Growth	Use fish bio-energetics models to estimate species-specific growth rates	Impact assessed on differences in growth rates between historical and predicted temperature scenarios	Air temperature to water temperature	Historical and predicted air and water temperatures; species-specific consumption, digestion, excretion, and respiration rates; diet composition of species of concern	Easy approach Bioenergetics and diet data may not be readily available; only addresses fish; does not consider changes in water quality or biotic interactions
Temperature	Temperature-dependent physiological processes	Predict species-specific rates of important physiological processes (such as metabolic rate, egg incubation rate, and growth rate) using models based on the Arrhenius rate equation	Impact assessed by evaluating the difference in predicted process rates between historical and predicted temperature scenarios	Air temperature to water temperature	Historical and predicted air and water temperatures; species-specific physiological parameters (dependent on the process of interest)	Applicable for variety of physiological processes; may be used for plankton, invertebrates, and fish Physiological data may not be available; does not consider species interaction or water quality

climate scenarios. These models can then be linked with fishery yield models to estimate how fishery yield will respond to estimated changes in precipitation.

Assessing the effects of precipitation changes on catch in riverine systems

Welcomme (1976) and others have reported on the relationships between catch and discharge or floodplain area, and discharge and floodplain area are directly related to precipitation. As described for lacustrine systems, empirical models for estimating catch as a function of discharge or floodplain area can be developed using regression analyses and historical catch, discharge, and floodplain data. Discharge and floodplain area can be estimated for various precipitation scenarios. Total annual catch is estimated by inputting the estimated floodplain area or discharge to the appropriate empirical model. For example, Welcomme (1976, 1980) developed empirical models estimating annual catch per kilometre of river reach as a function of floodplain area per kilometre of river reach for African rivers, and Sagua (1993) developed an empirical model relating mean total catch and mean river discharge for the Niger River at Mopti. Similar models can be developed using flood area or discharge data and total annual catch data.

Assessing the effects of temperature changes on fish yield in lacustrine systems

This method employs empirical models to estimate maximum sustainable yield in lakes as a function of mean annual air temperature and morphoedaphic index (MEI). The MEI is calculated as the total dissolved solids divided by the mean depth. A similar approach was used by Schlesinger and Regier (1983) to evaluate effects of environmental temperatures on the yields of subarctic and temperate fishes in North America. These authors developed a number of models of the form $\log_{10} MSY = aTEMP + b\log_{10} MEI + c$, where MSY is the maximum sustainable yield, TEMP is the mean annual air temperature, MEI is calculated as above, and a, b, and c are constants. Similar relationships could be developed for other areas of the world, including lakes within a particular country or a particular region. Such models are not suited for use with lakes that 1) exhibit wide fluctuations in depth, 2) do not conform to a typical carbonate-bicarbonate chemical type, or 3) contain a large area of swamp. Box 14.1 describes an example of using environmental data, fish yield regression equations, and temperature increase estimates to assess the impact of climate change on eastern Canadian lake fish yields.

Box 14.1 Example: Assessing the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canadian lakes

Minns and Moore (1992) used existing environmental data, fish yield regression equations developed by Schlesinger and Regier (1983), and climate model estimates of air temperature increase to estimate the effects of climate change on the spatial distribution of fish yield capability in eastern Canada.

A total of 406 watersheds were selected in eastern Canada (excluding the Great Lakes), ranging in size from 100 to 45,000 square kilometres. Watershed boundaries were then put into a GIS. Climatological data for 1951-1980 from 179 stations in eastern Canada were used to construct a mean annual temperature map of eastern Canada which, in turn, was used to estimate the average water temperature for each watershed unit. Output data from three different general circulation models were then used to produce maps of estimated mean annual air temperatures for eastern Canada and to estimate an average temperature increase for each watershed. These results were then used to develop a 1 °C isotherm map for eastern Canada. Species distributions were also developed for each watershed.

The fish yield regression equations of Schlesinger and Regier (1983) for lake whitefish, northern pike, and walleye were used to estimate yields of these species for current and estimated temperature regimes by watershed. The yield and species distribution maps were then combined to form a regional model estimating the spatial distribution of yield capability in eastern Canada with and without climate change. For a mean temperature increase of 4.5 °C, the model estimated a substantial redistribution of fishery capabilities. Areas currently supporting high yields became marginal, and areas at the margin or outside the current species ranges became optimal. Yield capabilities were estimated to be unchanged in only 12 to 19 percent of the three species' ranges, and the overall effect was a decline in yield capability.

Assessing the effects of precipitation changes on yield in marine systems

As in studies for freshwater systems, numerous studies have investigated potential climate effects on marine fisheries using time-series data and regression analysis, and these studies show good correlations between fishery yield and environmental conditions. For example, Megrey et al. (1995) used time-series data to develop models relating age-0 pollock abundance in the Gulf of Alaska to precipitation. Studies conducted in the United States, Senegal, the Gulf of Mexico, and Australia have demonstrated the influence of rainfall on shrimp production (see Garcia and Le Reste, 1981). Particularly good correlations between total annual shrimp catch and the previous two years of total annual rainfall have been identified; both positive and negative relationships have been found, depending on the specific area or the species. This approach only indirectly assesses the effects of continental discharge or variability in salinity.

Assessing the effects of temperature changes on yield in marine systems

Most studies evaluating climate impacts in marine systems have focused on the effects of temperature change (see Beamish, 1995). Many have evaluated time-series yield and climate data to develop empirical models that permit estimation of yield as a function of environmental temperature. For example, Regier et al. (1990) used empirical data from several sources to develop a model of the Arrhenius form for estimating the stabilised commercial penaeid shrimp yield (kilogram/hectare of intertidal vegetation) as a function of mean annual air temperature. The Arrhenius form of an exponential relationship may be given as $\log_e k = a - b\,(1/T)$, where k is the rate constant, T is the absolute temperature (K), and a and b are coefficients estimated by regression analysis. This same approach could be used to develop models for other fisheries. For example, Muter et al. (1995) evaluated North Pacific sea-surface temperatures (SST) and identified significant correlations between catches of pollock (large catches associated with warm temperatures in the Gulf of Alaska) and red king crab (decreased crab catch 10 years after a low SST anomaly) and SST.

14.2.3.2 Estimating changes in habitat quality, availability, and distribution

This approach draws qualitative evaluations of impacts to fisheries (species-specific or overall) from quantitative estimates of habitat suitability, availability, and distribution. The individual approaches discussed below include methods that 1) evaluate total habitat availability as a function of precipitation or sea level, 2) evaluate habitat quality as a function of temperature, or 3) evaluate habitat suitability as a function of multiple environmental parameters, including temperature and precipitation. Data needs may include bathymetric and topographic maps, aerial photographs, or satellite imagery for the surface waters for the habitats of concern; historical data on sea levels, lake levels, surface water area, streamflow, or river stage; species-specific physico-chemical habitat requirements; historical precipitation and temperature data; and future precipitation and temperature scenarios. Impacts are assessed by comparing habitat quality, availability, or distribution under historical and projected future climate conditions.

Assessing the effects of precipitation changes on habitat availability in lacustrine and riverine systems

River and stream hydrographs are graphical representations of changes in streamflow over time (e.g., minimum flows in late summer, maximum flows during spring). The shape of the yearly hydrograph and the magnitude, timing, and duration of flood events have been shown to play an important role in the maintenance of riverine fish stocks (Welcomme, 1976, 1985; Lowe-McConnell, 1987; Poff and Allan, 1995; Galat and Frazier 1996). Similar importance has been attributed to seasonal changes in lacustrine conditions (such as depth and shoreline inundation). In this approach, regression analyses are used to develop models for estimating aquatic habitat availability as a

function of lake level, surface water area, streamflow, or river stage. This type of approach is widely used in North America to monitor fish and wildlife (including submerged aquatic vegetation) habitat and to identify rates and trends of habitat loss (see Orth et al., 1991; Neale, 1994; Galat and Frazier, 1996). The regression models are developed for estimating lake level, river stage, streamflow, or surface water area at important fisheries habitats (such as nursery habitats and spawning areas) as a function of precipitation. These models can then be used to estimate habitat availability under different precipitation scenarios. The development and use of these models will require close interactions with water resource specialists to assist in estimating precipitation effects on water resources (see Chapter 6). Estimates can then be applied to the maps and photographs of the fisheries habitats to infer impacts from changes in water depth and inundation.

Assessing the effects of sea level rise on habitat availability in shallow water marine areas

A number of studies have shown positive relationships between habitat availability and the growth, recruitment, or annual yield of a fishery (for example, see Turner, 1977, 1992; Turner and Boesch, 1988). For habitats that are directly linked to sea level, such as coastal and estuarine areas and coral reefs, the loss or gain of habitat due to changes in sea level should reflect similar changes in the fishery resource. For some habitats, the rate of sea level rise may also be important. For example, if sea level rises at a rate that exceeds the capacity of coral to grow upward and remain in the photic zone, the corals may die.

The suggested approach uses regression analysis to develop models of the relationship between habitat availability and sea level. Depending on the fishery of concern, these habitats could include submerged aquatic vegetation, coral reefs, mangrove stands, mud flats, and others. The changes in habitat availability that could result from changes in sea level are estimated using map and image analyses together with the approach used to evaluate biogeophysical effects of sea level rise presented in the Coastal Zones chapter (Chapter 7). The rate of sea level rise may also be compared to data on the accretion rates of marshes or growth rates of corals to infer possible impacts associated with the rate of sea level rise. The rate of sea level rise may be estimated following the methodology discussed in the Coastal Zone chapter (Chapter 7).

If suitable yield and habitat data are available, it may be possible to develop models of the relationship between fishery yield and habitat availability (see Boesch, 1988; Turner, 1992). Habitat availability can then be input to the models to provide estimates of yield under different sea level scenarios, and impacts are assessed by comparing current yields with estimated yields under the different sea level scenarios.

Assessing the effects of temperature on habitat suitability – thermal habitat

This species-specific approach compares projected water temperatures to species-specific thermal habitat (i.e., thermal limits and preferences), and can be applied to a particular habitat or for multiple habitats within a large geographic area. For example, Meisner (1990) estimated loss of thermal habitat in two southern Ontario streams, and Eaton and Scheller (1996) estimated thermal habitat loss for the continental United States.

In this approach, maximum temperature profiles can be developed for selected aquatic habitats. Water temperatures for different climate scenarios can be obtained directly from climate models, or estimated from historical and projected air temperatures [see Stefan and Preud'homme (1993) for an approach to estimate stream temperatures, and Hill and Magnuson (1990) for an approach to estimate lake temperatures] or from expert opinion. The estimated temperatures are then compared to species-specific preferred temperatures and temperature limits to infer potential impacts. This procedure quantifies the amount of suitable thermal habitat within a particular water body, or the thermally suitable water bodies within a region, for a particular species on the basis of its thermal biology.

Assessing the effects of multiple stressors on habitat suitability using habitat suitability models

This species-specific approach includes the development of habitat suitability index (HSI) models for individual species of concern. Habitat suitability modelling was developed by the US Fish and Wildlife Service to aid in impact assessment and habitat management, and HSI models have been developed for more than 100 species of North American terrestrial, freshwater, and marine biota (Hays, 1987). The models incorporate environmental variables such as water temperature, water depth, dissolved oxygen (DO) concentrations, and substrate composition. These variables are measured on continuous scales, and individual suitability curves are developed for each variable. These individual variable curves are then combined to produce an index of habitat suitability that is also continuous, ranging from 0 (unsuitable habitat) to 1.0 (optimally suitable habitat). Because of the flexibility in incorporating variables, these models can be useful for species with complex life cycles, such as anadromous species.

The specific variables to be included will depend on the known habitat requirements of the target species and the availability of appropriate data. Estimated changes in water temperature can be directly put in the models and also used to estimate DO levels for model input. Estimated precipitation must be converted to changes in streamflow.

The strength of any HSI model is a direct function of the availability of the ecological and physiological data for each species of concern as well as the availability of habitat data. In the absence of such data, professional judgement may be used to develop some components of the models, although this will lessen the strength of the suitability estimation. If species interactions (competition, predation) are known, these parameters can be incorporated into the models. Following construction of species-specific HSI models, habitat suitability can be estimated for specific habitats using historical (or

current) climatic, hydrological and ecological data. Suitability values can then be calculated for climatic and hydrological conditions associated with future climate scenarios. Box 14.2 presents an example of the application of an HSI model in the evaluation of the effects of climate change.

Procedures for developing HSI models are presented in Hays (1987), and these procedures are amenable for developing spread-sheet based models. Alternately, Micro-HSI is an existing DOS-based software package used to calculate existing HSI models and develop new models.[3]

Box 14.2 Example: Habitat suitability model for white and brown shrimp and application to evaluating effects of climate change

Turner and Brody (1983) developed HSI models for white and brown shrimp inhabiting the northern Gulf of Mexico. The model parameters included water temperature, sea level, salinity, substrate composition, and amount of estuarine and intertidal vegetation. A mean water temperature between 20 °C and 30 °C was considered optimal for growth, and temperatures below or above this range were considered less than optimal. The percentage of marsh and submerged grassbeds in or near a bay or estuary was considered the most important variable in the shrimp HSI models. A 100 percent coverage of vegetation was considered to be optimal. To evaluate potential effects of climate change on habitat suitability, estimated changes in temperature can be directly put in the models; the effects of sea level rise must first be related to impacts on estuarine and intertidal vegetation. With all other parameters being optimal, with an increase in mean spring water temperature from 30 °C to 35 °C, the HSI models would estimate a 50 percent reduction in habitat suitability.

14.2.3.3 Evaluating physiological and life history constraints on growth and reproduction

This approach considers the potential effects of climate change on the growth and reproduction of target fish species as a function of species-specific physiological constraints. Specifically, the methods link climate parameters with specific physiological (thermal tolerance, growth rates, mortality rates) parameters to infer species-specific responses to estimated changes in climate. Data requirements may include historical and estimated climatic parameters and species-specific physiological data. Impacts to the fishery are assessed by comparing species-specific physiological responses under historical and estimated climate conditions. The greater the difference in the physiological response (such as in mortality or growth rates) between historical and estimated climate conditions, the greater the potential for impacts to the fishery.

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[3] Johnson Controls World Services, Inc., NERC Operation, Post Office Box 270308, Fort Collins, Colorado 80527 USA, 1+303-226-9493 (tel.). The software package costs $35 US. It requires the use of early versions of the BASIC programming language.

Assessing the effects of temperature changes on mortality

This species-specific method used the empirical relationships between natural mortality, asymptotic length or weight, a species-specific growth coefficient, and mean annual water temperature developed by Pauly (1980) to estimate the exponential coefficient of natural mortality under historical and estimated air temperatures. All else being equal, the higher the estimated coefficient of natural mortality, the greater the mortality of a particular fish stock. The empirical models were developed using data from 175 fish stocks from 84 species, including marine and freshwater species from tropical to polar habitats.

Use of these models will permit estimation of the natural mortality for particular fish stocks under various annual temperature scenarios. These models overestimate natural mortality for strongly schooling pelagic fishes such as herrings (Clupeidae) (Pauly, 1983). To address this, Pauly suggests reducing estimates of natural mortality for such species by 20 percent. The natural mortality estimates can also serve as input to stock assessment models to estimate changes in standing stock or annual yield.

Assessing the effects of temperature change on growth using bioenergetics modelling

This species-specific method uses a bioenergetics simulation model originally developed by Kitchell et al. (1977) and commercially available from the University of Wisconsin Sea Grant program as the Bioenergetics Model 3 (Hanson et al., 1997). The model is available in an IBM-compatible format.[4] It is applicable to riverine and lacustrine systems and may be especially useful for well-controlled aquaculture systems. The model processes data on fish physiology, diet composition, energy density and water temperature and generates consumption and growth estimates. The model includes a database containing specific information for 33 taxa, including 5 marine and 6 salmonid taxa. Species not included in this database can be added and modelled using species-specific parameter values. Climate change impacts on fisheries resources are inferred by putting historical and projected water temperatures into the model and estimating growth and feeding rates under those temperature conditions.

This model is data intensive. Data requirements include historical and projected water temperatures for the habitats of concern and species-specific physiological data for each species of interest, including consumption, respiration, and digestion/excretion data. The Bioenergetics 3 species database can be used to provide surrogate-species data in the absence of species-specific data.

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[4] University of Wisconsin Sea Grant Program, Communications Office, 1800 University Avenue, Madison, Wisconsin 53705-4094 USA, +1-608-263-3259 (tel.), +1-608-263-2063 (fax).

For a given temperature scenario, the bioenergetics model estimates growth and feeding rates for an individual of a species, and biomass production for the entire cohort. Results for individuals may be extrapolated to the resource as a whole.

Assessing the effects of temperature change on physiological processes

Because fish are poikilotherms, the rates of all their physiological functions are directly dependent on environmental temperature, and any climate-related changes in temperature may dramatically affect the biological processes controlling growth, reproduction, development and other physiological parameters. Wood and McDonald (1997) offer a review of the effects of temperature on the physiology of marine and freshwater fishes.

Regier et al. (1990) (also see Lin and Regier, 1995) used the Arrhenius equation, which describes the effect of temperature on the specific rate constant k in chemical reactions, to examine the effects of temperature on various aspects of fish physiology. Regier et al., (1990) used this relationship to relate standard metabolic rate, egg incubation period, and mortality rate to absolute temperature for a number of freshwater and marine fish; growth rates for marine and freshwater algae; and crustacean plankton biomass. Lin and Regier (1995) fitted appropriate versions of the Arrhenius equation to data for standard and active metabolic rates, hatching rate, growth rate, and critical swimming speed of sockeye salmon and largemouth bass. Similar models may be developed to examine the potential effects of climate-related temperature changes on other aquatic biota of interest.

14.2.3.4 Using historical analogy

Historical analogy can be used to estimate potential impacts to fisheries resources for areas for which extensive fisheries and oceanographic time-series data are available (Glantz, 1990). In this approach, the status and the response of fisheries resources to past environmental conditions are assessed and used to estimate the nature and direction of responses to future climate conditions. Many of the studies presented in Beamish (1995) follow this approach in evaluating potential climate effects on northern marine fish populations. Data needs include time-series data for any number of environmental parameters such as water temperature, hydrology, water chemistry, oceanic conditions, and atmospheric conditions, together with corresponding biological data (such as biomass, catch, primary productivity, and recruitment). These data can then be used to obtain qualitative or quantitative estimations of the resource in question. The availability of long-term time series of environmental and biological data sets represents the most significant limitation of this approach, and these types of data may be very limited or absent for specific fisheries resources. Box 14.3 presents an example of using historical analogy.

Box 14.3 Example: Using historical analogy to examine climate change and marine fish distributions

Murawski (1993) evaluated time-series data sets for 36 fish and squid species sampled in standardised bottom-trawl surveys of the north-west Atlantic Ocean from 1967 to 1991. Analyses of these data revealed a continuum of distributional responses associated with seasonal and annual variations in water temperature. Mean and maximum latitudes of occurrence of the species were regressed against average surface and bottom water temperatures and indices of relative abundance from spring and autumn trawl surveys, and significant regressions were developed for 17 of 36 species. Variations in water temperature were significant in explaining changes in mean latitude of occurrence for 12 of 36 species. For pelagic species, mean catches shifted poleward by 0.5-0.8º latitude for each 1 ºC increase in average water temperature. Species exhibiting the greatest poleward range extension in relation to water temperature were primarily temperate-water migrants.

Murawski postulated that variations in the functional responses of distributions to temperature change due to environmental warming may alter trophic relationships among fishes of the ecosystem, including species that are important prey for a variety of fish and marine birds and mammals. Changes in mean shelf temperatures may alter distributional overlap among some prey and their predators and thus may change the balance of predation mortality rates among competing predator species. Furthermore, the quantity, species composition, and geographic distribution of fisheries yields in marine ecosystems such as the North Atlantic are apt to shift considerably in response to climate warming.

14.3 Testing the method

Before proceeding with a full-scale assessment, it is critical to look at the feasibility of using any particular methods. Figure 14.1 presents a framework for identifying and evaluating methods and developing an appropriate assessment approach. The selection of appropriate methods will consider, in part, a number of factors, including:

1. the specific fishery resource of concern;
2. the nature of the estimated climate change;
3. the specific data needs of each method;
4. the availability of existing data;
5. the availability of time and resources to collect new data; and
6. the capability to integrate analyses with other sectors, mainly water resources and coastal resources.

The species-specific approaches may be the most difficult to accurately use, largely because of the relative absence of data on life history and physiology for species in some regions of the world. In some cases, data from other taxa, i.e., species of the same genera, family, or guild (Jobling 1981; Lin and Regier, 1995), may be used in place of species-specific data. In the absence of species-specific or other data, professional judgement may be used to estimate life history and bioenergetics variables. In contrast,

difficulties associated with the overall catch and yield approaches will be largely associated not with the lack of biological data but rather with the absence of hydrological and environmental information. Certain methods lend themselves better to use of expert judgement. For example, in the absence of suitable data, a Delphi approach can be used to develop HSI models based solely on expert judgement (Crance, 1987).

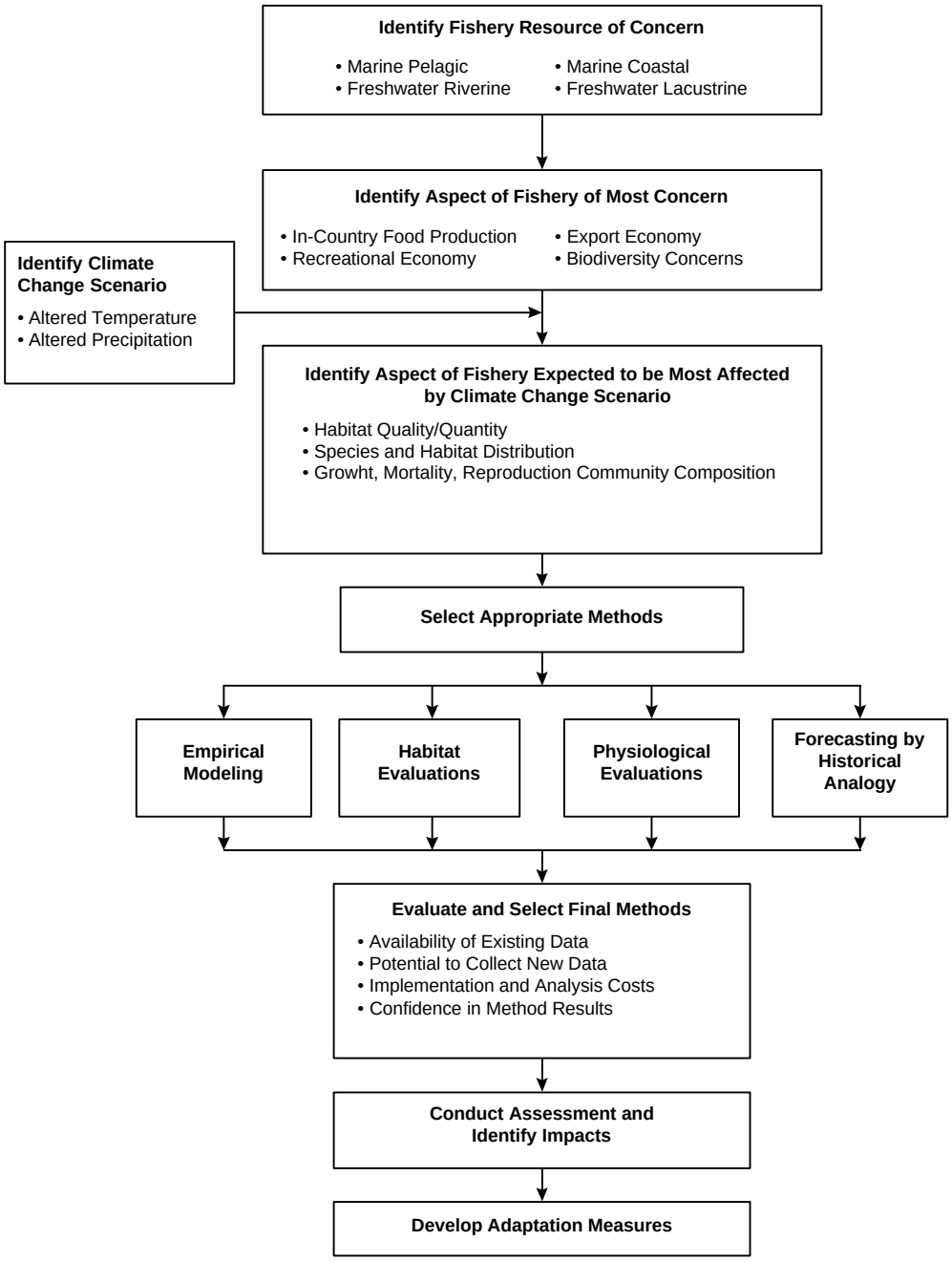

Figure 14.1 Process framework for selecting methods for assessing potential climate impacts to target fishery resources.

It is important to note that not all of the cited methods must be used. The methods should be selected to address the goals of the assessment, the expected changes in climate, and the best use of the available data. It may be true that a single method will be sufficient. Alternately, a weight-of-evidence approach employing multiple, independent assessment methods may be deemed appropriate, and in most cases will provide a more robust evaluation of potential climate effects. In situations where little data exist, expert judgement can be sufficient, although this will increase the level of uncertainty of, and decrease confidence in, the assessment results.

The descriptions of data requirements provided with the methods discussions above are the basis for screening background information and sources of data. Since the methods also tend to focus on a particular climate variable (or set thereof), those methods can be screened for their sensitivity to the appropriate climate factor (e.g., precipitation, temperature, water level). Specific geographic regions can be considered for their vulnerabilities to climate change. Particular species of fish or entire fisheries can be screened for their ecological and economic importance and for their potential vulnerabilities to climate change.

Models can be tested if sufficient data are available (Carter et al., 1994). Validation studies look at how closely estimations of a particular fisheries model track real-world observations. However, it is important to note that oftentimes sufficient data are lacking to carry out detailed validation studies. Nonetheless, a given fisheries model may be perfectly suitable to use for a climate change assessment. Sensitivity analysis examines how the output of a particular fisheries model changes with changes in its structure or the actual values that are input into the model. This kind of analysis is helpful to see if the model will respond reasonably to the likely changes in climate variables. In the end, the experts carrying out the assessment will need to make a judgement about the overall validity, applicability, and usefulness of any specific fisheries model and to what level of uncertainty will the results be considered acceptable.

14.4 Scenarios

14.4.1 Climate change considerations

Chapter 3 discusses climate change scenarios in detail. Of critical importance to the fisheries assessment is the conversion of the climate scenario data into useable input for the fisheries methods. For example, the output of climate models typically includes estimates of changes in air temperatures and in the magnitude, duration, and distribution of precipitation. These models do not, however, provide direct information on potential changes in water quality or hydrologic parameters that directly affect freshwater and marine coastal fisheries resources, or on potential changes in ocean

currents and the distribution of upwelling zones that are important to pelagic marine species.

To assess the vulnerability of the fisheries to climate change, estimated atmospheric climate changes must be translated into changes in environmental variables that are directly important to fisheries resources, such as lake and sea levels, ocean currents, streamflow and water temperatures (Meisner et al., 1987; Christie and Regier, 1988; Kennedy, 1990; see Figure 14.2). Only when these climate-induced hydrologic changes are estimated can the responses of the fishery resource (e.g., reduced growth rates or reproductive success, increased mortality, and altered distribution) be identified and evaluated. The assessment of fisheries impacts will depend critically on the analyses from the water resource and coastal resource sectors and their associated hydrologic models. Multisectoral, multidisciplinary teams will be necessary, and fisheries specialists will have to interact with technical specialists from other resource areas when developing riverine hydrographs; estimating sea and lake levels, water temperatures, and salinity; estimating the timing and extent of floodplain inundation and the fate of wetlands; and estimating the distribution of oceanic currents and upwelling zones under different climate change scenarios.

14.4.2 Socio-economic considerations

Changes in abundance of specific fisheries will have direct social and economic effects. Changes in commercial fisheries will have very direct economic impacts, either beneficial or negative. These economic impacts can be measured directly through changes in total monetary value of the catch and can be used in a cost-benefit analysis.

Changes to recreational fisheries may also incur socio-economic impacts. Decreases or increases in abundance of key recreational species will affect the likelihood of people travelling to a specific place to fish and thus directly affect the livelihood of that sector of the population employed supporting the recreational fishery. This in turn can affect local or regional economies (USEPA, 1995).

These same impacts to fisheries can affect subsistence activities. Areas that are highly dependent on fish as a daily food source may be significantly affected by climate change impacts to fisheries resources. Reduced subsistence catches may result in direct local or regional impacts on human health. In extreme cases the drying of a tropical water body could lead to entire villages having to move. In other cases it may require people to migrate on at least a seasonal basis to other fishing grounds. So it is important to look at socio-economic impacts outside of the formal economy. Chapter 2 discusses socio-economic scenarios in detail.

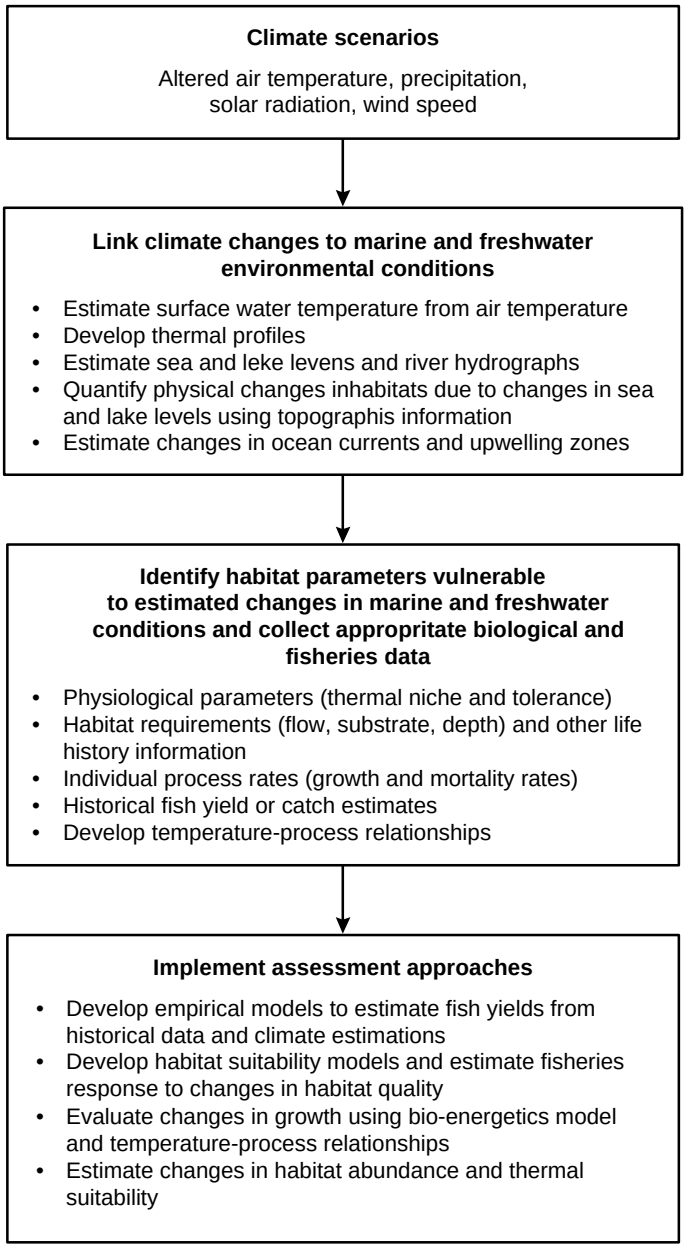

Figure 14.2 Conceptual framework for linking estimated climate changes to environmental conditions in aquatic habitats and estimating biological responses of target fish resources (Hlohowskyj et al., 1996).

14.5 Autonomous adaptation

Given any set of effects of climate change, certain changes in fishery populations and in the human social and economic systems that depend on them will happen without purposeful intervention. One of the more obvious examples will be the likely poleward redistribution of marine fisheries. There will not be significant barriers to this process occurring naturally. Other changes in fish distributions, including freshwater fisheries,

are also likely without human management and intervention. The changes estimated in the assessments will provide a guide for these adjustments, and monitoring programs can confirm these changes.

Some social and economic responses to climate change are likely to be virtually autonomous also. It would be expected that subsistence fishers will switch to other available species, and some groups may migrate to stay with favoured fish species or to find new fishing grounds. Stocking of at least some species better adapted to the changed conditions is likely, even without major public programs.

14.6 Planned adaptation

As previously discussed, global warming is expected to lead (on average) to higher air temperatures and changes in the geographic distribution, temporal pattern, and magnitude of precipitation. These changes in temperature and precipitation in turn affect marine and freshwater habitats and eventually lead to changes in the distribution, composition, and abundance of fisheries species around the world. However, specific estimations of effects to habitats and fisheries resources are difficult to develop given the uncertainty associated with the overall accuracy of estimations of climate change, and the very difficult problem of providing regional- or finer-scale estimations of climate changes. Nonetheless, the development of preliminary cost-effective adaptation measures is warranted and should be initiated if a potential for adverse impacts is indicated by the impact assessments. The adaptation measures may then be revised as confidence in the climate and impact projections increases and as technology improves.

The development of adaptation policies and strategies to address problems that may arise as a result of climate-induced impacts to fisheries will depend on a number of physical, ecological and socio-economic conditions. These conditions include 1) the nature of the climate change impact on the fisheries resource (changes in thermal habitat, habitat dewatering, alteration in timing of flood flows, etc.); 2) whether the fisheries resource of concern is marine, estuarine, or freshwater based; 3) the location (latitude) of the fishery resource; 4) whether the resource of concern comprises cold-water or warmwater species; 5) the current status or condition of the fishery of concern; 6) whether the fishery is commercial or subsistence (or some combination thereof); and 7) the overall importance of the fishery of concern to a local, national, or regional economy. Equally important, the development of adaptation responses specific to the fishery resource will be dependent on and interrelated with the adaptation activities in other sectors, particularly water resources, coastal zone resources, and agriculture and land use.

Adaptation responses (Table 14.5) specific to fishery resources may address issues of water management strategies; habitat construction, modification, and protection; management of catch levels, development of new fishing techniques and equipment; development of new processing infrastructure; development of new species strains for stocking; and management of land use within important watersheds. In many countries,

the development and implementation of appropriate adaptation strategies will be strongly dependent on the availability of financing. Adaptation can become increasingly important, relative to autonomous adjustments, for scenarios that lead to a net reduction in available fishery resources. This net reduction may come about either from actual reductions in productivity or from significant geographic redistribution of the resources.

Table 14.5 Summary of adaptation measures (some measures from IPCC, 1996).

Marine and estuarine fisheries
• negotiate allocation of EEZ and international catches • implement coastal zone and land use management/restrictions on development areas • develop coastal wetland mitigation banks • identify substitute or develop new fisheries • develop financing for shifting to new fisheries • reduce current catch on fully and overexploited fisheries to restore health of fisheries (e.g. implement limited entry schemes, reduction of subsidies) • build capacity — training/education for use of new equipment • construct/restore wetlands • educate coastal populations on the economic value for supporting sustainability of coastal environments
Freshwater and anadromous fisheries
• implement land use policies that protect critical habitats (particularly seasonally flooded spawning areas and endangered species habitats) • revise catch allocations among commercial, recreational and subsistence fishers • ensure that markets can supply equipment for recreational fishers • develop capacity to manage for fisheries in reservoirs/impoundments developed for other sectors (e.g. agriculture, drinking water, hydroelectric power) • develop capacity for fish stocking (hatcheries, technicians, distribution mechanisms) • create training/extension service/financing options for assistance to commercial and subsistence fishers • minimise new physical barriers to fish migration from dams/other uses of water • remove/modify existing physical barriers to migration • educate floodplain populations on the economic value of supporting sustainability of floodplain environments
Aquaculture
• co-ordinate/plan with water resources sector for water conservation in arid regions • construct new aquaculture facilities to offset loss of natural habitats • change to more environmentally tolerant species as necessary • develop faster growing strains

14.6.1 Marine fisheries

Impacts to marine fishery resources will most likely result from climate-induced changes in ocean currents (IPCC, 1996) and upwelling zones (Glantz, 1994). Fishery responses to these changes may include shifts in the locations of major fishing grounds, reductions in overall fish production (biomass), and changes in species compositions. Potential changes to the physical environment may be among the most difficult changes

to estimate with any reliability, and technical options to directly modify climate effects on the open ocean environment, in contrast to estuarine and freshwater habitats, are limited or non-existent.

In general, measures for adapting to potentially major redistributions of fisheries stocks may include 1) developing fishing fleets capable of travelling greater distances to new fishing grounds or 2) building coastal and ocean-going processing facilities to expedite delivery of catch to customers. It is likely that countries with modern fishing fleets and the most refrigeration and processing capability will be willing to pursue relocated fisheries even at the cost of travel to more distant and different locations. Because of the heavy capital investment and debt in many of the marine fishing fleets of wealthier nations, there will be a real need to locate new or substitute fisheries to pay for this investment (Glantz and Feingold, 1992).

Land use may also be an important factor in this process of change. Fish processing plants may have to locate to new areas along with the fishing fleets. Available land in the coastal zone for new processing facilities may be scarce, and in some countries too valuable for this use (Feingold, 1992). Alternately, ocean-going processing capabilities will need to be developed.

As difficult, if not more so, will be establishing new catch limits or geographic restrictions. This may require international negotiations and fishing treaties or implementation of limited entry schemes. This type of fisheries management has been difficult in the past, and is not likely to be easier in the future (IPCC, 1996). For example, shifts to substitute fish stocks may add stress to stocks currently under significant fishing pressure (Regier and Goodier, 1992). Nevertheless, reducing fishing pressure now on overexploited species may increase their resilience to the direct effects of climate change and to the possible effects of redistributed fishing pressure.

14.6.2 Estuarine fisheries

Estuarine fisheries are anticipated to be most at risk to climate change as a result of sea level rise and its effects on coastal habitats such as wetlands. In contrast to the uncertainty associated with estimates of precipitation and temperature change, there is a greater capacity for estimating sea level rise and anticipating its expected impacts on fisheries. There is some certainty to the estimated current and future rate and magnitude of sea level change (Douglas 1991; Titus and Narayanan, 1995), and the importance of sea level to some critical estuarine fisheries (e.g., shrimp) is at least partially understood. For example, the world-wide catch of shrimp is directly related to the acreage of wetland nursery habitat (Turner, 1977, 1992). Shrimp are frequently major exports and sources for hard currency. Furthermore, in some developing countries the bycatch from fishing for shrimp is saved, rather than disposed overboard, and used for domestic consumption. Oftentimes, the fish that comprise the bycatch are too expensive to gather directly even though they serve as an important domestic protein source.

In addition to the greater confidence in estimates of sea level rise, present day technology provides an opportunity to design and if necessary implement adaptation strategies for addressing anticipated impacts to estuarine fisheries resources. Estimates of sea level rise provide some capability to estimate the fate of specific coastal wetlands and other nearshore nursery areas that are important for specific fisheries resources. This capability thus gives coastal and island countries some ability to plan for the impacts of sea level rise on these nursery areas and therefore the long-term health of their fisheries. Countries that are committed to maintaining their coastal fisheries will have to maintain undeveloped inshore areas to which coastal wetlands (like mangroves) can retreat (Kjerfve et al., 1994). For example, mangroves, an abundant and important coastal nursery habitat, are quite vulnerable to sea level rise (Ellison, 1993). These habitats may be lost as sea level rises. However, if inland areas estimated to be inundated as a result of sea level rise are protected from development, they will be available for mangrove colonisation and establishment. Thus, government policies related to development in the coastal zone will be critical to maintaining wetland nursery areas and thus fisheries. Fisheries adaptation will be potentially competing with various parts of the public and commercial land use/development sector.

14.6.3 Freshwater fisheries

Climate impacts to freshwater fisheries will be more directly related to changes in water temperature (at higher latitudes) and to changes in water availability (lower latitudes). In northern latitudes, inland freshwaters are estimated to become warmer, and some coldwater species are likely to be replaced by warmer water species (Meisner et al., 1987; Shuter and Post, 1990). The warmwater species may naturally expand their ranges into newer, thermally suitable habitats if invasion routes are available, or may be stocked into isolated water bodies. These warmer water habitats are also likely to show increases in fisheries production if nutrients are present and if prey are present for higher order species. However, the rates of environmental change (mainly temperature extremes as well as thermal structure) and the availability of replacement species will greatly affect a system’s intrinsic ability to adapt to different climate conditions.

Countries are likely to have more technical capabilities to address freshwater impacts when compared to marine or estuarine impacts. Stocking with new species may be the most feasible technical solution where there are natural or human-made barriers to migration into newly warmer habitats. Some countries already have the hatcheries and associated infrastructure for stocking major aquatic systems like the Great Lakes in the USA, and aquaculture is practised at least on a small scale in most countries throughout the world. For freshwater habitats with human-made obstacles to fish passage, removing or modifying obstructions may represent the most straightforward and effective adaptation measure. This approach may be necessary to maintain and restore threatened and endangered stocks of anadromous fisheries.

Perhaps the greater impacts that may occur to fishery resources will be to the existing drought- prone regions that may become even drier, such as Southern Africa (Hulme,

1996) Changes in the magnitude, timing, and duration of precipitation events could lead to significant regional or local reductions of aquatic habitat. Reduced precipitation with resultant declines in lake or stream levels could reduce or eliminate critical habitats such as spawning areas. Alternately, changes in the timing of precipitation events could lead to a lack of water during key stages of the life cycle and thus threaten the health and diversity of fisheries populations. Temperature changes in drought-prone regions could also affect runoff and therefore affect hydrological changes.

Maintaining productive fisheries in the face of changes such as these will be difficult. Some countries may lack sufficient technical or monetary capability to respond to altered climatic conditions. In addition, current droughts in some regions are already putting increasing pressure to use diminishing water supplies for irrigation and hydro-power generation, and these needs are likely to conflict with the need for protecting fisheries resources.

14.6.4 Aquaculture

Aquaculture may become a major area for freshwater fisheries resource adaptation. With climate warming, aquaculture is likely to become more productive (IPCC, 1996). Fish production rates will be higher, other things being equal, in warmer water. The aquaculture practised throughout the world includes both marine and freshwater fisheries. As a consequence, technical knowledge for fisheries production using aquaculture methods is well developed and widely available. The use of aquaculture may be most appropriate for areas (i.e., equatorial latitudes) which will experience altered precipitation regimes that result in reduced water availability. In these areas, the development of large-scale aquaculture facilities could be used to increase fish production to offset losses in natural fish production.

Although aquaculture may represent a major area for adaptation, the suitability of aquaculture will be highly dependent on the availability of water, and the implementation of aquaculture measures will most likely require co-ordination with the water demands for agriculture, industry, and domestic use. Additionally, a number of aspects currently associated with aquaculture practises world-wide may affect the suitability and acceptability of aquaculture as an adaptation activity. For example, current problems associated with aquaculture include 1) accidental introduction of non-native species to the wild; 2) water quality and habitat degradation due to discharge of operational wastes, 3) direct conversion of natural fish habitat to aquacultural facilities; and 4) the abuse of additives in aquaculture stocks.

Use of aquaculture to offset losses in the marine environment may be more problematic. Species raised in sea pens may be just as vulnerable to major changes in currents as are wild stocks.

14.7 Summary and implications

As the world's fisheries shift in distribution and abundance and the human population continues to grow, the demand for fish in the diet is likely to continue growing. Where fishing remains profitable, commercial fishers will respond with the necessary changes in gear. An even more motivated group will be people around the world who depend on fish for subsistence or for the major part of protein in their diet. These people will adapt to the extent feasible out of sheer necessity. They will fish new species and make feasible modifications to their gear. Yet adapting for the long run in fisheries will require shifting attitudes away from a short-term economic and social focus. Productive fisheries collapse from the economic pressures that lead to overfishing, particularly in combination with environmental variability (Glantz and Feingold, 1992). As most fisheries are currently fully exploited or overexploited (IPCC, 1996), there is little evidence that people have yet learned to manage fisheries resources for the long term. Yet this is critically important. The countries whose people are most dependent on natural resources like fish are typically those with the least capacity to cope with the coming changes. These countries need sustainable development strategies that relieve current levels of pressure on their resources and increase their resilience to climate change (Secrett, 1992).

Adaptation planning must begin with the results of the impact analysis and the best estimate of which fishery resources are at risk. Adaptation policies and techniques must be screened (Benioff and Warren, 1996) for their effectiveness in reducing vulnerability of fishery resources. One can map an iterative process of performing a impact assessment, screening for high priority adaptation options, and then again examining the vulnerabilities. High priority adaptations to climate change (Smith et al., 1997) may address (also see Chapter 5, Adaptation):

- irreversible consequences;
- habitat loss/extinction;
- decisions, such as coastal land use, that keep options open for the long term; and
- reversing unfavourable trends such as declining fish stocks.

Given the uncertainties of the impacts of climate change, it is important to begin with feasible, cost-effective adaptations and those adaptations that may provide benefits even without significant climate change effects. An example of this might be the preservation and restoration of wetlands. Wetlands are often important spawning areas for fish and critical nursery areas for early life stages. But wetlands also are known to provide benefits such as flood control and improved water quality. Another example might be the reduction of fishing pressure on overexploited stocks. This would improve the condition of a fish stock even without climate change, and should make those stocks more resilient in the face of this new stress. A step like this may not be costly; however, if more than one country is involved, it may still be difficult to accomplish. This

example shows, however, that there may be steps that will provide value to society regardless of the extent of climate change.

If quantitative methods such as cost-effectiveness analysis or benefit-cost analysis to select adaptation options are not appropriate to a specific situation, other qualitative methods may work. Multicriteria analysis can use qualitative approaches that do not rely on quantifying benefits in dollars or other metrics. Decision makers are asked to identify policy objectives and subjectively determine how well the adaptation measures may meet the objectives (Benioff and Warren, 1996).

The management of water resources is frequently a result of a mix of government policies and market forces that promote conflicting activities such as navigation, flood control, agricultural irrigation, and hydroelectric power production. This conflict among water use sectors has affected fisheries for decades in many countries. Rarely are fisheries the primary consideration in large-scale management of water resources. Indeed, the growing world population is likely to increase demand for all these other uses of water, in addition to the fisheries, even without climate warming. Thus as various water management practices become increasingly necessary for irrigation, hydroelectric power, and drinking water supplies, policies for fisheries management will have to evolve to fit within those constraints. These policies can be modified to support fisheries if sufficient consensus within a society exists that there are key fisheries resources worth preserving. Thus, adaptation measures for fisheries must be consistent with adaptation measures in other sectors. Nevertheless, it is unlikely that fisheries would ever take precedence in direct competition with these other sectors. Promoting integrated water management should become a high level policy goal if societies are to give fisheries their greatest opportunity to prosper under a new climate regime.

One of the most important considerations in assessing potential impacts and developing adaptation strategies is the understanding of the relationships among fisheries and the other sectors. The fisheries analysis must be built primarily on the analyses of water availability within the water resources sector and, for coastal marine fisheries resources, also on the analyses of the loss of coastal wetland areas performed for the coastal zone sector. In addition, the management of other resource sectors must be considered when developing any fisheries adaptation strategies. For example, the preservation of wetlands is as much an issue of land use and water management as it is of fisheries production. Water availability is also a major issue for agriculture and must be considered in the development of fisheries adaptation strategies. This thread of interaction and integration of the water-dependent fisheries sector with other sectors will need to be considered throughout any specific impact and adaptation assessment for any particular fisheries resource.

References

Beamish, R.J. 1993. Climate and exceptional fish production off the West Coast of North America. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 2270-2291.

Beamish, R.J. (ed). 1995. Climate Change and Northern Fish Populations. *Canadian Special Publication of Fisheries and Aquatic Sciences*, No. 121, National Research Council of Canada, Ottawa.

Benioff, R., and J. Warren. 1996. *Steps in Preparing Climate Change Action Plans: a Handbook, Version 1.0.* US Country Studies Program, Washington, DC.

Benioff, R., Guill, S. and J. Lee (eds). 1996. *Vulnerability and Adaptation Assessments: An International Guidebook.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Brander, K. 1997. Effects of climate change on cod (*Gadus morhua*) stocks. In *Global Warming: Implications for Freshwater and Marine Fish.* C.M. Wood and D.G. McDonald, (eds). Society for Experimental Biology Seminar Series 61, Cambridge University Press, United Kingdom, pp. 255–278.

Carter, T.R., Parry, M.L., Harasawa, H. and S. Nishioka. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* Working Group II of the Intergovernmental Panel on Climate Change, University College, London.

Christie, G.C. and H.A. Regier. 1988. Measures of optimal thermal habitat and their relationship to yields of four commercial fish species. *Canadian Journal of Fisheries and Aquatic Sciences* 45, 301-314.

Crance, J.H. 1987. Guidelines for Using the Delphi Technique to Develop Habitat Suitability Index Curves, Biological Report 82 (10.134), National Ecology Center, Division of Wildlife and Contaminant Research, U.S. Fish and Wildlife Service, Fort Collins, Colorado, USA.

Crul, R.C.M. 1992. *Models for Estimating Potential Fish Yields of African Inland Waters.* CIFA Occasional Paper No. 16. Food and Agriculture Organization of the United Nations, Rome.

Douglas, B.C. 1991. Global sea level rise. *Journal of Geophysical Research* 96, 6981-6992.

Eaton, J.G. and R.M. Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography* 41, 1109-1115.

Edwards, E.F. and B.A. Megrey (eds). 1989. *Mathematical Analysis of Fish Stock Dynamics.* American Fisheries Society Symposium 6. American Fisheries Society, Bethesda, Maryland, USA.

Ellison, J.C. 1993. Mangrove retreat with rising sea-level, Bermuda. *Estuarine, Coastal and Shelf Science* 37, 75-87.

Feingold, LE. 1992. The menhaden fishery: Interactions of climate, industry, and society. In *Climate Variability, Climate Change and Fisheries*, Glantz, M.H. (ed). Cambridge University Press, Cambridge, United Kingdom.

Freon, P., Mullon C., and G. Pichon. 1993. Experimental interactive software for choosing and fitting surplus production models including environmental variables. ORSTOM, Institut Francais de Recherche Scientifique pour le Developpement en Cooperation, 213 rue Lafayette, 75480 Paris Cedex 10, France. In *Introduction to Tropical Fish Stock Assessment.* FAO Fisheries Technical Paper. Viale delle Terme di Caracalla, 00100 Rome, Italy.

Galat, D.L. and A.G. Frazier (eds). 1996. *Overview of River-Floodplain Ecology in the Upper Mississippi River Basin.* Vol. 3 of *Science for Floodplain Management into the 21st Century*, Kelmelis, J.A., (ed). U.S. Government Printing Office, Washington, DC.

Garcia, S. and L. Le Reste. 1981. *Life Cycles, Dynamics, Exploitation, and Management of Coastal Penaeid Shrimp Stocks*, FAO Technical Paper No. 203, Food and Agriculture Organization of the United Nations, Rome.

Glantz, M.H. 1990. Does history have a future? Forecasting climate change effects on fisheries by analogy. *Fisheries* 15(6), 39-44.

Glantz, M.H. 1994. *The Impacts of Climate on Fisheries.* UNEP Environment Library No. 13. United Nations Environmental Programme, Nairobi, Kenya.

Glantz, M.H. and L.E. Feingold. 1992. Climate variability, climate change, and fisheries: A summary. In *Climate Variability, Climate Change and Fisheries*, Glantz, M.H. (ed). Cambridge University Press, Cambridge.

Hanson, P.C., T.B. Johnson, D.E. Schindler, and J.F. Kitchell. 1997. *Fish Bioenergetics 3.0*. Board of Regents, University of Wisconsin System, Sea Grant Institute, Madison, Wisconsin, USA.

Hays, R.L. 1987. *A Users Manual for Micro-HSI, Habitat Suitability Index Modelling Software for Microcomputers, Version 2.* National Ecology Center, U.S. Fish and Wildlife Service, Fort Collins, Colorado, USA.

Hill, D.K. and J.J. Magnuson. 1990. Potential effects of global climate warming on the growth and prey consumption of Great Lakes fish. *Transactions of the American Fisheries Society* 119, 265-275.

Hlohowskyj, I., Brody, M.S., and R.T. Lackey. 1996. Methods for assessing vulnerability of African fisheries resources to climate change. *Climate Research, Special Issue* 6(2), 97-106.

Hulme, M. (ed). 1996. *Climate Change and Southern Africa: an Exploration of Some Potential Impacts and Implications in the SADC Region*. A report commissioned by WWF International and co-ordinated by the Climate Research Unit, UEA, Norwich, United Kingdom.

IPCC. 1996. *Working Group II Report.* Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Jobling, M. 1981. Temperature tolerance and the final preferendum – Rapid methods for the assessment of optimum growth temperatures. *Journal of Fish Biology* 19, 439-455.

Jobling, M. 1997. Temperature and growth: Modulation of growth rate via temperature change. In *Global Warming: Implications for Freshwater and Marine Fish,* C.M.

Wood and D.G. McDonald (eds). Society for Experimental Biology, Seminar Series: 61. Cambridge University Press, Cambridge, pp. 225-253.

Kennedy, V.S. 1990. Anticipated effects of climate change on estuarine and coastal fisheries. *Fisheries* 15(6), 16-24.

Kitchell, J.F., D.J. Stewart, and D. Weininger. 1977. Applications of a bioenergetics model to yellow perch (*Perca flavescens*) and walleye (*Stizostedion vitreum vitreum*). *Journal of the Fisheries Research Board of Canada* 34, 1922-1935.

Kjerfve, B., WK Michener and LR Gardner. 1994. Impacts of climate change in estuary and delta environments. In *Impacts of Climate Change on Ecosystems and Species: Marine and Coastal Ecosystems*, J. Pernetta, R. Leemans, D. Elder, and S. Humphrey (eds). A Marine Conservation and Development Report. IUCN, Gland, Switzerland.

Lin, P. and H.A. Regier. 1995. Use of Arrhenius models to describe temperature dependence on organismal rates in fish. In *Climate Change and Northern Fish Populations*, R.J. Beamish (ed). Canadian Special Publication of Fisheries and Aquatic Sciences, No. 121. National Research Council of Canada, Ottawa, pp. 211-225.

Lowe-McConnell, R.H. 1987. *Ecological Studies in Tropical Fish Communities.* Cambridge University Press, Cambridge.

Magnuson, J.J. and B.T. DeStasio. 1997. Thermal niche of fishes and global warming. In *Global Warming: Implications for Freshwater and Marine Fish, Seminar Series 61*, C.M. Wood and D.G. MacDonald (eds). Society for Experimental Biology. Cambridge University Press, Cambridge, pp. 377-408.

Mann, K.H. and J.R.N. Lazier. 1996, *Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans.* 2nd Edition. Blackwell Science, Inc., Cambridge, Massachusetts, USA.

Marshall, B.E. 1984. *Predicting Ecology and Fish Yields in African Reservoirs from Preimpoundment Physico-Chemical Data*, CIFA Technical Paper 12. Food and Agriculture Organization of the United Nations, Rome.

Megrey, B.A., S.J. Bogard, W.C. Rugen, A.B. Hollowed, P.J. Stabeno, S.A. Macklin, J.D. Schumacher, and W.J. Ingraham, Jr. 1995. An exploratory analysis of associations between biotic and abiotic factors and year-class strength of Gulf of Alaska walleye pollock (*Theragra chalcograma*). In *Climate Change and Northern Fish Populations*, R.J. Beamish (ed). Canadian Special Publications of Fisheries and Aquatic Sciences No. 121, National Research Council of Canada, Ottawa, pp. 227-243.

Meisner, J.D. 1990. Potential loss of thermal habitat for brook trout, due to climatic warming, in two southern Ontario streams. *Transactions of the American Fisheries Society* 119, 282-291.

Meisner, J.D. and B.J. Shuter. 1992. Assessing potential effects of global climate change on tropical freshwater fishes. *GeoJournal* 28, 21-27.

Meisner, J.D., J.L. Goodier, H.A. Regier, B.J. Shuter, and W.J. Christie. 1987. An assessment of the effects of climate warming on Great Lakes basin fishes. *Journal of Great Lakes Research* 13, 340-352.

Minns, C.K. and J.E. Moore. 1992. Predicting the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canadian lakes. *Climate Change* 22, 327-346.

Murawski, S.A. 1993. Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of the American Fisheries Society* 122, 647-658.

Muter, F-J., B.L. Norcross, and T.C. Royer. 1995. Do cyclic temperatures cause cyclic fisheries? In *Climate Change and Northern Fish Populations,* R.J. Beamish (ed). Canadian Special Publication of Fisheries and Aquatic Sciences No. 121, National Research Council of Canada, Ottawa, pp. 119-129.

Neale, C.M.U. (ed). 1994. *Color Aerial Photography and Videography for Resource Monitoring.* Proceedings of the 14th Biennial Workshop. American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, USA.

Orth, R.J., J.F. Nowak, A.A. Frisch, K.P. Kiley, and J.R. Whiting. 1991. *Distribution of Submerged Aquatic Vegetation in the Chesapeake Bay and Tributaries and Chincoteague Bay – 1990.* US Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, Maryland, USA.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *Journal du Conseil, Conseil International pour l'Exploration de la Mer* 39(2), 175-192.

Pauly, D. 1983. *Some Simple Methods for the Assessment of Tropical Fish Stocks.* FAO Fisheries Technical Paper No. 234. Food and Agriculture Organization of the United Nations, Rome.

Poff, N.L. and J.D. Allan. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. *Ecology* 76, 606-627.

Regier, H.A. and J.L. Goodier. 1992. Irruption of sea lamprey in the upper Great Lakes: Analogous events to those that may follow climate warming. In *Climate Variability, Climate Change and Fisheries,* Glantz, M.H. (ed). Cambridge University Press, Cambridge, United Kingdom.

Regier, H.A. and J.D. Meisner. 1990. Anticipated effects of climate change on freshwater fishes and their habitat. *Fisheries* 15, 10-15.

Regier, H.A., J.A. Holmes, and D. Pauly. 1990. Influence of temperature changes on aquatic ecosystems: An interpretation of empirical data. *Transactions of the American Fisheries Society* 119, 374-389.

Sagua, V.O. 1993. *The Effects of Climate Change on the Fisheries of the Sahel.* Food and Agriculture Organization of the United Nations, Rome.

Schlesinger, D.A. and H.A. Regier. 1983. Relationship between environmental temperature and yields of subarctic and temperate zone fish species. *Canadian Journal of Fisheries and Aquatic Science* 40, 1829-1837.

Secrett, C. 1992. Planned Adaptation to Global Warming: A Preliminary Framework. Paper presented to the First SADCC Conference on Climate Change, Windhoek, Namibia.

Shuter, B.J. and J.D. Meisner. 1992. Tools for assessing the impact of climate change on freshwater fish populations. *GeoJournal* 28, 7-20.

Shuter, BJ and J.R. Post. 1990. Climate, population viability, and the zoogeography of temperate fishes. *Transactions of the American Fisheries Society* 119, 314-336.

Smith, JB, S.E. Ragland, and G.J. Pitts. 1997. A process for evaluating anticipatory measures for climate change. *Journal of Water, Air & Soil Pollution* 92, 229-238.

Sparre, P. and S.C. Venema. 1992. *Introduction to Tropical Fish Stock Assessment, Part 1-Manual*. FAO Fisheries Technical Paper 306/1, Rev. 1. Food and Agriculture Organization of the United Nations, Rome.

Stefan, H.G. and E.B. Preud'homme. 1993. Stream temperature estimation from air temperature. *Water Resources Bulletin* 29, 27-45.

Stefan, H.G., M. Hondzo, J.G. Eaton, and J.H. McCormick. 1995. Predicted effects of global climate change on fishes in Minnesota lakes. In *Climate Change and Northern Fish Populations,* R.J. Beamish (ed). Canadian Special Publication of Fisheries and Aquatic Sciences, No. 121, National Research Council of Canada, Ottawa, pp. 57-72.

Titus, J.G. and V.K. Narayanan. 1995. The Probability of Sea Level Rise. EPA 230-R-008, , US Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC.

Turner, R.E. 1977. Intertidal vegetation and commercial yields of penaeid shrimp. *Transactions of the American Fisheries Society* 106(5), 411-416.

Turner, R.E. 1992. Coastal wetlands and penaeid shrimp habitat. In *Stemming the Tide of Coastal Fish Habitat Loss,* R.H. Stroud (ed). Marine Recreational Fisheries Report No. 14. National Coalition for Marine Conservation, Savannah, Georgia, USA, pp. 97-104.

Turner, R.E. and D.F. Boesch. 1988. Aquatic animal production and wetland relationships: Insights gleaned following wetland loss or gain. In *The Ecology and Management of Wetlands. Vol. 1, Ecology of Wetlands,* D.D. Hook et al. (eds). Timber Press, Portland, Oregon, USA, pp. 25-39.

Turner, R.E. and M.S. Brody. 1983. *Habitat Suitability Index Models: Northern Gulf of Mexico Brown Shrimp and White Shrimp*. FWS/OBS-82/10.54. US Department of the Interior, Fish and Wildlife Service, Washington, DC.

USEPA. 1992. *Framework for Ecological Risk Assessment*. EPA/630/R-92/001. US Environmental Protection Agency. Risk Assessment Forum, Washington, DC.

USEPA. 1995. *Ecological Impacts from Climate Change*: An Economic Analysis of Freshwater Recreational Fishing. EPA-230-R-95-004. US Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC.

Welcomme, R.L. 1976. Some general and theoretical considerations on the fish yield of African rivers. *Journal of Fish Biology* 8, 351-364.

Welcomme, R.L. 1980. *Some factors affecting the catch of tropical river fisheries. In Comparative Studies on Freshwater Fisheries*. FAO Fisheries Technical Paper No. 198, Food and Agriculture Organization of the United Nations, Rome, pp. 268-275.

Welcomme, R.L. 1985. *River Fisheries*. FAO Fisheries Technical Paper No. 262, Food and Agriculture Organization of the United Nations, Rome.

Wood, C.M., and D.G. McDonald (eds). 1997. *Global Warming: Implications for Freshwater and Marine Fish*. Cambridge University Press, Cambridge, UK.