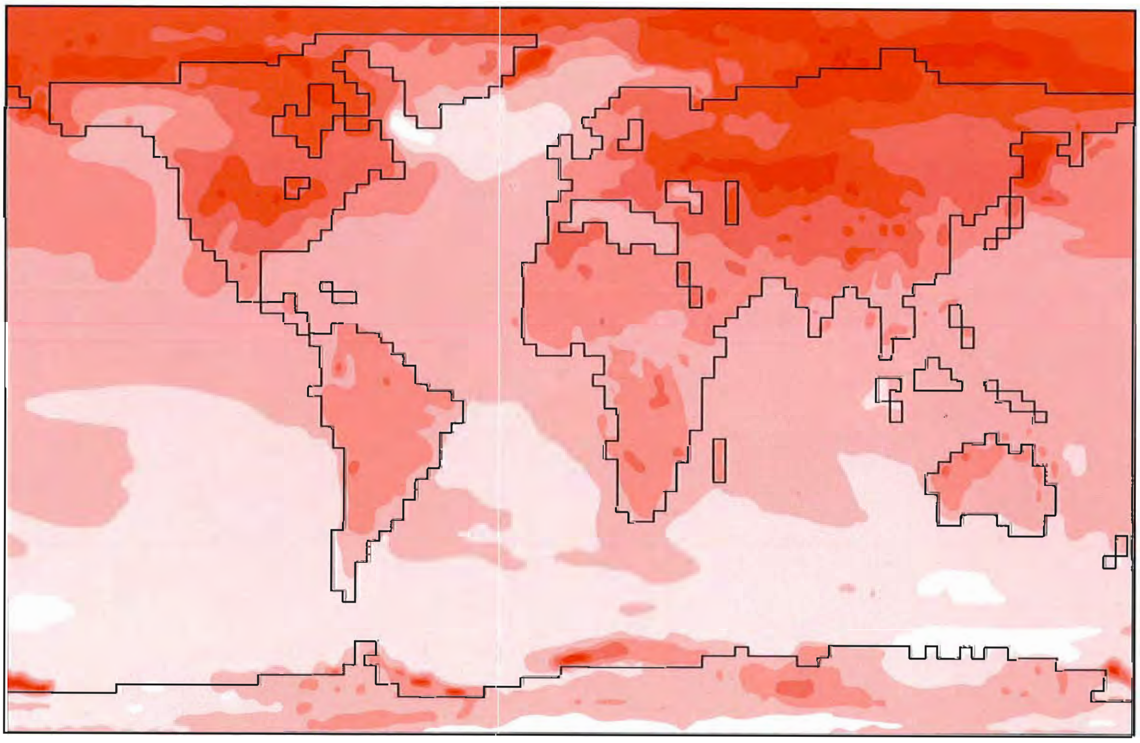
CGER-I015-'94

CLIMATE CHANGE IMPACTS AND ADAPTATIONS

IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations



PART OF THE IPCC SPECIAL REPORT
TO THE FIRST SESSION OF THE CONFERENCE OF THE PARTIES
TO THE UN FRAMEWORK CONVENTION ON CLIMATE CHANGE

INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

WMO World Meteorological Organization/United Nations Environment Programme UNEP

This report has been published by the Department of Geography, University College London (London, United Kingdom) and the Center for Global Environmental Research, National Institute for Environmental Studies (Tsukuba, Japan), with the assistance of the UK Department of the Environment and the Environment Agency of Japan.

Further copies can be obtained from:

Department of Geography,
University College London,
26 Bedford Way,
London, WC1H 0AP
United Kingdom.

Center for Global Environmental Research
National Institute for Environmental Studies
16-2 Onogawa,
Tsukuba,
Ibaraki 305,
Japan.

ISBN 0 904813 11 8

Printed in the United Kingdom and Japan
This publication is printed on recycled paper.

Designed and illustrated by Words and Publications, Oxford,
United Kingdom.

IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations

T. R. Carter

M. L. Parry

H. Harasawa

S. Nishioka

PART OF THE IPCC SPECIAL REPORT
TO THE FIRST SESSION OF THE CONFERENCE OF THE PARTIES
TO THE UN FRAMEWORK CONVENTION ON CLIMATE CHANGE
The other parts are:
Radiative Forcing of Climate Change;
Evaluation of the IPCC IS92 Emission Scenarios; and the
IPCC Guidelines for National Greenhouse Gas Inventories.

Department of Geography,
University College London, UK
and
Center for Global Environmental Research
National Institute for Environmental Studies, Japan

WORKING GROUP II OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

PREFACE

When the Intergovernmental Panel on Climate Change (IPCC) completed its first Impacts Assessment in 1990 it became clear that much more work was needed if a credible global picture was to be drawn of the potential effects of climate change. In particular, the Assessment revealed how difficult it was to compare impacts in different regions and economic sectors that had been assessed using different methods. A compatible set of methods was needed to yield comparable regional and sectoral impact assessments.

Working Group II of the IPCC therefore established an expert group to develop some guidelines for the assessment of impacts of climate change. The work of this group resulted in the publication in 1992 of an initial report entitled *Preliminary Guidelines for Assessing Impacts of Climate Change* (Carter *et al.*, 1992).

The major objective in producing and distributing that report was to solicit comments and suggestions for an improved set of guidelines that could be tabled and reviewed as part of the IPCC Second Assessment. The present report is the product of that process. It should be considered as a set of technical guidelines for the scientist, which does not seek to prescribe a single preferred method but a range of methods, some of which may be more suitable than others to the task in hand, but which can yield broadly comparable results. The United Nations Environment Programme is currently developing a set of Workbooks, designed to translate the technical procedures outlined here into practical methods of impact and adaptation assessment at the country and sectoral level.

The authors acknowledge the help of the IPCC Expert Group on Guidelines, the Lead Authors involved in the IPCC WGII Second Assessment, the reviewers and the governments of the United Kingdom and Japan in the preparation and printing of this report. Technical support was provided by I. Higashi, M. I. McDonnell and C. J. Parry.

T. R. Carter
Finnish Meteorological Institute
Box 503, FIN-00101, Helsinki
Finland

M. L. Parry
Department of Geography
University College London
26 Bedford Way, London
WC1H 0AP
United Kingdom

H. Harasawa and S. Nishioka
Center for Global Environmental
Research
National Institute for Environmental
Studies
162 Onogawa, Tsukuba
Ibaraki 305, Japan

THE IPCC EXPERT GROUP ON GUIDELINES

Co-chairmen

Dr Shuzo Nishioka, Japan
Professor Martin Parry, United Kingdom

Lead Authors

Dr Timothy Carter, Finland
Professor Martin Parry, United Kingdom
Dr Hideo Harasawa, Japan
Dr Shuzo Nishioka, Japan

Assisting Lead Authors

Dr R. Christ, UNEP
Dr P. Epstein, USA
Dr N. S. Jodha, Nepal
Dr E. Stakhiv, USA
Dr J. Scheraga, USA

Experts

Dr A. J. Al-Saati, Saudi Arabia
Dr L. Amadore, Philippines
Dr R. Andressen, Venezuela
Dr M. Beniston, Switzerland
Dr L. Bijlsma, Netherlands
Dr I. Burton, Canada
Dr O. F. Canziani, Argentina
Mr F. Chege, Kenya
Dr L. Chun-zhen, China
Dr S. Cohen, Canada
Professor B. R. Döös, Austria
Dr J. Everett, USA
Dr J. Fouts, USA
Dr I. M. Goklany, USA
Dr D. Greene, USA
Dr R. Klein, Netherlands
Ms H. Kolb, Austria
Dr S. Kotagama, Sri Lanka
Dr R. Leemans, Netherlands
Dr C. Magadza, Zimbabwe
Mr A. Magunia Lopez, Peru
Mr G. Mailu, Kenya
Dr B. Mieremet, USA
Professor W. Moomaw, USA
Dr R. A. Moreno, Cuba
Dr T. Morita, Japan
Dr R. Moss, IPCC
Dr R. Munn, Canada
Dr H. Muturi, Kenya
Dr I. Noble, Australia
Dr R. Odongo, Kenya
Dr G. M. E. Perillo, Argentina
Dr W. Piver, USA
Professor S. Prasith-rathsint, Thailand
Dr N. Rosenberg, USA
Dr C. Rosenzweig, USA
Dr M. Rounsevell, UK
Mr M. Sanwal, India
Dr J. Schefter, USA
Dr C. Scoppa, Argentina
Dr M. Scott, USA
Professor J. Skea, UK
Professor B. Smit, Canada
Dr W. Sombroek, FAO
Dr R. B. Street, Canada
Dr G. Tegart, Australia
Dr N. Thi Loc, Vietnam
Dr A. Yakovlev, Russian Federation

LIST OF REVIEWERS

N. Arnell, UK
E. B. Barbier, UK
M. Boer, Spain
F. Bultot, Belgium
G. Dedieu, France
T. E. Downing, UK
K. Frohberg, Germany
R. de Groot, Netherlands
K. Hanaki, Japan
A. Henderson-Sellers, Australia
M. Hulme, UK
N. Mimura, Japan
H. Morisugi, Japan
D. Norse, UK
T. Okita, Japan
E. P. Olaguer, USA
T. O'Riordan, UK
D. Pearce, UK
B. Pittock, Australia
J. R. Porter, Denmark
J. Reilly, USA
W. E. Riebsame, USA
M. B. de Rozari, Indonesia
J. B. Smith, USA
N. Sundararaman, IPCC
M. M. Yoshino, Japan

CONTENTS

1. BACKGROUND AND OBJECTIVES

2. APPROACHES TO THE ASSESSMENT OF IMPACTS AND ADAPTATIONS

3. DEFINITION OF THE PROBLEM

4. SELECTION OF THE METHOD

5. TESTING THE METHOD

6. SELECTING THE SCENARIOS

7. ASSESSMENT OF IMPACTS

8. ASSESSMENT OF AUTONOMOUS ADJUSTMENTS AND EVALUATION OF ADAPTATION STRATEGIES

CONTENTS

SUMMARY FOR POLICY MAKERS

Working Group II of IPCC has prepared Guidelines to assess the impacts of potential climate change and to evaluate appropriate adaptations. They reflect current knowledge and will be updated as improved methodologies are developed. The Guidelines outline a study framework which will allow comparable assessments to be made of impacts and adaptations in different regions/geographical areas, economic sectors and countries. The Guidelines are intended to help contracting parties meet, in part, their commitments under Article 4 of the UN Framework Convention on Climate Change.

Impact and adaptation assessments involve several steps:

- Definition of the problem.
- Selection of the methods.
- Testing the method.
- Selection of scenarios.
- Assessment of biophysical and socio-economic impacts.
- Assessment of autonomous adjustments.
- Evaluation of adaptation strategies.

Definition of the problem includes identifying the specific goals of the assessment, the ecosystem(s), economic sector(s) and geographical area(s) of interest, the time horizon(s) of the study, the data needs and the wider context of the work.

The selection of analytical method(s) depends upon the availability of resources, models and data. Impact assessment analyses can range from the qualitative and descriptive to the quantitative and prognostic.

Testing the method(s), including model validation and sensitivity studies, before undertaking the full assessment is necessary to ensure credibility.

Development of the scenarios requires, firstly, the projection of conditions expected to exist over the study period in the absence of climate change and, secondly, the projection of conditions associated with possible future changes in climate.

Assessment of potential impacts on the sector(s) or area(s) of interest involves estimating the differences in environmental and socio-economic conditions projected to occur with and without climate change.

Assessment of autonomous adjustments implies the analysis of responses to climate change that generally occur in an automatic or unconscious manner.

Evaluation of adaptation strategies involves the analysis of different means of reducing damage costs. The methodologies outlined in the Guidelines for analysing adaptation strategies are meant as a tool only to compare alternative adaptation strategies and thereby identify the most suitable strategies for minimizing the effects of climate change were they to occur.

EXECUTIVE SUMMARY

1 Objectives

These Guidelines, which are a further development of those previously published (Carter *et al.* 1992) provide a means for assessing the impacts of potential climate change and of evaluating appropriate adaptations. They reflect current knowledge and will be updated as improved methodologies are developed. They do not aim to prescribe a single preferred method, but provide an analytical outline that comprises a number of steps. A range of methods is identified at each step. Where possible, the merits and drawbacks of different methods are briefly discussed, with some suggestions on their selection and use.

The ultimate purpose of the Guidelines is to enable estimations of impacts and adaptations which will allow comparable assessments to be made for different regions/geographical areas, sectors and countries. The Guidelines are intended to help contracting parties meet, in part, commitments under Article 4 of the UN Framework on Climate Change.

2. Approaches

A general framework for conducting a climate impacts and adaptations assessment contains seven steps:

- Definition of the problem.
- Selection of the method.
- Testing the method.
- Selection of scenarios.
- Assessment of biophysical and socio-economic impacts.
- Assessment of autonomous adjustments.
- Evaluation of adaptation strategies.

At each step, a range of study methods is available. These are described and evaluated in the following sections. For reasons of brevity, however, only the essence of each method is introduced, along with references to sources of further information.

3. Step One–Definition of the Problem

This involves identifying the goals of the assessment, the exposure unit of interest, the spatial and temporal scope of the study, the data needs, and the wider context of the work.

3.1 Goals of the Assessment

It is important to be precise about the specific objectives of a study, as these will affect the conduct of the investigation. For example, an assessment of the hydrological impacts of future climatic change in a river catchment would have quite different requirements for data and expertise if the goal is to estimate the capacity for power generation than if it is to predict changes in agricultural income as a result of changes in the availability of water for irrigation.

3.2 Exposure Unit to be Studied

The exposure unit (i.e. the impacted object) to be assessed determines, to a large degree, the type of researchers who will conduct the assessment, the methods to be employed and the data required. Studies can focus on a single sector or activity (e.g., agriculture, forestry, energy production or water resources), several sectors in parallel but separately, or several sectors interactively.

3.3 Study Area

The selection of a study area is guided by the goals of the study and by the constraints on available data. Some options are reasonably well-defined, including governmental units, geographical units, ecological zones, and climatic zones. Other options requiring more subjective selection criteria include sensitive regions and representative units.

3.4 *Time Frame*

The selection of a time horizon for study is also influenced by the goals of the assessment. For example, in studies of industrial impacts the planning horizons may be 5–10 years, while investigations of tree growth may require a 100-year perspective. However, as the time horizon increases, the ability to accurately project future trends declines rapidly. Most climate projections and scenarios rely on general circulation models (GCMs) which are subject to uncertainties. Projections of socio-economic factors such as population, economic development and technological change need to be made for periods exceeding 15–20 years.

3.5 *Data Needs*

The availability of data is probably the major limitation in most impact and adaptation assessment studies. The collection of new data is an important element of some studies, particularly for monitoring purposes regarding expected climate changes, but most rely on existing sources. Thus, before embarking on a detailed assessment, it is important to identify the main features of the data requirements, namely the variables for which data are needed, the time period, spatial coverage and resolution of the required data, the sources and format of the data and their quantity and quality, and the data availability, cost and delivery time.

3.6 *Wider context of the work*

In order to assist policy makers in evaluating the wider significance of an assessment, it is important to place it in the context of similar studies and of the political, economic and social system of the region.

4. Step Two–Selection of the Method

A variety of analytical methods can be adopted ranging from qualitative descriptive studies, through more diagnostic and semi-quantitative assessments, to quantitative and prognostic analyses. Any single impact assessment may contain elements of one or more of these types. Four general methods can be identified: experimentation, impact projections, empirical analogue studies and expert judgement.

4.1 *Experimentation*

In the physical sciences, a standard method of testing hypotheses or of evaluating processes of cause and effect is through direct experimentation. In the context of climate impact and adaptation assessment, however, experimentation has only a limited application. Clearly it is not possible physically to simulate large-scale systems such as the global climate. Only where the scale of impact is manageable, the exposure unit measurable, and the environment controllable, can experiments be usefully conducted (for example, gas enrichment experiments with plants).

4.2 *Impact Projections*

One of the major goals of climate impact assessment, especially concerning aspects of future climatic change, is the prediction of future impacts. A main focus of much recent work has been on impact projections, using an array of mathematical models to extrapolate into the future. First-order effects of climate are usually assessed using biophysical models, second- and higher-order effects using a range of biophysical, economic and qualitative models. Finally, attempts have also been made at comprehensive assessments using integrated systems models.

4.2.1 *Biophysical Models*

Biophysical models may be used to evaluate the physical interactions between climate and an exposure unit. There are two main types: empirical-statistical models and process-based models. Empirical-statistical models are based on the statistical relationships between climate and the exposure unit. Process-based models make use of established physical laws and theories to express the dynamics of the interactions between climate and an exposure unit.

4.2.2 *Economic Models*

Economic models of several types can be employed to evaluate the implications of first-order impacts for local and regional economies. The main types of models are firm-level (which depict a single firm or enterprise), sectoral (which simulate behaviour within a specific economic sector) and macro-economic (which simulate entire economies).

4.2.3 *Integrated Systems Models*

Integrated systems models represent an attempt to combine elements of the modelling approaches described above into a comprehensive model of a given regionally- or sectorally- bounded system. Two main approaches to integration can be identified: the aggregate cost-benefit approach, which is more economically orientated, and the regionalized process-based approach, which focuses more on biophysical effects.

4.3 *Empirical Analogue Studies*

Observations of the interactions of climate and society in a region can be of value in anticipating future impacts. The most common method employed involves the transfer of information from a different time or place to an area of interest to serve as an analogy. Four types of analogy can be identified: historical event analogies, historical trend analogies, regional analogies of present climate and regional analogies of future climate.

4.4 *Expert Judgement*

A useful method of obtaining a rapid assessment of the state of knowledge concerning the effects of climate on given exposure units is to solicit the judgement and opinions of experts in the field. Literature is reviewed, comparable studies identified, and experience and judgement used in applying all available information to the current problem.

5. Step Three–Testing the Method

Following the selection of the assessment methods, it is important that these are tested in preparation for the main evaluation tasks. Three types of activity may be useful in evaluating the methods: feasibility studies, data acquisition and compilation, and model testing.

5.1 *Feasibility Studies*

These usually focus on a subset of the study region or sector to be assessed. Such case studies can provide information on the effectiveness of alternative approaches, of models, of data acquisition and monitoring, and of research collaboration.

5.2 *Data Acquisition and Compilation*

Data must be acquired both to describe the temporal and spatial patterns of climate change and their impacts and to develop, test and calibrate predictive models. Data collection may rely on existing information obtained and compiled from different sources, or require the acquisition of primary data, through survey methods, direct measurement or monitoring.

5.3 Model Testing

The testing of predictive models is, arguably, the most critical stage of an impact assessment. Most studies rely almost exclusively on the use of models to estimate future impacts. Thus, it is crucial for the credibility of the research that model performance is tested rigorously. Standard procedures should be used to evaluate models, but these may need to be modified to accommodate climate change. Two main procedures are recommended: validation and sensitivity analysis. Validation involves the comparison of model predictions with real world observations to test model performance. Sensitivity analysis evaluates the effects on model performance of altering its structure, parameter values, or values of its input variables.

6. Step Four–Selection of the Scenarios

Impacts are estimated as the differences between two states: environmental and socio-economic conditions expected to exist over the period of analysis in the absence of climate change and those expected to exist with climate change.

6.1 Establishing the Present Situation

In order to provide reference points with which to compare future projections, three types of 'baseline' conditions need to be specified: the climatological, environmental and socio-economic baselines.

6.1.1 Climatological baseline

The climatological baseline is usually selected according to the following criteria:

- Representativeness of the present-day or recent average climate in the study region.
- Of sufficient duration to encompass a range of climatic variations.
- Covering a period for which data on all climatological variables are abundant, adequately distributed and readily available.
- Including data of sufficient quality for use in evaluating impacts.

It is recommended that the current standard WMO normal period (1961–90) be adopted in assessments where appropriate.

6.1.2 Environmental baseline

The environmental baseline refers to the present state of other, non-climatic environmental factors, that affect the exposure unit. Examples include: groundwater levels, soil pH, extent of wetlands, etc.

6.1.3 Socio-economic baseline

The socio-economic baseline describes the present state of all the non-environmental factors that influence the exposure unit. The factors may be geographical (e.g., land use), technological (e.g., pollution control), managerial (e.g., forest rotation), legislative (e.g., air quality standards), economic (e.g., commodity prices), social (e.g., population), or political (e.g., land tenure). All of these are liable to change in the future, so it is important that baseline conditions of the most relevant factors are noted.

6.2 Time Frame of Projections

A critical consideration for conducting impact experiments is the time horizon over which estimates are to be made. Three elements influence the time horizon selected: the limits of predictability, the compatibility of projections and whether the assessment is continuous or considers discrete points in time.

6.2.1 Limits of predictability

The time horizon selected depends primarily on the goals of the assessment. However, there are obvious limits on the ability to project into the future. Climate projections, since they are a key element of climate impact studies, define one possible outer limit on impact projections. GCM estimates seldom extend beyond about 100 years, due to the uncertainties attached to such long-term projections and to constraints on computational resources. This fixes an outer horizon at about 2100. In many economic assessments on the other hand, projections may not be reliable for more than a few years ahead.

6.2.2 Compatibility of projections

It is important to ensure that future climate, environment and socio-economic projections are mutually consistent over space and time. It is important to be clear about (i) the relative timing of increases in greenhouse gas concentrations and climate change and (ii) the relative timing of a 2 x CO_2 compared to a 2 x CO_2 'equivalent' atmosphere[1]. With regard to the former, there is a lag time of several decades in the response of the climate system to increases in greenhouse gas concentrations. With regard to the latter, a 2 x CO_2 'equivalent' atmosphere occurs earlier than a 2 x CO_2 atmosphere because gases such as CH_4, N_2O, and troposphere O_3 also contribute to radiative forcing.

6.2.3 Point in time or continuous assessment

A distinction can be drawn between considering impacts at discrete points in time in the future and examining continuous or time-dependent impacts. The former are characteristic of many climate impact assessments based on doubled-CO_2 equivalent scenarios. In contrast, transient climatic scenarios allow time-dependent phenomena and dynamic feedback mechanisms to be examined and socio-economic adjustments to be considered.

6.3 Projecting Environmental Trends in the Absence of Climate Change

The development of a baseline describing conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. It is highly probable that future changes in other environmental factors will occur even in the absence of climate change, which may be of importance for an exposure unit. Examples, as appropriate, include changes in land-use, changes in groundwater level and changes in air, water and soil pollution. Most factors are related to, and projections should be consistent with trends in socio-economic factors. Greenhouse gas concentrations may also change, but these would usually be linked to climate (which is assumed unchanged here).

6.4 Projecting Socio-Economic Trends in the Absence of Climate Change

Global climate change is projected to occur over time periods that are relatively long in socio-economic terms. Over that period it is certain that the economy and society will change, even in the absence of climate change. Official projections exist

---

[1] A 2 x CO_2 'equivalent' atmosphere is one where the radiative forcing due to changes in all greenhouse gases (CO_2, CH_4, N_2O, O_3, halocarbons) is the same as that of an atmosphere where the concentration of CO_2 has doubled with the concentration of other greenhouse gases remaining unchanged.

for some of these changes, as they are required for planning purposes. These vary in their time horizon from several years (e.g., economic growth, unemployment), through decades (e.g., urbanisation, industrial development, agricultural production), to a century or longer (e.g., population).

6.5 Projecting Future Climate

In order to conduct experiments to assess the impacts of climate change, it is first necessary to obtain a quantitative representation of the changes in climate themselves. No method yet exists of providing confident predictions of future climate. Instead, it is customary to specify a number of plausible future climates. These are referred to as 'climatic scenarios', and they are selected to provide climatic data that are spatially compatible, mutually consistent, freely available or easily derivable, and suitable as inputs to impact models.

There are three basic types of scenario of future climate: synthetic scenarios, analogue scenarios and scenarios from general circulation models.

6.5.1 Synthetic scenarios

A simple method of specifying a future climate is to adjust the baseline climate in a systematic, though essentially arbitrary manner. Adjustments might include, for example, changes in mean annual temperature of ± 1, 2, 3 °C ..., etc. or changes in annual precipitation of ± 5, 10, 15% ... etc. relative to the baseline climate. Adjustments can be made independently or in combination. In this way information can be obtained on:

- *Thresholds or discontinuities* of response that might occur under a given magnitude or rate of change. These may represent levels of change above which the nature of the response alters (e.g., warming may promote plant growth, but very high temperatures cause heat stress).
- *Tolerable climate change,* which refers to the magnitude or rate of climate change that a modelled system can tolerate without major disruptive effects (sometimes termed the 'critical load'). This type of measure is potentially of value for policy, as it can assist in defining specific goals or targets for limiting future climate change.

One of the main drawbacks of the approach is that adjustments to combinations of variables may not to be physically plausible or internally consistent.

6.5.2 Analogue scenarios

Analogue scenarios are constructed by identifying recorded climatic regimes which may serve as analogues for the future climate of a given region. These records can be obtained either from the past (temporal analogues), or from another region at the present (spatial analogues).

Temporal analogues are of two types: those based on past instrumental observations (usually within the last century) and those based on proxy data, using palaeoclimatic indicators such as plant or animal remains and sedimentary deposits (from the more distant past geological records). The main problem with this technique concerns the physical mechanism and boundary conditions that would almost certainly be different between a warmer climate in the past and a future greenhouse-gas induced warming.

Spatial Analogues require the identification of regions today having a climate analogous to the study region in the future. This approach is severely restricted, however, by frequent lack of correspondence between other non-climatic features of two regions that may be important for a given impact sector (e.g. daylength, terrain, soils or economic development.

6.5.3 Scenarios from general circulation models

Three dimensional numerical models of the global climate system (including atmosphere, oceans, biosphere and cryosphere) are the only credible tool currently available for simulating the physical processes that determine global climate. Although simpler models have also been used to simulate the radiative effects of increasing greenhouse gas concentrations, only general circulation models (GCMs), possibly in conjunction with nested regional models, offer the possibility to provide estimates of regional climate change, which are required in impact analysis.

GCMs produce estimates of climatic variables for a regular network of grid points across the globe. Results from about 20 GCMs have been reported to date (e.g., see IPCC, 1990 and 1992). However, these estimates are highly uncertain because of some important weaknesses of GCMs. These include: 1) poor model representation of cloud processes, 2) a coarse spatial resolution (at best employing grid cells of some 250 km horizontal dimension), 3) generalized topography, disregarding some locally important features and 4) a simplified representation of land-atmosphere and ocean-atmosphere interactions. As a result, GCMs are currently unable accurately to reproduce even the seasonal pattern of present-day climate at a regional scale. Thus, GCM outputs represent, at best, broad-scale sets of possible future climatic conditions and should not be regarded as predictions.

GCMs have been used to conduct two types of experiment for estimating future climate: equilibrium-response and transient-forcing experiments. The majority of experiments have been conducted to evaluate the equilibrium response of the global climate to an abrupt increase (commonly, a doubling) of atmospheric concentrations of carbon dioxide. A measure that is widely used in the intercomparison of various GCMs, is the climate sensitivity parameter. This is defined as the global mean equilibrium surface air temperature change that occurs in response to an increase in radiative forcing due to a doubling of atmospheric CO_2 concentration (or equivalent increases in other greenhouse gases). Values of the parameter obtained from climate model simulations generally fall in the range 1.5-4.5°C (IPCC, 1992). Knowledge of the climate sensitivity can be useful in constructing climate change scenarios from GCMs.

Recent work has focused on fashioning more realistic experiments with GCMs, specifically, simulations of the response of climate to a transient forcing. These simulations offer several advantages over equilibrium-response experiments. First, the specifications of the atmospheric perturbation are more realistic, involving a continuous (transient) change over time in GHG concentrations. Second, the representation of the oceans is more realistic, the most recent simulations coupling atmospheric models to dynamical ocean models. Finally, transient simulations provide information on the rate as well as the magnitude of climate change, which is of considerable value for impact studies.

The following types of information are currently available from GCMs for constructing scenarios:

- Outputs from a 'control' simulation, which assumes fixed GHG concentrations, and an 'experiment' which assumes future concentrations. In the case of equilibrium-response experiments, these are values from multiple-year model simulations for the control and 2 x CO_2 (or equivalent increases in other greenhouse gases) equilibrium conditions. Transient-response experiments provide values for the control equilibrium conditions and for each year of the transient model run (e.g., 1990 to 2100).

- Values of surface or near-surface climatic variables for model grid boxes characteristically spaced at intervals of several hundred kilometres around the globe.
- Values of air temperature, precipitation (mean daily rate) and cloud cover, which are commonly supplied for use in impact studies. Data on radiation, windspeed, vapour pressure and other variables are also available from some models.
- Data averaged over a monthly time period. However, daily or hourly values of certain climatic variables, from which the monthly statistics were derived, may also be stored for a number of years within the full simulation periods.

6.6 *Projecting Environmental Trends with Climate Change*

Changes in environmental conditions not due to climatic factors should already have been incorporated in the development of the environmental trends in the absence of climate changes, the only changes in these trends to be incorporated here are those due solely to climate change. The two factors most commonly required in assessments are greenhouse gas concentrations and sea level rise. Future changes in these are still under discussion, but the estimates reported by the IPCC may serve as a useful basis for constructing scenarios (IPCC, 1990). Other factors that are directly affected by climate (such as river flows, runoff, erosion) would probably require full impact assessments of their own, although some might be incorporated as 'automatic adjustments' in projections.

6.7 *Projecting Socio-Economic Trends with Climate Change*

The changes in environmental conditions that are attributable solely to climate change serve as inputs to economic models that project the changes in socio-economic conditions due to climate change both within the study area and, where relevant and appropriate, outside it, over the study period. All other changes in socio-economic conditions over the period of analysis are attributable to non-climatic factors and should have been included in the estimation of socio-economic changes in the absence of climate change.

7. Step Five–Assessment of Impacts

Impacts are estimated as the differences over the study period between the environmental and socio-economic conditions projected to exist without climate change and those that are projected with climate change. Assessments may include:

7.1 *Qualitative description*

The success of this method rests on the experience and interpretive skills of the analyst, especially the analyst's ability to consider all factors of importance and their interrelationships. Formal methods of organizing qualitative information also exist (for example, cross impact analysis).

7.2 *Indicators of change*

These are particular regions, activities or organisms that are intrinsically sensitive to climate, and which can provide an early or accurate indication of effects due to climate change.

7.3 *Compliance to standards*

This may provide a reference or an objective against which to measure the impacts of climate change. For example, the effect on water quality could be gauged by reference to current water quality standards.

7.4 *Costs and benefits*

These should be estimated quantitatively to the extent possible and expressed in economic terms. This approach makes explicit the expectation that a change in resources and resource allocation due to climate change is likely to yield benefits as well as costs. It can also examine the costs or benefits of doing nothing to mitigate potential climate change.

7.5 *Geographical analysis*

Impacts vary over space, and this pattern of variation is of concern to policy makers operating at regional, national or international scales because these spatial differences may have consequent policy and planning implications. The geographical depiction of the effects of climate change using geographical information systems (GIS) is one method of describing impacts.

7.6 *Dealing with uncertainty*

Uncertainties pervade all levels of a climate impact assessment, including the projection of future GHG emissions, atmospheric GHG concentrations, changes in climate, their potential impacts and the evaluation of adjustments. There are two methods which attempt to account for these uncertainties: uncertainty analysis and risk analysis.

7.6.1 *Uncertainty analysis*

Uncertainty analysis comprises a set of techniques for anticipating and preparing for the impacts of uncertain future events. It is used here to describe an analysis of the range of uncertainties encountered in an assessment study.

7.6.2 *Risk analysis*

Risk analysis deals with uncertainty in terms of the risk of impact. Risk is defined as the product of the probability of an event and its effect on an exposure unit. Since it is extreme events that produce the most significant impacts, there is value in focusing on the changing probability of climatic extremes and of their impacts. Another form of risk analysis, decision analysis, is used to evaluate response strategies to climate change. It can be used to assign likelihoods to different climatic scenarios, identifying those response strategies that would provide the flexibility, at least cost, (minimizing expected annual damages), that best ameliorates the anticipated range of impact.

8 Steps Six and Seven–Assessment of Autonomous Adjustments and Evaluation of Adaptation Strategies

Impact experiments are usually conducted to evaluate the effects of climate change on an exposure unit in the absence of any responses which might modify these effects and are not already automatic or built into future projections. Two broad types of response can be identified: mitigation and adaptation.

8.1 *Mitigation and adaptation*

Mitigation or 'limitation' attempts to deal with the causes of climate change. It achieves this through actions that prevent or retard the increase of atmospheric greenhouse gas (GHG) concentrations, by limiting current and future emission from sources of GHGs and enhancing potential sinks for GHGs. The evaluation of mitigation policies is outside the scope of these Guidelines.

Adaptation is concerned with responses to both the adverse and positive effects of climate change. It refers to any adjustment, whether passive, reactive or anticipatory, that can respond to anticipated or actual consequences associated with climate change. It thus implicitly recognizes that future climate changes will occur and must be accommodated in policy.

8.2 Steps in evaluation of an adaptation strategy

A broad framework for the evaluation of adaptation strategies to cope with climate change can be identified. This comprises the following steps:

- Define the objectives.
- Specify the climatic impacts of importance.
- Identify the adaptation options.
- Examine the constraints.
- Quantify measures and formulate alternative strategies.
- Weight objectives and evaluate trade-offs.
- Recommend adaptation measures.

8.2.1 Defining the objectives

Any analysis of adaptation must be guided by some agreed overall goals and evaluation principles. Two examples of general *goals* commonly propounded are: (i) the promotion of sustainable development, and (ii) the reduction of vulnerability. These are open to various interpretations, however, so specific objectives need to be defined that complement the goals. *Objectives* are usually derived either from public involvement, from stated public preferences, by legislation, through an interpretation of goals such as those stated above, or any combination of these.

8.2.2 Specifying the climatic impacts of importance

This step involves an assessment, following the methods outlined elsewhere above, of the possible impacts of climate variability or change on the exposure unit. Where climatic events are expected that will cause damage, these need to be specified in detail so that the most appropriate adaptation options can be identified.

8.2.3 Identifying the adaptation options

The main task of assessment involves the compilation of a detailed list of possible adaptive responses that might be employed to cope with the effects of climate. The list can be compiled by field survey and by interviews with relevant experts, and should consider all practices currently or previously used, as well as possible alternative strategies that have not been used, and newly created or invented strategies.

Six types of strategy for adapting to the effects of climate have been identified:

- *Prevention of loss*, involving anticipatory actions to reduce the susceptibility of an exposure unit to the impacts of climate.
- *Tolerating loss*, where adverse impacts are accepted in the short term because they can be absorbed by the exposure unit without long term damage.
- *Spreading or sharing loss*, where actions distribute the burden of impact over a larger region or population beyond those directly affected by the climatic event.
- *Changing use or activity*, involving a switch of activity or resource use to adjust to the adverse as well as the positive consequences of climate change.
- *Changing location*, where preservation of an activity is considered more important than its location, and migration occurs to areas that are more suitable under the changed climate.
- *Restoration*, which aims to restore a system to its original condition following damage or modification due to climate.

Numerous options exist for classifying adaptive measures, but generally, regardless of the resources of interest (e.g., forestry, wetlands, agriculture, water) the prospective list may include among other management measures:

- Legal
- Financial
- Economic
- Technological
- Public education
- Research and training

8.2.4 Examining the constraints

Many of the adaptation options identified in the previous step are likely to be subject to legislation or be influenced by prevailing social norms, which may encourage, restrict or totally prohibit their use. Thus, it is important to examine closely, possibly in a separate study, what these constraints are and how they might affect the range of feasible choices available.

8.2.5 Quantifying the measures and formulating alternative strategies

The next step is to assess the performance of each adaptation measure with respect to the stated objectives. It may be possible, if appropriate data and analytical tools exist, to use simulation models to test the effectiveness of different measures under different climatic scenarios. Historical and documentary evidence, survey material or expert judgement are some other alternative sources of this information. Uncertainty analysis and risk assessment are also considered at this stage. This step is a prelude to developing strategies which maximize the level of achievement of some objectives while maintaining baseline levels of progress towards the remaining objectives.

8.2.6 Weighting objectives and evaluating trade-offs

This is the key evaluation step, where objectives must be weighted according to assigned preferences and then comparisons made between the effectiveness of different strategies in meeting these objectives. Standard impact accounting systems can be used in the evaluation. For example, a four-category system might consider: (i) national economic development; (ii) environmental quality; (iii) regional economic development; and (iv) other social effects. Selection of preferred strategies then requires the determination of trade-offs between the categories.

8.2.7 Recommending adaptation measures

The results of the evaluation process should be compiled in a form that provides policy advisers and decision makers with information on the best available adaptation strategies. This should include some indication of the assumptions and uncertainties involved in the evaluation procedure, and the rationale used (e.g., decision rules, key evaluation principles, national and international support, institutional feasibility, technical feasibility) to narrow the choices.

9 References

Carter, T.R., Parry, M.L., Nishioka, S., and Harawasa, H. (1992). *Preliminary Guidelines for Assessing Impacts of Climate Change,* Environmental Change Unit, Oxford and Center for Global Environmental Research, Tsukuba, 28 pp.

IPCC (1990). *Climate Change: The IPCC Scientific Assessment.* Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds). Report of Working Group I of the Intergovernmental Panel on Climate Change, Cambridge University Press, 364 pp.

IPCC (1992). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Houghton, J.T., Callander, B.A. and Varney, S.K. (eds). Cambridge University Press, 200 pp.

BACKGROUND AND OBJECTIVES

1

1.1 Introduction

Variations in seasonal weather patterns are as much a feature of the modern world as they were in historical times and the effects of such variability are manifest across a range of natural systems and human activities. Until recently, these variations have been assumed to represent natural fluctuations about an essentially stable average climate. However, the observation that concentrations of certain trace gases in the atmosphere have been increasing rapidly, primarily as a result of human activities, has led to the realisation that changes in atmospheric composition are capable of affecting the surface climate of the earth.

The trace gases, especially carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide, have the property of permitting the fairly free passage of short wavelength solar radiation from the sun through to the earth's surface, but absorbing the re-radiated radiation (at lower temperatures and longer wavelengths) from the earth. With the exception of CFCs, which are human-made, the natural occurrence of these gases in the atmosphere (along with water vapour, another strong absorber of terrestrial radiation) has maintained the earth's surface at an average temperature some 33°C higher than would be the case in their absence. Analogous to the effect of glass in a greenhouse, this mechanism has become known as the 'greenhouse effect', and the gases as greenhouse gases (GHGs).

Observed increases in GHG concentrations are thought to be altering the radiation balance of the earth, warming the surface and affecting the atmospheric circulation. It is this anticipated global warming of climate, the 'enhanced greenhouse effect', that has recently become the subject of great concern both locally and internationally. At a global scale, the rate and magnitude of predicted changes in climate are unprecedented in historical times, thus raising the question of their likely effects on physical processes, natural ecosystems and human activities and what, if any, measures there are for preventing or mitigating the more serious impacts.

1.2 Origins of this Report

In an attempt to clarify the issues and to identify the possible policy implications of the enhanced greenhouse effect at international level, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC was charged with assessing the scientific information relating to three aspects of the climate change issue:

- Changes in climate arising from increasing greenhouse gas concentrations in the atmosphere.
- The environmental and socio-economic consequences of climate change.
- The formulation of response strategies.

These three tasks were assigned respectively to three Working Groups: I, II and III.

The IPCC published its First Assessment Report in 1990. One component of this, The IPCC Impacts Assessment, was contributed by Working Group II (IPCC, 1990b). The IPCC agreed to continue its work within a long term framework, and entered a new phase, using the First Assessment Report as the starting point.

In August 1991, Working Group II, in its Fourth Plenary, agreed to establish an expert group to develop some guidelines for the assessment of impacts of climate change. A summary of those deliberations forms part of the Working Group II contribution to the IPCC 1992 Supplement (IPCC 1992b). The full version of the guidelines document was published in 1992 as Preliminary Guidelines for Assessing Impacts of Climate Change (Carter *et al.*, 1992).

As part of its Second Assessment Report, IPCC Working Group II agreed to expand and revise the guidelines. This report is the product of that work.

1.3 General Objectives of Climate Impact Assessment

Climate impact assessment is a sequential set of activities designed to identify, analyse and evaluate the impacts of climate variability and climate change on natural systems, human activities and human health and well-being, to estimate the uncertainties surrounding these impacts, and to examine the possible adaptive responses for reducing adverse effects or exploiting new opportunities.

Climate impact assessment has two general objectives:

- To assess climate change impacts and adaptations in a scientific manner.
- To provide a mode of analysis that will enable policy makers and decision makers to choose among a set of adaptation options and develop a suitable mixed strategy of response that combines adaptation and mitigation measures, as appropriate.

The general responsibility of science is to expand the knowledge base for the common benefit. This should be achieved by developing the research methodology for assessment, collecting information on trends in the environment and in society, developing predictive tools for evaluating impacts, forging scientific links across disciplinary, institutional and political boundaries and communicating results objectively to other scientists, decision makers and the public.

Policy makers require climate impact assessments to provide them with the necessary scientific information for policy decisions. These decisions include considering the options for mitigating climatic change and/or those for adapting to it, either by coping with, mitigating or exploiting its projected impacts. Assessments are required for different time and space scales, reflecting the time horizons and areas to which planning and decision-making apply. They could also provide a basis for negotiating global and transnational protocols for addressing climatic change issues, which lie outside the jurisdiction of individual policy makers.

Climate impact assessment must address an inherently global phenomenon affecting all nations, so it is desirable that assessments be conducted in a transparent manner, with comparable assumptions and internally consistent procedures. Comparability among assessments is of great importance in appraising the range of appropriate response actions at the international, national and regional levels. Decision makers must have confidence that, at a minimum, the basic assumptions are uniform (e.g., use of a common set of scenarios), that the various models and analytical tools are used correctly, and that the evaluation of impacts properly takes into account future impacts due to socio-economic and technological changes that would occur even in the absence of climate change.

1.4 Purpose and Scope of the Report

This report provides a review of the methods of climate impact and adaptation assessment. It is primarily oriented to the technical analyst responsible for organizing and undertaking a complex series of interrelated tasks. However, the methodology it adopts is itself designed to provide information for policy makers that is scientifically credible and useful for assisting in decision-making under uncertainty.

The term 'climate impact assessment' is used hereafter to refer to assessments both of the impacts of climatic variability and change and of possible adaptations to these. The report outlines a basic framework for the study of climate-environment-society interactions, with a particular emphasis on assessing the impacts of possible future changes in climate due to the enhanced greenhouse effect. Experience with assessing the social and economic impacts of climatic change is at present limited, while generalized methods for evaluating adaptation strategies for changing climate do not yet exist. Thus, these guidelines represent an early effort at formalizing some of these methods into workable procedures, and are amenable to refinement and development in future years.

The report does not aim to prescribe a single preferred method, but provides an analytical framework that comprises seven steps. A range of methods is identified at each step. Where possible the merits and drawbacks of different methods are discussed briefly, with some suggestions on their selection and use. Guidance is also offered on the organization of research and the communication of results.

APPROACHES TO THE ASSESSMENT OF IMPACTS AND ADAPTATIONS

2

2.1 Purpose of Assessment

There are several different reasons for conducting a climate impact assessment. First, there is a need to evaluate how climate affects human activities and well-being and natural systems along with estimates of the uncertainties surrounding these effects. The effects may be physical (e.g., on water availability), biological (e.g., on plant growth), economic (e.g., on industrial profitability), social (e.g., on regional employment) or a combination of these. Second, it may assist in evaluating sensitivities, vulnerabilities or thresholds to likely scenarios of climate change and in evaluating potential environmental standards. Third, it can identify and/or evaluate the range of possible options for adapting to and, where possible, exploiting the effects of climate change. Fourth, it can help with the assessment of the costs of impacts of climate change so that these can then be compared with the costs associated with adaptation and mitigation measures in order to assist with the formulation of balanced policy responses. Fifth, it can identify impacts of limitation or adaptation options. Sixth, it can assist in pinpointing gaps in climate research that require attention because of their importance in assessing impacts. Finally, it can alert public awareness to issues of common concern (for example, to educate people about the need for improving the efficiency of resource use) and establish a basis for political decisions.

2.2 Definitions of Some Important Terms

A number of the terms used in this report can have various connotations. To reduce the risk of misinterpretation, some simple definitions are given below. Definitions of other terms are provided elsewhere in the text.

- An **exposure unit** is the activity, group, region or resource exposed to significant climatic variations.
- An **effect** is directly produced by a process or agent (e.g., climate) acting on an exposure unit.
- An **impact** is an effect on the exposure unit having some assigned relative value or importance.
- **Assessment** refers to the scientific appraisal of effects.
- **Evaluation** is the assignment of significance or importance to effects or to alternative strategies.
- **Adaptation** is concerned with responses to the effects or impacts of climate change.
- A **scenario** is a coherent, internally consistent and plausible description of a possible future state of the world.
- **Sensitivity** (in its general sense) refers to the degree of responsiveness of an exposure unit to climate, whether beneficial or detrimental.
- **Vulnerability** is the degree to which an exposure unit is disrupted or adversely affected as a result of climatic effects. Both socio-economic and physical factors are important in determining vulnerability.

2.3 Approaches

Climate impact assessments may be conducted according to one of three general methodological approaches (Kates, 1985): impact, interaction and integrated approaches.

2.3.1 Impact approach

The simplest approach follows a straightforward 'cause and effect' pathway whereby a climatic event acting on an exposure unit has an impact (Figure 1). In layperson's terms it can be thought of as an 'If-Then-What' approach: if the climate were to alter like this then what would be its impacts? In adopting the approach it is assumed that the effect of other non-climatic factors on the exposure unit can be held constant. Where this assumption is justified, (for example, in biological studies of pristine environments not subject to any non-climatic changes), the approach can be informative. However, the narrow focus on the effects of climate alone on human activities is also a major weakness of the approach. Another problem is that the whole assessment is reliant on the initial choice of a climatic event, which is not always selected according to criteria that are relevant to the climate-sensitivity of the exposure unit. Finally, a major drawback of this approach is an inability to assign a likelihood to the assumed changes in climatic factors.

The impact approach is usually adopted for studies of individual activities or organisms in order to establish 'dose-response' functions, but it is also applied to sectoral studies where impacts may propagate through a hierarchy of levels. Thus, direct impacts represent the direct biophysical effects of climate on organisms or activities (e.g., on plants, animals, heating demand, water). The direct effects lead, in turn, to indirect impacts (e.g., changes in grass growth leading to changes in livestock productivity). The chain of impacts may then extend to higher-order economic and social impacts (e.g., changes in farm income, changes in national agricultural production, changes in farm employment).

In order to follow this hierarchical approach assumptions are required at each level of analysis. Inevitably, accompanying these assumptions are uncertainties, which may themselves propagate through the system. Given the large uncertainties, the exclusion of other influencing factors and the lack of consideration of possible feedback effects, it is rare that such a formal methodology can be followed successfully in impact assessment. More commonly an integrated or partially integrated approach must be adopted (see 2.3.3).

Figure 1. Schema of the impact approach (after Kates, 1985)

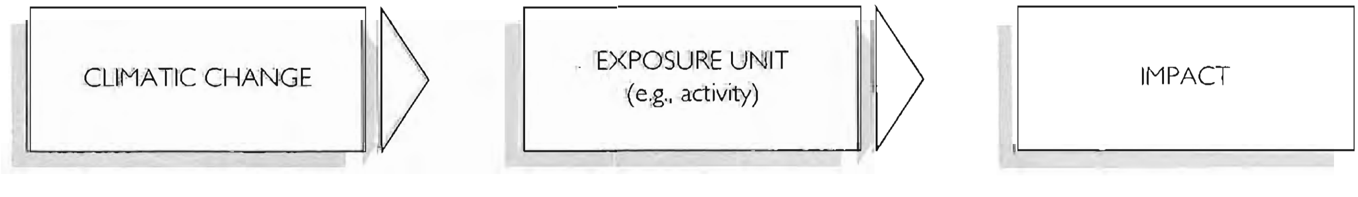
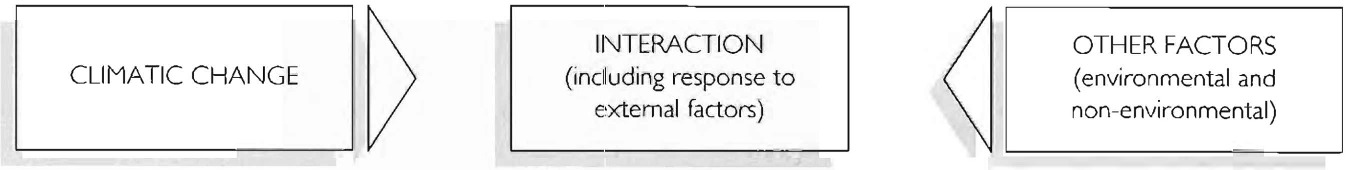


Figure 2. Schema of the interaction approach (after Parry and Carter, 1988)



2.3.2 Interaction approach

The interaction approach recognizes that climate is only one of a set of factors that influence or are influenced by the exposure unit (Figure 2). For instance, the effects of an equivalent shortfall of rainfall may be felt quite differently in different parts of the world, some experiencing hunger or malnutrition due to underlying factors such as poverty, war or social marginalization, others profiting from increased food prices at a time of general shortage. Only if these other factors are fully accounted for will an accurate evaluation of the effects be achieved.

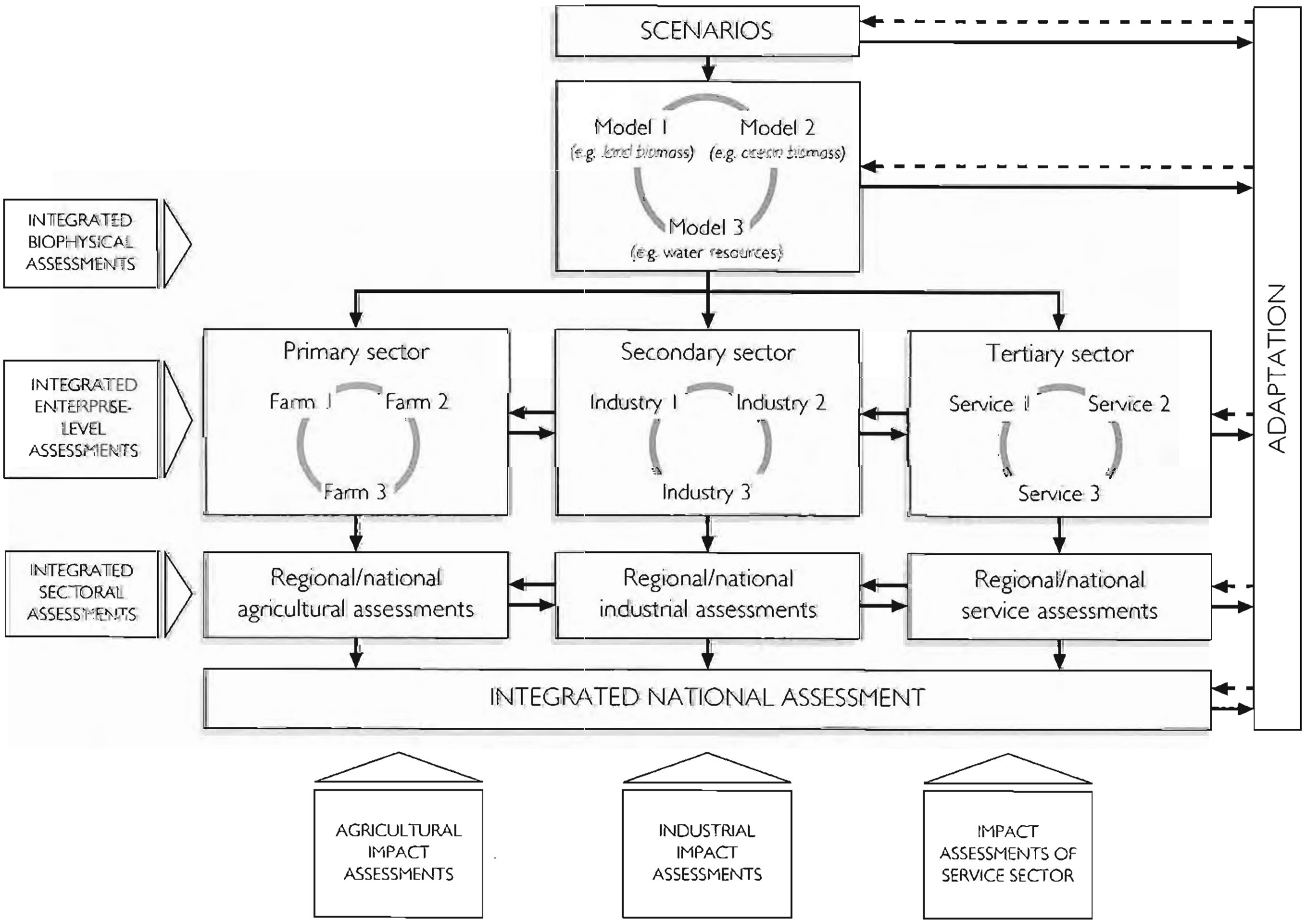
The interaction approach also allows for feedbacks that may regulate or enhance an effect. To illustrate a simple feedback at a global level: a change in climate may lead to a shift in natural vegetation zones. However, this shift in zones may itself influence the climate through changes in fluxes of gases to and from the atmosphere, and through changes in surface reflectivity.

A study method that fits closely into the structure of the interaction approach is the adjoint method (Parry and Carter, 1988; Parry, 1990). In simple terms this can be thought of as a 'What-Then-If' approach: What points of a system are sensitive to what types of climatic change and then what might the impacts be if those changes in climate were to occur? It differs from the impact approach, described above, in that the climate event is selected according to the climate-sensitivity of the exposure unit.

2.3.3 Integrated approach

An integrated approach is the most comprehensive treatment of the interactions of climate and society. It seeks to encompass the hierarchies of interactions that occur within sectors, interactions between sectors, and feedbacks, including adaptation, which serves to modify impacts and scenarios alike (Figure 3). In practice, since the knowledge base is insufficient to envisage conducting fully integrated assessments, only partially integrated assessments are feasible. These can be achieved by linking together parallel studies for different sectors in the same region (usually a nation or large administrative unit). This approach is being implemented in an

Figure 3. An integrated approach to climate impact and adaptation assessment (Modified from Parry and Carter, 1988)



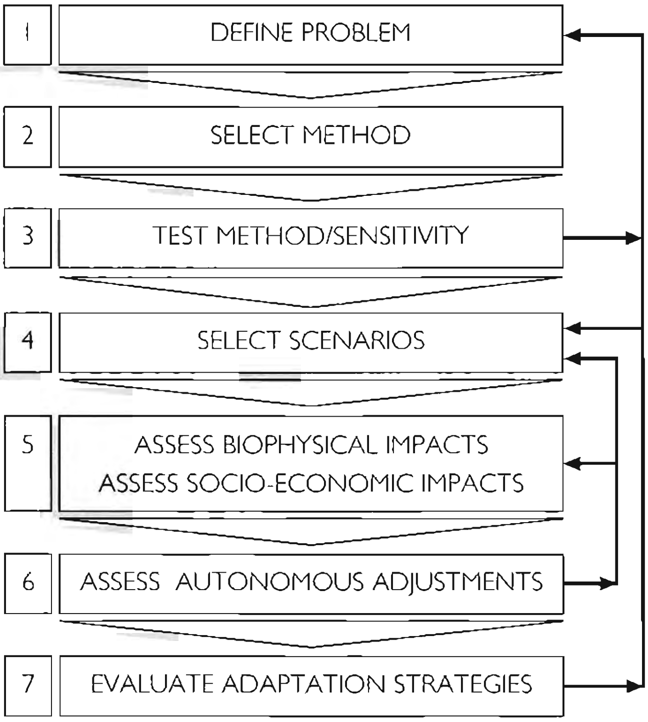
Integrated Regional Impact Assessment (IRIA) in the MacKenzie Basin, Canada (Cohen, 1993; Yin and Cohen, 1994), perhaps the most ambitious regional level assessment to have been undertaken to date. A similar approach was also adopted in the MINK study on the US Corn Belt (Rosenberg, 1993—see Box 13), at national scale in Egypt (Strzepek *et al.*, in press) and, though less detailed, in south-east Asia (Parry *et al.*, 1992). Other approaches focus on different sectors in a wide variety of regions to examine impacts on, for example, food supply or water resources (see, for example, Strzepek and Smith, in press).

A major shortcoming of most climate impact assessments to date has been their lack of an in-depth treatment of adaptation, due in part to its complexity and in part to the lack of a suitable methodological framework. While it is represented in a simple form in Figure 3, various aspects of adaptation are implied, including adjustments that are endogenous to a system, and thus cannot be separated from the assessment of impacts, as well as exogenous adaptation, which is imposed externally on a system.

2.4 A Seven Step Framework for Assessment

A general framework for conducting a climate impact assessment is shown in Figure 4. It consists of seven main steps of analysis. The first five steps can be regarded as common to most assessments. Steps 6 and 7 are included in fewer studies. The steps are consecutive (open arrows in Figure 4), but the framework also allows for the redefinition and repetition of some steps (thin bold arrows). At each step, a range of study methods is available. These are described and evaluated in the following sections. For reasons of brevity, however, only the essence of each method is introduced, along with references to sources of further information.

Figure 4. Seven steps of climate impact assessmment



Each of the seven general steps includes more detailed procedures, sometimes themselves arranged in a comparable multi-step framework. For example, Section 8.3 describes seven equivalent steps in evaluating adaptation strategies. Those steps fit directly into Step 7 of the overall assessment framework, but they also parallel all the general assessment steps, because the information required for evaluating adaptation is derived from, and depends on, many of the other steps, such as sensitivity analysis, impact assessment and reliance on specific models.

STEP 1: DEFINITION OF THE PROBLEM

3

A necessary first step in undertaking a climate impact assessment is to define precisely the nature and scope of the problem to be investigated. This usually involves identifying the goals of the assessment, the exposure unit of interest, the spatial and temporal scope of the study, the data needs, and the wider context of the work.

3.1 Goals of the Assessment

Some general reasons for conducting an assessment were outlined in Section 2.1. Once the general objectives are defined, the specific goals of the study may be addressed, as these will affect the conduct of the investigation. To illustrate, an assessment of the future hydrological impacts of climatic change in a river catchment has quite different requirements for data and expertise if the goal is to estimate the capacity for power generation, than if it is to predict changes in agricultural income as a result of changes in the availability of water for irrigation.

3.2 Exposure Unit to be Studied

The exposure unit to be assessed is likely to determine, to a large degree, the type of researchers who will conduct the assessment, the methods that can be employed and the data required. The choice of exposure unit should reflect the goal of the assessment and the region, group or activity at risk. Studies can focus on a single sector of activity (e.g., agriculture, forestry, energy production or water resources), several sectors in parallel but separately, or several sectors interactively. Alternatively, the exposure unit may be non-sectoral in character (e.g., an ecosystem, a distinct regional unit such as an island, or a specific population cohort).

3.3 Study Area

The selection of a study area is likely to be guided by the goals of the study and by the constraints on available data. Options include:

- Administrative units (e.g., district, town, province, nation), for which most economic and social data are available and at which level most policy decisions are made.
- Geographical units (e.g., river catchment, plain, mountain range, lake region), which are useful integrating units for considering multi-sectoral impacts of climate change.
- Ecological zones (e.g., moorland, savannah, forest, wetland), which are often selected for considering issues of conservation or land resource evaluation.
- Climatic zones (e.g., desert, monsoon zone, rain shadow area), which are sometimes selected because of the unique features and activities associated with the climatic regime.
- Sensitive regions (e.g., ecotones, tree lines, coastal zones, ecological niches, marginal communities), where changes in climate are likely to be felt first and with the greatest effect.
- Representative units, which may be chosen according to any of the above criteria, but in addition are selected to be representative of that regional type and thus amenable to generalization. For instance, a single river catchment may serve as a useful integrating unit for considering impacts of climate on water resources, agriculture, forestry, fisheries, recreation, natural vegetation, soil erosion and hydroelectric power generation. Information from this type of study may then be applicable to other similar catchments in a region.

3.4 Time Frame

The selection of a time horizon for study is also governed, in the main, by the goals of the assessment. For example, in studies of industrial impacts the planning horizons may be 5–10 years, investigations of tree growth may require a 100–year perspective, while considerations of nuclear waste disposal must accommodate time spans of well over 1000 years. However, as the time horizon increases, so the ability to project future trends declines rapidly. Many climate projections rely on general circulation models, and are subject to uncertainties over all projection periods. The only prediction horizon of proven reliability is that provided by weather forecast models extending for days or, at most, a few weeks into the future (Lorenz, 1968). In general, few accurate projections of rates of change in socio-economic factors such as population, economic development and technological change can be made for periods beyond 15–20 years into the future.

3.5 Data Needs

The availability of data is a limitation in many impact studies. The collection of new data is an important element of some studies, but most rely on existing sources (an important source of bias in some studies). Thus, before embarking on a detailed assessment, it is important to identify the main features of the data requirements, namely:

- Types of data required.
- Time period, spatial coverage and resolution.
- Sources and format of the data.
- Quantity and quality of the data.
- Availability, cost and delivery time of the data.
- Licensing and copyright restrictions on data distribution.

There is of course, a close interdependency between the identification of data needs and the selection of methods of analysis. In practice the two procedures operate simultaneously, but they are treated consecutively here for ease of presentation.

3.6 Wider Context of the Work

Although the goals of the research may be quite specific, it is still important to place the study in context, with respect to:

- Similar or parallel studies that have been completed or are in progress.
- The political, economic and social system of the study region.
- Other social, economic and environmental changes occurring in the study region.
- Issues of scale, where studies conducted at one scale should recognize and take advantage of related information or studies at a larger scale.
- Multiple effects of changes in other sectors, in markets or in population.
- The study's policy context.

Consideration of these aspects may assist policy makers in evaluating the wider significance of individual studies.

STEP 2: SELECTION OF THE METHOD

4

A variety of analytical methods can be adopted in climate impact assessment. These range from qualitative descriptive studies, through more diagnostic and semi-quantitative assessments to quantitative and prognostic analyses. Any single impact assessment may contain elements of one or more of these types, but whatever methods are selected, these should be clearly set out and explained. Transparency in the description of the methods, models and assumptions is essential both to evaluate the credibility of the different approaches and to compare between different assessments. Four general methods can be identified: experimentation, impact projections, empirical analogue studies and expert judgement.

4.1 Experimentation

In the physical sciences, a standard method of testing hypotheses or of evaluating processes of cause and effect is through 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 plant species under controlled conditions of climate and atmospheric composition (e.g., see Strain and Cure, 1985; van de Geijn *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 which 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), crop pests and diseases (often in conjunction with host plants), trees (usually saplings, but also some mature species), and natural vegetation species and communities (where aspects of competition can be studied). Controlled experiments have also been reported on freshwater ecosystems (to study effects on water quality and the food chain) and soils (examining decomposition rates, nutrient leaching and microbial activity).

There are other sectors in which experimentation may yield useful information for assessing impacts of climatic change. For instance, building materials and design are continually being refined and tested to account for environmental influences and for energy-saving. Information from these tests may provide clues as to the performance of such materials, assuming they were widely employed in the future, under altered climatic conditions.

The information obtained from experiments, while useful in its own right, is also invaluable for calibrating models which are to be used in projecting impacts of climatic change (see below).

4.2 Impact Projections

One of the major goals of climate impact assessment, especially concerning aspects of future climatic change, is the prediction of future impacts. A growing number of model projections have become available on how global climate may change in the future as a result of increases in GHG concentrations (e.g., see IPCC, 1990a; 1992a). These results, along with scientific and public concerns about their possible implications, have mobilized policy makers to demand qualitative assessments of the likely impacts within the time horizons and regional constraints of their jurisdiction.

Thus, a main focus of much recent work has been on impact projections, using an array of mathematical models to extrapolate into the future. In order to distinguish them from 'climate models', which are used to project future climate, the term 'impact model' has now received wide currency.

At the start of any climate impact assessment, researchers are commonly confronted with an important choice with regard to impact models—either to adopt existing models or to develop new models. Bearing in mind that most assessments have severe time and resource constraints, the most sensible strategy for model selection is first, to conduct a rigorous survey of existing models that are applicable to the issue being investigated. This exercise is best conducted by experienced modellers, but some information for non-specialists can also be provided by international organizations, who can advise on suitable models or even supply them directly. Examples of these can be found in the following sections.

The second important step is to examine a model's data needs. Without suitable input data, even the most perfect of models cannot be used. If there are suitable data, the models can be tested according to the procedures described in Section 5.3. If input data are not available, or inadequate, then for some applications it may be necessary or desirable to collect the appropriate information (cf. Section 5.2).

Finally, if suitable models cannot be identified, then it may become necessary to develop new models. In some regions with appropriate data it may be possible, in quite a short time, to construct simple statistically-based models which are robust enough to be applicable to climate change problems. This has often been the practice in many less developed countries, where access to more sophisticated models is sometimes limited, and the development of such models may be constrained by poor data quality and lack of modelling expertise. Even in developed countries, however, in the context of an impact assessment study, construction of these models from first principles is likely to be too time and resource intensive and is rarely undertaken. It is more common for model development to involve refinements of existing models which take account of altered conditions under a changing climate. For example, many crop growth models developed for yield prediction under present-day conditions, have been modified for climate impact studies to account for the effects of increasing CO_2 on carbon uptake and water use (assumed constant in conventional applications).

Some of the specific procedures for projecting future impacts are described in Section 6. Here, the major classes of predictive models and approaches are described. It is convenient, in categorizing impact models, to follow the hierarchical structure of interactions that was introduced in Section 2.3.1. Direct effects of climate are usually assessed using biophysical models, while indirect or secondary effects are generally assessed using a range of biophysical, economic and qualitative models. Finally, attempts have also been made at comprehensive assessments using integrated systems models.

4.2.1 Biophysical models

Biophysical models are used to evaluate the physical interactions between climate and an exposure unit. There are two main types: empirical-statistical models and process-based models. The use of these in evaluating future impacts is probably best documented for the agricultural sector (e.g., see WMO, 1985), the hydrological aspects of water resources (e.g., WMO, 1988) and ecosystems (e.g., Bonan, 1993), but the principles can readily be extended to other sectors.

Empirical-statistical models are based on the statistical relationships between climate and the exposure unit. They range from simple indices of suitability or potential (e.g., identifying the temperature thresholds defining the ice-free period on important shipping routes), through univariate regression models used for prediction (e.g., using air temperature to predict energy demand) to complex multivariate models, which 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 fertilizer application).

Empirical-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 criticized 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. Empirical-statistical models are often simple to apply, and less demanding of input data than process-based models (see below).

Process-based models make use of established physical laws and theories to express the interactions between climate and an exposure unit. In this sense, they attempt to represent processes that can be applied universally to similar systems in different circumstances. For example, there are well-established methods of modelling leaf photosynthesis which are applicable to a range of plants and environments. Usually some kind of model calibration is required to account for features of the local environment that are not modelled explicitly, and this is generally based on empirical data. Nevertheless, there are often firmer grounds for conducting predictive studies with these process-based models than with empirical-statistical models. The major problem with most process-based models is that they generally have demanding requirements for input data, both for model testing and for simulating future impacts. This tends to restrict the use of such models to only a few points in geographical space where the relevant data are available. In addition, theoretically-based models are seldom able to predict system responses successfully without considerable efforts to calibrate them for actual conditions. Thus, for example, crop yields may be overestimated by process-based yield models because the models fail to account for all of the limitations on crops in the field at farm level.

During the past twenty years, or so, there has been an enormous proliferation of process-based models, which have developed to describe many different kinds of system. Many of these have been applied in climate impact assessment, but the documentation of these models is often poor or difficult to obtain, computer code may not be readily available, and the selection of appropriate models for a particular problem or region can be very difficult. Recently, efforts have been made to organize model intercomparison exercises, (e.g., for computation of evapotranspiration; Smith, 1992), to coordinate the standardization of model structure (e.g., within the International Benchmark Sites Network for Agrotechnology Transfer, IBSNAT), and to make generic or alternative models available to users in a single package (e.g., CROPWAT, a computer program for irrigation planning and management available from FAO along with a climate data base of 3261 stations in 144 countries; FAO, 1992a; and the agricultural decision support system for a range of crops supplied by IBSNAT; IBSNAT, 1989).

New techniques are also being developed to simplify the results of process-based simulation models using statistical techniques (Buck *et al.*, in press). The idea of this approach is to fit statistical response surfaces to numerous outputs derived from simulation models. Applied with care, this method can provide a rapid means of exploring the sensitivity of the more detailed simulation models without having to run the models themselves.

4.2.2 Economic models

Economic models of many kinds can be employed to evaluate the implications of climate change for local and regional economies. To simplify their classification, it is useful to distinguish between three types of economic model, according to the approach used to construct them, and three scales of economic activity that different model types can represent.

4.2.2.1 Types of economic model

Three broad classes of economic model can be identified: programming, econometric and input-output models.

Programming models have an objective function and constraints. The objective function represents the behaviour of the producer (e.g., profit maximizing or cost minimizing). If the objective function and constraints are linear, the model is known as a Linear Programming (LP) model. If the objective function is quadratic and the constraints linear, the model is a Quadratic Programming (QP) model. If either the objective function or the constraints are nonlinear, the resulting model is a Nonlinear Programming model. However, LP models can also incorporate nonlinear relations (for example, technical relations) in a piecewise manner. Programming models can also be of the partial equilibrium type, i.e., they determine production (supply) and demand simultaneously. They are usually calibrated to a set of data in a given year. In this sense they are empirically based. Programming models can be static or dynamic. An example of the application of LP models to assessing impacts of climate change is the study by Adams *et al.* (1989) on U.S. agriculture.

Econometric models consist of supply and/or demand functions which use as independent variables prices and a number of 'technical' variables, and usually include time to represent those parts of the economy that undergo steady change. Like programming models, these models also have their parameters numerically quantified, but econometric models differ substantially in their structure from programming models. Conventionally, econometric models do not state any decision rules. However, in the last decade a new set of econometrically specified models has emerged: the so-called dual models. These assume decision rules such as profit maximizing or cost minimizing of producers and utility maximizing or expenditure minimizing of the consumer. In these cases, data fitting is usually done by statistical methods (regression analysis) or a simple calibration procedure is used. The bulk of econometric models are static (including those that embed a time trend), whilst among the few examples of dynamic models are the so-called adaptive models.

Input-output (IO) models are developed to study the interdependence of production activities. The outputs of some activities become the inputs for others, and vice versa (Lovell and Smith, 1985). These input-output relationships are generally assumed to be constant, which is a weakness of the approach, since re-organization of production or feedback effects (such as between demand and prices) may change the relationships between activities. This is of particular concern when projecting production activities beyond a few years into the future. More recently, dynamic versions of IO models have been developed, but these still lack many of the dynamic aspects of economic behaviour. Nonetheless, the approach is relatively simple to apply and the data inputs are not demanding. Moreover, these models are already in common usage as planning tools. Examples of their application in climate impact assessment include studies of possible impacts of climate change on the economy of Saskatchewan (Williams *et al.*, 1988—see Box 12 on page 37) and on economic activity in the states of Missouri, Iowa, Nebraska and Kansas (the MINK study) in the USA (Rosenberg, 1993—see Box 13, on page 38).

4.2.2.2 *Scales of model application*

Three scales of economic activity are commonly represented by economic models: firm-level, sector-level and economy-wide.

Firm-level models depict a single firm or enterprise (i.e., a decision unit for production). These are often programming models but are rarely of the econometric type, due to constraints on available information about firms. Typical examples include farm level simulation models, which attempt to mirror the decision processes facing farmers who must choose between different methods of production and allocate adequate resources of cash, machines, buildings and labour to maximize returns (e.g., Williams *et al.*, 1988). Such models may also require data on productivity, and it is this which constitutes the entry point for potential linkages with the outputs from biophysical models. Model outputs include farm-level estimates, for example, of income, cash flow and resource costs for obtaining selected production plans. These models are sometimes referred to as microsimulation models.

Sector-level models encompass an entire sector or industry. They can be programming models or of the econometric type, to depict production. For climate change studies, these models should be of a partial equilibrium type, to include demand so that price changes are generated as well. It is quite common for such models to consider a firm as representative of the average of the entire sector under study. Such models are then similar to firm-level models, but require aggregation and assumptions about average technical relations. Some sector-level models are also of the IO type, and have supply and demand included. These models usually have no or very few links to developments in the rest of the economy.

Economy-wide models, sometimes referred to as macroeconomic models (which are actually a large subset of this class), link changes in one sector to changes in the broader economy, dealing with all economic activities of a spatial entity like a country, a region within a country or a group of countries. Typical economy-wide models for climate impact assessment include all types of general equilibrium (GE) models and IO models. Most GE models belong to the group of dual econometric models, but there are also programming models among them. The distinctive feature of GE models is that they determine endogenously (equilibrium) prices which clear the market in the same way as partial equilibrium models. However, unlike partial equilibrium models, GE models encompass all economic activities of the region. The static form of the GE model is the computable general equilibrium (CGE) model. Some of the studies of climate impacts conducted to date with CGE models have used as inputs the results of studies of sectoral impacts. For example, the results of an agricultural impacts study by Adams *et al.* (1989), along with results from studies on coasts (related to sea level rise) and electricity demand, were used as inputs to a general equilibrium model of the US economy to assess the wider implications in all sectors of the economy (Scheraga *et al.*, 1993). There are also dynamic GE models, which can treat the evolution of an economy through time, ensuring at each time step that the markets are in equilibrium. For example, a (recursively) dynamic GE model of global food trade, the Basic Linked System, has been used to study the potential effects of climatic change on global food supply, using information on potential yield changes of major crops taken from crop modelling studies conducted at 112 sites in 18 countries (Rosenzweig and Parry, 1994).

Economic models are the only credible tools for deriving meaningful estimates of likely effects of climate change on measurable economic quantities such as income, GDP, employment and savings. However, great care is required in interpreting the results. Specifically, caution must be exercised in using any of the measures of economic activity as indicators of social welfare. Potentially more serious, however, is the failure of most models (exceptions include the models of Cline (1992) and Fankhauser (1993)) to account for non-market effects of climate change. For example, many inputs to production are directly affected by climate change (e.g., land and water) but are not contained in most macroeconomic models. Economic models are also widely used to consider the relative cost-effectiveness of mitigation and adaptation options that are proposed to ameliorate the adverse impacts of climate change, along with associated economic, social and environmental impacts of these options. Some of these points are further addressed below in relation to integrated models.

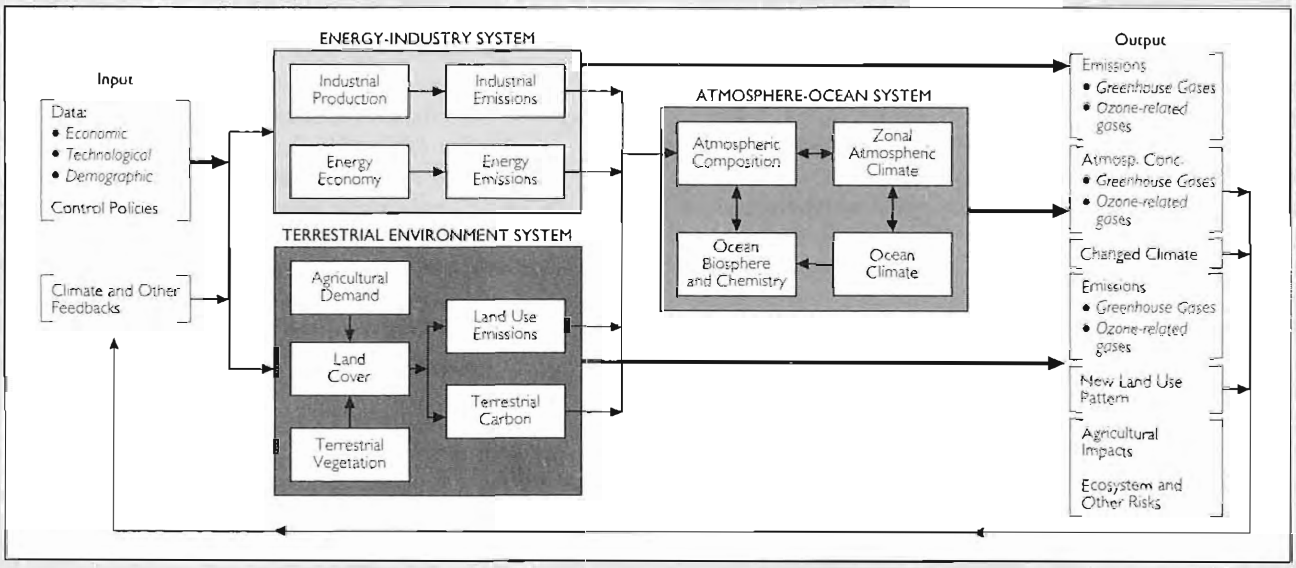
4.2.3 Integrated systems models

The issue of greenhouse gas-induced climate change now assumes a high profile in national and international policy making. In order to inform policy, however, it is necessary to identify and address all of the different components of the problem. This has been the motive force behind recent efforts to integrate the causes, impacts, feedbacks and policy implications of the 'greenhouse problem' within a modelling framework. Two

BOX 1
AN APPLICATION OF IMAGE 2.0
A GLOBALLY INTEGRATED SYSTEMS MODEL

Background: IMAGE 2.0 is a global model designed to provide a science-based overview of climate change issues to support the national and international evaluation of policies (Alcamo, 1994).

Model: IMAGE 2.0 consists of three fully linked components: energy-industry, terrestrial environment and atmosphere-ocean (see figure). Dynamic calculations are performed for a one hundred year time horizon and the model is embedded in a geographical information system.



The energy-industry set of models are used to compute the emissions of greenhouse gases in each region as a function of energy consumption and industrial production. The terrestrial environment component simulates land use and land cover dynamically through time over a 0.5° x 0.5° latitude longitude grid, employing these changes to determine greenhouse gas emissions from the terrestrial biosphere to the atmosphere. The atmosphere-ocean set of models computes the build-up of greenhouse gases in the atmosphere and the resulting change in climate. Emissions from the energy-industry and terrestrial environment components are combined and used to determine the uptake of carbon by the oceans and the atmospheric gas and aerosol composition. The climatic response to atmospheric forcing is determined with an atmospheric energy balance model, which is used in conjunction with information from GCMs to provide regional climate change scenarios.

Application: determining feedback processes in the response of the terrestrial carbon cycle to climate change.

Methods: the terrestrial environment component of IMAGE 2.0 was used to compute the carbon fluxes between the terrestrial biosphere and the atmosphere. The model can simulate the effects of feedback processes occurring under increased atmospheric CO_2 concentrations and a changing climate: the enhancement of plant growth (CO_2 fertilization) and increased water use efficiency, temperature responses of plant photosynthesis and respiration, temperature and soil water responses of decomposition processes and climate-induced changes in vegetation and agricultural patterns and consequent changes in land cover. A unique feature of the model is its ability to relate changes in land cover to the demand for agricultural land. This component is driven by regional population and economic activity. The agricultural demands are combined with regional potential crop productivity and distribution to determine the amount of agricultural land required. If this exceeds the current amount, simple rules are applied to determine the expansion of agricultural land into areas currently under other land cover types (e.g., using the nearest areas with the highest potential productivity first).

Scenarios: the projection horizon is 1970 to 2050. The IPCC 'Best Estimate scenario' (IS92a) is used to define the socio-economic projections: a world population increase of 93 per cent and GNP increase of 134 per cent by 2050. The climatic scenario is based on the Geophysical Fluid Dynamics Laboratory (GFDL) 2 x CO_2 equilibrium experiment (Manabe and Wetherald, 1987), assumed to be concurrent with an equivalent-CO_2 concentration of 686 ppm by 2050 (570 ppm for CO_2 alone) relative to 1970.

Impacts: changes in climate and in water use efficiency induce shifts in vegetation patterns relative to 1970. CO_2 fertilization decreases net carbon emissions to the atmosphere while changed decomposition rates increase emissions, though regionally there are large differences. Changes in the global balance between photosynthesis and respiration make little net difference. Neglecting land use changes, the terrestrial biosphere acts as a net carbon sink (negative feedback) relative to the current situation. However, with increasing population, the demand for new agricultural land is large, and land cover changes with associated carbon emissions are likely completely to counteract the negative feedbacks described above.

Source: Vloedbeld and Leemans (1993)

main approaches to integration can be identified: the aggregate cost-benefit approach and the regionalized process-based approach.

The aggregate cost-benefit approach seeks to estimate the likely monetary costs and benefits of GHG-induced climate change in order to evaluate the possible policy options for mitigating or adapting to climate change. This is a macroeconomic modelling approach (see above), and has been applied to certain aspects of the greenhouse problem for many years. In particular, the methods have been used to compute the development paths for emissions of carbon dioxide and other greenhouse gases in the atmosphere (the driving force for climate change).

The approach commonly combines a set of economic models with a climate model and a damage assessment model. The economic models provide global projections (sometimes disaggregated into major regional groupings of countries) of likely future paths of supply and demand in commodities that can affect greenhouse gas emissions, on the basis of future world population and economic development. The models use price to determine the relative competitiveness of different technologies of energy production, while accounting for the long-term depletion of fossil fuels, allowing for the development of more efficient technologies and accommodating likely policies of emissions abatement. The time horizon considered can range from a few decades to several centuries.

Climate models refer to a suite of functions that are needed: first, to convert GHG emissions into atmospheric concentrations; second, to estimate radiative forcing of the climate; and third, to compute the climate sensitivity of the forcing (global mean temperature response to radiative forcing equivalent to a doubling of CO_2). They usually comprise simplified representations of the gas cycles, empirical methods of determining radiative forcing, and highly simplified equations for computing temperature response.

Damage assessment models are functions that provide an estimate of the likely impacts (costs) of climate change, usually as a percentage of GNP. They commonly provide a global estimate of 'damage' as a function of global mean temperature change. To date, such functions have been selected subjectively, on the basis of expert opinion or using the few quantitative estimates that are available of the possible sectoral impacts of climate change at the global scale. Great caution must be exercised, however, since simulation outcomes with these models can be very sensitive to assumptions, such as those concerning future discount rates and the estimated damage response. A further major difficulty is the assignment of value to intangible non-market 'goods' such as human well-being, a pollution-free environment, and biological diversity.

Recent examples of models exhibiting this type of three-component framework include DICE (Nordhaus, 1992); CETA (Peck and Teisberg, 1992); and MERGE (Manne *et al.*, 1993).

The regionalized process-based approach attempts to model the sequence of cause and effect processes originating from scenarios of future GHG emissions, through atmospheric GHG concentrations, radiative forcing, global temperature change, regional climate change, possible regional impacts of climate change and the feedbacks from impacts to each of the other components. Regional impacts can be aggregated, where appropriate, to give global impacts which can then be used in evaluating the likely effectiveness of global or regional policies. The approach is derived from the applied natural sciences, especially ecology, agriculture, forestry and hydrology, where climate impact assessment has evolved from site or local impact studies towards large area assessments, using process-based mathematical models in combination with geographical information system (GIS) technology. Examples include two related models: ESCAPE (European focus) and MAGICC (global) (Rotmans *et al.*, 1994; Hulme *et al.*, 1995a), and two versions of a global model: IMAGE 1.0 (Rotmans, 1990) and IMAGE 2.0 (Alcamo, 1994). Box 1 illustrates an application of IMAGE 2.0, probably the most advanced model of this kind yet to have been developed.

In contrast to the aggregate cost-benefit approach, the estimates of biophysical impacts in these models are quantitative and regionally explicit. In addition, the treatment of gas cycling and climate change are usually more sophisticated than in the former approach. The economic impacts of climate change are not yet incorporated, however, and future versions of these models will strengthen their regional economic and global trade components, thus offering a quantitative assessment of the 'damage' quantities described above. Some of these developments are discussed further in relation to IMAGE 2.0 (Alcamo, 1994), AIM (Asian-Pacific Integrated Model; Morita *et al.*, 1993) and GCAM (a model being developed for the United States and other industrialized countries; Edmonds *et al.*, 1993).

The two types of approach outlined above originate from quite different disciplinary perspectives and were developed for contrasting reasons. However, it is becoming increasingly evident that major refinements of one approach will require significant contributions from the other. Indeed, it appears that the two approaches are rapidly converging towards a common, interdisciplinary method that will become a standard tool in policy analysis. Nevertheless, there are numerous problems associated with integrated system models, including their complexity, lack of transparency and demanding data requirements for calibration and testing. Further, modellers should take care to balance the sensitivity and uncertainties of model components, so that the results do not merely reflect noise in the most sensitive components of a model. Moreover, a major concern remains about the ability of these models to represent the uncertainties propagating through each level of the modelled system. This is discussed further in Section 7.6.

4.3 Empirical Analogue Studies

Observations of the interactions of climate and society in a region can be of value in anticipating future impacts. The most common method employed involves the transfer of information from a different time or place to an area of interest to serve as an analogy. Four types of analogy can be identified: historical event analogies; historical trend analogies; regional analogies of present climate; and regional analogies of future climate. Analogues can also be used as climate scenarios (see Section 6.5.2)

4.3.1 Historical event analogies

Historical event analogies use information from the past as an analogue of possible future conditions. Data collection may be guided by anomalous climatic events in the past record (e.g., drought or hot spells) or by the impacts themselves (e.g., periods of severe soil erosion by wind). The assessment follows a 'longitudinal' method (Riebsame, 1988), whereby indicators are compared before, during and after the event. Examples of this approach are found in Glantz (1988). However, the success of this method depends on the analyst's ability to separate climatic and non-climatic explanations for given effects.

4.3.2 Historical trend analogies

There are several examples of historical trends that may be unrelated to greenhouse gases but which offer an analogy of GHG-induced climate change. Long-term temperature increases due to urbanization are one potential source for a warming analogue (as yet seldom considered by impact analysts). Another example is past land subsidence, the impacts of which have been used as an analogue of future sea level rise associated with global warming.

4.3.3 Regional analogies of present climate

These refer to regions having a similar present-day climate to the study region, where the impacts of climate on society are also judged likely to be similar. To justify these premises, the regions generally have to exhibit similarities in other environmental factors (e.g., soils and topography), in their level of development and in their respective economic systems. If these conditions are fulfilled, then it may be possible to conduct assessments that follow the 'case-control' method (Riebsame, 1988). Here, a target case is compared with a control case, the target area experiencing abnormal weather but the other normal conditions.

4.3.4 Regional analogies of future climate

Regional analogies of future climate work on the same principle as analogies 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 study region in the future. In this case, 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). These characteristics would provide indicators of how the landscape and human activities might change in the study region in the future. Of course, for a full assessment of this, it would be necessary to consider the ability of a system or population to adapt to change. This principle has proved valuable in extending the range of applicability of some impact models. For example, a model of grass growth in Iceland has been 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. For a hydrological example, and discussion of the considerable problems involved with regional analogues, see Arnell *et al.* (1990). One method of circumventing these problems is to consider altitudinal differences in the same region.

4.4 Expert Judgement

A useful method of obtaining a rapid assessment of the state of knowledge concerning the effects of climate on given exposure units is to solicit the judgement and opinions of experts in the field. Of course, expert judgement plays an important role in each of the other analytical methods described above. On its own, however, the method is widely adopted by government departments for producing position papers on issues requiring policy responses. In circumstances where there may be insufficient time to undertake a full research study, literature is reviewed, comparable studies identified, and experience and judgement are used in applying all available information to the current problem.

The use of expert judgement can also be formalized into a quantitative assessment method, by classifying and then aggregating the responses of different experts to a range of questions requiring evaluation. This method was employed in the National Defense University's study of Climate Change to the Year 2000, which solicited probability judgements from experts about climatic change and its possible impacts (NDU, 1978, 1980).

The pitfalls of this type of analysis are examined in detail in the context of the NDU study by Stewart and Glantz (1985). They include problems of questionnaire design and delivery, selection of representative samples of experts, and the analysis of experts' responses.

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. Participatory assessment is another approach which is being tested in the McKenzie Basin study in Canada (cf. Section 2.3.3)

STEP 3: TESTING THE METHOD

5

Following the selection of the assessment methods, it is important that these are thoroughly tested in preparation for the main evaluation tasks. There are many examples of studies where inadequate preparation has resulted in long delays in obtaining results. Moreover, this step provides an opportunity to refine goals and evaluate constraints that may have been overlooked (for example, in selecting 'off the shelf' models). Three types of analysis may be useful in evaluating the methods: feasibility studies, data acquisition and compilation, and model testing.

5.1 Feasibility Studies

One way of testing some or all of the methods, is to conduct a feasibility or pilot study. This usually focuses on a subset of the study region or sector to be assessed. Case studies such as these can provide information on the effectiveness of alternative approaches, of models, of data acquisition and monitoring, and of research collaboration.

Feasibility studies are most commonly adopted as a preliminary stage of large multidisciplinary and multisectoral research projects. Here, effective planning and scheduling of research relies on the assurance that different research tasks can be undertaken promptly and efficiently. Several approaches can be suggested for conducting feasibility studies:

- Evaluation of available information.
- Qualitative screening analysis.
- Preliminary scenarios.
- Geographical zoning.
- Microcosm studies.
- Response surfaces.
- Analogue studies.

5.1.1 Evaluation of available information

The importance of identifying the main data requirements in an impact assessment has already been stressed in Section 3.5. In addition, a review of the published literature should always be undertaken, to provide a background understanding of the study region, system or activity being investigated, to examine parallel or related studies that have been completed, to obtain new ideas on methods, to locate new sources of data, and to identify possible research collaborators.

5.1.2 Qualitative screening analysis

Assuming that the general sector or sectors of interest have already been identified, a useful first step in defining the specific exposure units to be studied is to conduct a climatic vulnerability analysis (e.g., Downing, 1992; Scott, 1993). This is a qualitative screening procedure which classifies climate vulnerability in a matrix format. Different exposure units within the sector(s) are entered on one axis, classified, for instance, by type or by scale. On the other axis some effects of climate are categorized, for example, by type of climatic event, by possible future climate changes, or by a combination of these. Qualitative ratings are then assigned to each cell in the matrix, indicating both the likely size of the effect and its probability of occurrence. These estimates can be made using whatever information there is available, i.e., from previous studies, expert opinion, literature review or simple quantitative assessments (see below). An example is presented of a vulnerability rating for human settlements in Table 1.

In this way, an impression can be gained of the relative vulnerability of different exposure units to variations in climate at different scales. This may then assist in selecting appropriate exposure units for closer examination, the geographical scale of analysis, the time frame of the study and hence the projection horizon for different scenarios and the types of assessment tools that are appropriate for conducting assessments (including models, survey methods, visualization tools and decision support systems). However, caution should be exercised in interpreting too much from a preliminary assessment of this kind, and this type of procedure should not be regarded as a substitute for an in-depth assessment.

5.1.3 Preliminary scenarios

The qualitative screening procedure is a useful device for identifying the important climatic variables, the region of interest and the projection horizon that are needed in constructing climatic, environmental and socio-economic scenarios. While the devel-

Table 1. Hypothetical example of a qualitative screening analysis to assess the vulnerability of human settlements to climatic variations (after Scott, 1993)

	CLIMATE VULNERABILITY RATING (Examples)			
Settlement	Drought effects on agriculture	Drought effects on water supply	Flooding effects on buildings	Rural-urban migration
Villages < 500 people	1, U	2, U	4, L	2, L
Market towns, 500-1000 people	2, U	2, U	4, L	2, U
City A	4, U	3, U	2, L	1, L

Ratings: 1 = Large or very important; 5 = Trivial; L = Likely; U = Unlikely opment of detailed scenarios can be a time-consuming exercise, preliminary large scale projections can usually be made from information in the literature. For example, it may be possible to derive central, upper and lower estimate projections of trends in measures such as population, GNP, income, employment, energy demand, food demand, GHG concentrations, temperature and precipitation (e.g., see Box 3, on page 19). Simple scenarios of this kind could be very useful in conducting simple assessments of the type described below.

5.1.4 Geographical zoning

In many impact assessments, the geographical scope of the study is already pre-determined (e.g., focusing on an administrative region or a physiographic feature such as a river catchment). Even so, selection of an appropriate study region can pose some problems. First, the region should be relevant to the exposure unit. Second, it should provide adequate data, expertise and conditions for carrying out the assessment. Third, within its bounds, the exposure unit should exhibit measurable sensitivity to climatic variations. Fourth, it should provide representative results that can, if necessary, be extrapolated to a larger region.

One method of targeting appropriate areas for study is to use simple, large area geographical zonation. This has been widely used in assessing agricultural impacts, but is potentially applicable in other sectors. It involves the calculation of simple bioclimatic indices, which combine information on climate, soils and topography into measures of suitability for crops, trees or natural vegetation. Some of the more sophisticated measures can indicate plant biomass or even crop yield potential. Examples include Köppen's climatic classification (Köppen, 1931), Holdridge Life Zones (Holdridge, 1947), or the FAO Agro-Ecological Zones (FAO, 1978)

Where these have been mapped for both present-day climate and possible future climate changes, it is possible to identify those zones or regions where there is likely to be a high sensitivity of a particular exposure unit to climate change. For example, it could indicate zones where new species could be cultivated or regions where species may be threatened. These areas can then be targeted for more detailed analysis (e.g., using simulation models, village surveys or field experiments). Alternatively, zoning may simply serve as a classification method for selecting representative sites for further study.

5.1.5 Microcosm case studies

In studies where there is likely to be a heavy reliance on a specific type of analysis (e.g., model-based, experimental, survey-based) or where data requirements are uncertain, it can be instructive to conduct a small scale pilot study under conditions representative of those anticipated in the main study. These 'microcosm' case studies allow different analysis tools to be selected, tested and evaluated. In addition, they can assist in identifying the personnel required to carry out research. They also offer researchers some experience in addressing problems they are likely to encounter in the main project. For instance, in a project on regional tourism, a representative tourist resort might be chosen as a pilot case study, or for a study of coping strategies for drought in an agriculturally-based, rural subsistence economy, a representative village might be selected for a pilot survey and analysis.

5.1.6 Response surfaces

A growing number of detailed climate impact studies are being reported for different sectors and from many regions of the world. While these frequently make use of sophisticated analytical methods or models, their results can often be summarized more simply, using generalized response surfaces. For example, hydrological models may have been applied to different points in a river catchment and run for different climate change scenarios. The hydrological responses can be complex, but it may still be possible to separate out the most important responses to climate as simple empirical relationships (for example relating river discharge to monthly precipitation).

Where simple relationships of this kind can be identified from previous studies, there may then be an opportunity to apply them to similar regions in the new study, to provide a preliminary assessment of possible responses to climate change. The use of response surfaces in studying system sensitivities to climate change is discussed further in Box 5 on page 22.

5.1.7 Analogue studies

Another method of obtaining a rapid evaluation of the likely climate sensitivity of an exposure unit is to identify analogues of possible future conditions. These have already been discussed in the context of a full impact assessment (Section 4.3)—here they are used as a screening device. These might be regional analogues, where the present-day climate and its effects on an exposure unit are thought to be comparable to possible future conditions in the study region. This is an attractive device for illustrating the possible extent of future climate change, as well as offering useful information on the conditions experienced under the analogue climate. Alternatively, they could be temporal analogues, which identify climatic events and their impacts in the past as analogues of events which could occur again in the future, possibly with an altered frequency under a changed climate.

5.2 Data Acquisition and Compilation

An essential element in all climate impact assessment studies is the acquisition and compilation of data. Quantitative data are required both to describe the temporal and spatial patterns of climatic events and their impacts and to develop, calibrate and test predictive models. Four main types of data collection can be identified: empirical compilation, objective survey, targeted measurement and monitoring.

Empirical compilation of evidence (both quantitative and qualitative) from disparate sources is the mainstay of most historical analysis of past climate-society interactions. The data are pieced together to produce a chronology of events, which can then be used to test hypotheses about the effects of past climate (e.g., see Parry, 1978), or simply as a qualitative description of past events (e.g., see Lamb, 1977; Pfister, 1984; Grove, 1988; Mikami 1992).

Objective survey utilizes established procedures to collect data from contemporary sources (the information itself may relate to the present or the past). Such survey material may represent either a subset of a population (e.g., a sample of plant species at randomly selected locations within given ecological zones, to be related to climate at the same localities) or the complete population (e.g., a regional register of all reported illnesses during a given period that can be related to extreme weather conditions). The tools employed in data acquisition include use of government statistical sources, different methods of questionnaire survey and biological survey techniques. The types of studies reliant on this kind of information include most social impact assessments (Farhar-Pilgrim, 1985), studies of perception (Whyte, 1985), and studies of biophysical impacts where quantitative data are lacking (e.g., of village-level drought effects on agriculture; Akong'a *et al.*, 1988; Gadgil *et al.*, 1988).

Targeted measurement refers to the gathering of unique data from experiments where data and knowledge about vital processes or interactions are lacking. This type of measurement is especially important in considering the combined effects of future changes in climate and other environmental factors, combinations which have never before been observed. In many cases these data offer the only opportunity for testing predictive models (for example, observations of the effects of enhanced atmospheric CO_2 on plant growth).

Monitoring is a valuable source of information for climate impact assessment. Consistent and continuous collection of important data at selected locations is the only reliable method of detecting trends in climate itself, or in its effects. In most cases, impact studies make use of long-term data from other sources (e.g., observed climatological data, remotely-sensed data). However, in some projects monitoring may form the central theme of research. In these, it is important to consider aspects such as site selection, multiple-uses of single sites, design of measurements and their analysis. It should be noted that there are numerous national and international monitoring programmes, including one initiated by the IPCC (WG II). It is important that results from such programmes be made available to impact researchers for assessment studies.

Impact assessments are often hampered by the failure to assemble appropriate data for a given task. This can be due to many causes, including a failure to locate where data are held, bureaucratic delays in the release of data, particularly across national boundaries, and the high cost of obtaining some types of information. This problem is particularly relevant in developing countries.

Where existing data are concerned, government offices often hold valuable data for impact assessment, although the custodians of such data may not be aware of its special relevance. In many cases, data held by the central statistical office of a country is often limited in its subject matter and regional coverage, and researchers may need to access data archived in departmental or regional offices. In some cases, national or regional data may be more easily accessible from international organizations, The UNEP GEMS 'Harmonization of Environmental Monitoring' disk is a useful guide to data banks held by various organizations. Some important international sources of data are listed in Appendix 4. Other potentially valuable sources of longitudinal data are in private organizations such as ornithological or botanical societies.

The quality of data should always be checked, both in terms of its level of accuracy and its consistency over time. Measuring equipment may deteriorate or be replaced and observation procedures or sites often change over time, requiring corrections to maintain consistency.

5.3 Model Testing

The testing of predictive models is, arguably, the most critical stage of an impact assessment. Most studies rely almost exclusively on the use of models to estimate future impacts. Thus, it is crucial for the credibility of the research that model performance is tested as rigorously as possible. Standard procedures should be used to evaluate models, but these may need to be modified to accommodate climate change. Two main procedures are recommended—validation and sensitivity analysis—and these should always precede more formal impact assessment.

Validation involves the comparison of model predictions with real world observations to test model performance. The validation procedures adopted depend to some extent on the type of model being tested. For example, the validity of a simple regression model of the relationship between temperature and grass yield should necessarily be tested on data from additional years not used in the regression. Here, the success of the model is judged by its outputs, namely the ability to predict grass yield. Conversely, a process-based model might estimate grass yield based on basic growth processes, which are affected by climate, including temperature. Here, the different internal components of the model (such as plant development and water use) as well as final yield each need to be compared with measurements.

One problem often encountered in applying process-based models in less developed countries (LDCs) is that the models, while extensively validated in the data-rich developed world, are found to be ill-suited or poorly calibrated for use under the different conditions often experienced in LDCs. A lack or paucity of data for validation may mean that a data-demanding model cannot be used under these circumstances and that a model less dependent on detailed data may be more appropriate.

Climate change introduces some additional problems for validation, since there may be little local data that can be used to test the behaviour of a modelled system in conditions resembling those in the future. Process-based models ought, in theory, to be widely applicable (see Section 4.2.1), and anyway should be tested in a range of environments. There are fewer grounds, however, for extrapolating the relationships in empirical-statistical models or in most economic models outside the range of condition for which they were developed. The use of regional analogies of future climate is one possible method of addressing certain aspects of this problem (see Section 4.3.4).

Sensitivity analysis evaluates the effects on model performance of altering the model's structure, parameter values, or values of its input variables. Extending these principles to climatic change requires that the climatic input variables to a model be altered systematically to represent the range of climatic conditions likely to occur in a region. In this way, information can be obtained on:

- The sensitivity of the outputs to changes in the inputs. This can be instructive, for example, in assessing the confidence limits surrounding model estimates arising from uncertainties in the parameter values (e.g., see Buck *et al.*, forthcoming).
- Model robustness, (i.e., the ability of the model to behave realistically under different input specifications, and the circumstances under which it may behave unrealistically).
- The full range of potential model application (including its transferability from one climatic region to another, and the range of climatic inputs that can be accommodated).

Sensitivity analysis, which is a model testing procedure, should be distinguished from the use of synthetic scenarios (cf. Section 6.5.1), which explicitly seeks to explore system behaviour under given variations in climate. For a useful introduction to sensitivity analysis in ecological modelling see Swartzman and Kaluzny, 1987.

It is worth noting here that while predictive models offer the most promising means of obtaining estimates of possible future impacts of climate change, in some sectors these are not yet sufficiently developed to be used for this purpose. Where the systems are complex and/or poorly understood (e.g., marine ecosystems), considerable efforts are still required to obtain an understanding even of variations in the present-day system. Only after such basic research is completed can meaningful projections be made in the future.

STEP 4: SELECTING THE SCENARIOS

6

Impacts are estimated as the differences between two states: the environmental and socio-economic conditions expected to exist over the period of analysis in the absence of climate change and those expected to exist with climate change. Each of these states is described by a scenario, which can be defined as 'a coherent, internally consistent and plausible description of a possible future state of the world'.

In this section, aspects of the selection and construction of scenarios for use in climate impact assessment are outlined. At the outset, it is important to recognize that the environment, society, and economy are not static. Environmental, societal, and economic changes will continue, even in the absence of climate change. In order to estimate the environmental and socio-economic effects of climate change, it is necessary to separate them from unrelated, independent environmental and socio-economic changes occurring in the study area. Thus, there is a need first to develop baselines that describe current climatological, environmental, and socio-economic conditions. It is then possible to project environmental and socio-economic conditions over the study period in the absence of climate change. Projections should take into account, as far as is possible, autonomous adjustments (cf. Section 8.2) which are likely to occur in response to changes in these conditions (Frederick *et al.*, 1994). The resulting baseline conditions are then compared, after impact projections, with environmental and socio-economic conditions under climate change. Thus development of baselines representing current and projected conditions in the absence of climate change is a key and fundamental step in assessment.

An interesting alternative to scenario projections is the 'normative' reference scenario. This describes a desired future, and can be related to issues such as development targets and self-sufficiency goals. Such scenarios also portray a target condition to strive for under a changing climate.

It is worth noting here that there are assessments which may not explicitly require a scenario component, it being sufficient that system sensitivities are explored without making any assumptions about future climate. Examples of such assessments might include model-based studies where extrapolation of model relationships to future climatic conditions cannot be justified, and where only an indication of the likely direction of system response to climate change is required. In addition, reliance on climatic scenarios may actually be misleading or inappropriate if, for example, the projected climate changes are non-critical for the system being studied.

6.1 Establishing the Present Situation

In order to provide reference points for the present-day with which to compare future projections, three types of 'baseline' conditions need to be specified: the climatological, environmental and socio-economic baselines.

6.1.1 Climatological baseline

The climatological baseline is usually selected according to the following criteria:

- Representativeness of the present-day or recent average climate in the study region.
- Of a sufficient duration to encompass a range of climatic variations, including a number of significant weather anomalies (e.g., severe droughts or cool seasons). Such events are of particular use as inputs to impact models, providing a means to evaluate the impacts of the extreme range of climatic variability experienced at the present-day.
- Covering a period for which data on all major climatological variables are abundant, adequately distributed and readily available.
- Including data of sufficient quality for use in evaluating impacts.
- Consistent or readily comparable with baseline climatologies used in other impact assessments.

A popular climatological baseline is a 30-year 'normal' period as defined by the World Meteorological Organization (WMO). The current standard WMO normal period is 1961-1990. While it would be desirable to provide some consistency between impact studies by recommending this as an appropriate baseline period to select in future assessments, there are also difficulties in doing so. A number of points illustrate this. First, this period coincides conveniently with the start of the projection period commonly employed in estimating future global climate (for example, the IPCC projections begin at 1990; IPCC, 1990a). On the other hand, most general circulation models providing regional estimates of climate are initialized using observational data sets taken from earlier periods. Second, the availability of observed climatological data, particularly computer-coded daily data, varies considerably from country to country, thus influencing the practical selection of a baseline period. Third, it is often desirable to compare future impacts with the current rather than some past condition. However, while it can justifiably be assumed in some studies that present-day human or natural systems subject to possible future climate change are reasonably well adapted to the current climate, in other assessments this is not a valid assumption (e.g., many ecological systems have a lag in response of many decades or more relative to climate). Finally, there is the problem that more recent averaging periods (particularly those that include the 1980s), may already exhibit a significant global warming 'signal', although this signal is likely to vary considerably between regions, being absent from some.

Climatological data from the baseline period are used as inputs for impact models. Some models produce estimates for years or decades (e.g., crop growth models). These can generally utilize the original climatological station data for years within the baseline period. Other models run over long time periods of multiple decades or centuries (e.g., soil erosion models). One option here is to select a long baseline period, but lack of data usually precludes this. An alternative is to use the baseline data on a repeating basis. For example, year 1 in a thirty year baseline could be used as years 1, 31, 61 and 91 of a one hundred year simulation. One problem with this method is that chance trends or cycles in the baseline climate are then repeated in a manner that may be unrealistic over the long term.

To overcome some of the problems of data sparsity and of long-term cycles, some modelling studies now employ weather generators. These simulate daily weather at a site randomly, based on the statistical features of the observed climate. Once developed, they can produce time series of climatological data having the same statistical description as the baseline climate, but extending for as long a period as is required (see Hutchinson, 1987). However, many weather generators are unable to represent extreme events such as drought realistically, which can be a critical drawback in assessing impacts.

6.1.2 Environmental baseline

The environmental baseline refers to the present state of non-climatic environmental factors that affect the exposure unit. It can be defined in terms of fixed or variable quantities. A fixed baseline is often used to describe the average state of an environmental attribute at a particular point in time. Examples include: mean atmospheric concentration of carbon dioxide in a given year, physiographic features, mean soil pH at a site, or location of natural wetlands. A notable case is the mean sea level, which is expected to change as a result of future climate change. Furthermore, a fixed baseline is especially useful for specifying the 'control' in field experiments (e.g., of CO_2 effects on plant growth).

A representation of variability in the baseline may be required for considering the spatial and temporal fluctuations of environmental factors and their interactions with climate. For example, in studies of the effects of ozone and climate on plant growth, it is important to have information both on the mean and on peak concentrations of ozone under present conditions.

6.1.3 Socio-economic baseline

The socio-economic baseline describes the present state of all the non-environmental factors that influence the exposure unit. The factors may be geographical (e.g., land use, communications), technological (e.g., pollution control, crop cultivation, water regulation), managerial (e.g., forest rotation, fertilizer use), legislative (e.g., water use quotas, air quality standards), economic (e.g., commodity prices, labour costs), social (e.g., population, diet), or political (e.g., land set-aside, land tenure). All of these are liable to change in the future, so it is important that baseline conditions of the most relevant factors are noted, even if they are not required directly in impact experiments.

6.2 Time Frame of Projections

A critical consideration for conducting impact experiments is the time horizon over which estimates are to be made. Three elements influence the time horizon selected: the limits of predictability, the compatibility of projections and whether the assessment is continuous or considers discrete points in time.

6.2.1 Limits of predictability

The time horizon selected depends primarily on the goals of the assessment. However, there are obvious limits on the ability to project into the future. Since they are a key element of climate impact studies, climatic projections define one possible outer limit on impact projections. Due to the large uncertainties associated with such long-term projections and to constraints on computational resources, most GCM simulations have been conducted for periods of up to about 100 years into the future, although a few have also been made over longer time periods of several centuries. For this reason, the outer horizon commonly adopted in impact studies has been 2100.

Within the context of the Framework Convention on Climate Change, there is a requirement to specify 'dangerous' levels of GHG concentrations. Such levels, and the climate changes associated with them, may not be reached until after 2100, so there may be a need for impact assessments over periods extending beyond the conventional time horizon of 2100.

Of course, long time scale projection periods may be wholly unrealistic for considering some impacts (e.g., in many economic assessments where projections may not be reliable for more than a few years ahead). On the other hand, if the projection period is too short, then the estimated changes in climate and their impacts may not be easily detectable, making it difficult to evaluate policy responses. Caution must be exercised, therefore, in ensuring that the projection period is both relevant for policy but also valid within the limitations of the approach.

6.2.2 Compatibility of projections

It is important to ensure that future climate, environment and socio-economic projections are mutually consistent over space and time. Many of these are in any case intimately related. For instance, changes in greenhouse gas concentrations are related to economic activity and resource use, which are themselves a function of increasing human population. A common area of confusion concerns the relative timing of CO_2 increase and climate change. Thus, it should be noted that an equivalent 2 x CO_2 atmosphere, in which the combined effect of CO_2 and other greenhouse gases such as CH_4, N_2O and tropospheric O_3 on the earth's radiation balance is equivalent to the effect of doubling CO_2 alone, does not coincide in time with an atmosphere in which CO_2 levels themselves have been doubled. Moreover, there is a time lag of several decades in the climate response to the radiative forcing (Box 2). Hereafter the terms '2 x CO_2' or 'doubled-CO_2' imply a radiative forcing equivalent to 2 x CO_2.

This issue is especially important in CO_2 enrichment experiments, where the response of a plant is compared for ambient and assumed future CO_2 concentrations. The standard convention is to consider a doubling of CO_2 relative to ambient, but the ambient level is rising, and experiments conducted in the mid-1970s, when the ambient level was near 330 ppm (versus 660 ppm) are not comparable with experiments conducted in the mid-1990s (360 ppm versus 720 ppm). Furthermore, the experimental treatments often combine temperature changes with elevated CO_2. In this case, projections of regional temperature change are needed that are contemporaneous with the CO_2 level being used. For this, reference must be made first, to global assessments (see Box 2), and then to regional climate change scenarios (cf. Section 6.5.3 and Box A2, Appendix). It is also important to note that enrichment experiments require treatments that are sufficiently different from each other to induce measurable differences in response. Thus, for example, while a feasible and consistent scenario could be developed for the year 2020, where CO_2 increases by about 50 ppm relative to ambient and regional temperature increases by 0.5°C, this level of change may not produce statistically significant responses in enrichment experiments.

6.2.3 Point in time or continuous assessment

A distinction can be drawn between considering impacts at discrete points in time in the future and examining continuous or time-dependent impacts. The former are characteristic of many climate impact assessments based on doubled-CO_2 scenarios. These scenarios have the advantage of being mutually comparable, and consider impacts occurring at the time specified by the scenario climate (although that time is often not easy to define and can vary from place to place). However, they ignore any effects occurring during the interim period that might influence the final impacts. They also make it very difficult to assess rates of change and thus to evaluate adaptation strategies.

In contrast, transient climatic scenarios allow time-dependent phenomena and dynamic feedback mechanisms to be examined and socio-economic adjustments to be considered. Nevertheless, in order to present results of impact studies based on transient scenarios, it is customary to select 'time slices' at key points in time during the projection period.

6.3 Projecting Environmental Trends in the Absence of Climate Change

The development of a baseline describing conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. It is highly probable that future changes in other environmental factors will occur, even in the absence of climate change, which may be of importance for an exposure unit. Examples include deforestation, changes in grazing pressure, changes in groundwater level and changes in air, water and soil pollution. Official projections may exist to describe trends in some of these (e.g., groundwater level), but for others it may be necessary to use expert judgement. Most factors are related to, and projections should be consistent with trends in socio-economic factors (see Section 6.4, below). Greenhouse gas concentrations may also change, but those would usually be linked to climate (which is assumed unchanged here).

6.4 Projecting Socio-Economic Trends in the Absence of Climate Change

Global climate change is projected to occur over time periods that are relatively long in socio-economic terms. Over that period it is certain that the economy and society will change, even in the absence of climate change. One of the most difficult aspects of establishing trends in socio-economic conditions without climate change over the period of analysis is the forecasting of future demands on resources of interest. Simple extrapolation of historical trends without regard for changes in prices, technology, or population will often provide an inaccurate base against which to measure impacts.

Official projections exist for some of these changes, as they are required for planning purposes. These vary in their time horizon from several years (e.g., economic growth, unemployment), through decades (e.g., urbanization, industrial development, agricultural production) to a century or longer (e.g., population). Reputable sources of such projections include the United Nations, Organization of Economic Cooperation and Development, World Bank, International Monetary Fund and national governments. Some examples of recent global projections are given in Box 3. Nevertheless, many of these are subject to large uncertainties due to political decisions (e.g., international regulations with respect to production and trade) or unexpected changes in political systems (e.g., in the USSR, eastern Europe and South Africa during the early 1990s).

Other trends are more difficult to estimate. For example, advances in technology are certain to occur, but their nature, timing and effect are almost impossible to anticipate. In some sectors, it is possible to identify trends in past impacts as attributable to the effects of technology (e.g., on health, crop yields). In these cases, changes in technology can be factored in either by examining past trends in resource productivity or by expert judgement consider-

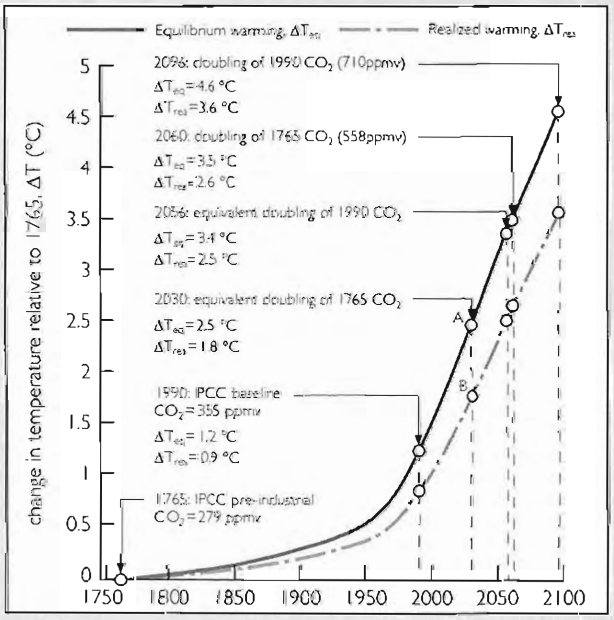
BOX 2
THE RELATIONSHIP OF EQUILIBRIUM AND TRANSIENT WARMING TO INCREASES IN CARBON DIOXIDE AND IN EQUIVALENT CARBON DIOXIDE

The figure below is based on simulations with the MAGICC model (see Box 3) of the 'best estimate' of global mean annual temperature change under the IS92a emissions scenario produced for the IPCC (IPCC, 1992a), assuming no negative forcing due to sulphate aerosols. It illustrates three important points that are a frequent source of confusion and misunderstanding among impact analysts:

(1) The projected doubling dates for atmospheric CO_2 occur at different times depending on the selection of a baseline. Climatologists often refer to pre-industrial CO_2 levels (shown in the figure as a concentration of 279 ppmv in the year 1765) as a baseline to examine effects on climate of subsequent CO_2-forcing. In contrast, impact assessors are more likely to favour selecting a baseline from recent years (e.g., 1990, concentration 355 ppmv), to provide compatibility with other baseline environmental or socio-economic conditions of importance in impact assessment.

(2) The projected doubling dates for CO_2 alone occur significantly later than the doubling dates for equivalent atmospheric CO_2, where all greenhouse gases are considered. Hence, the doubling date for 1765 CO_2 (2060; 558 ppmv) occurs 30 years later than the equivalent doubling date (2030). Similarly doubling of 1990 CO_2 to 710 ppmv is projected at 2096, whereas equivalent doubling occurs at 2056.

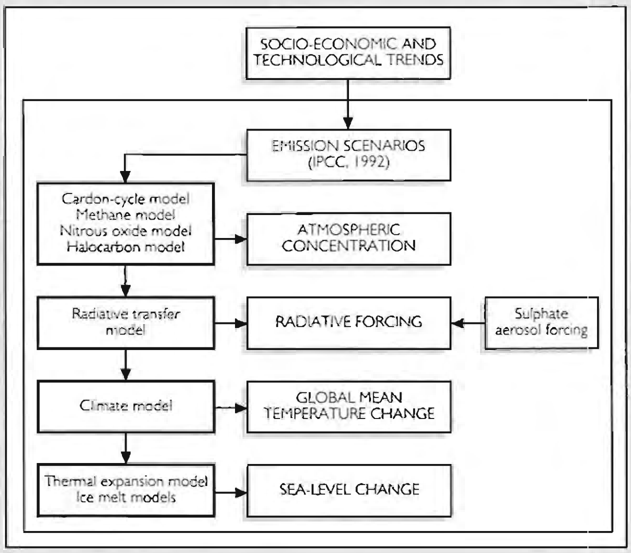
(3) The actual or 'realised' warming at a given time in response to GHG-forcing (as depicted in transient-response GCM simulations) is less than the full equilibrium response (as estimated by 2 x CO_2 GCM simulations), owing to the lag effect of the oceans. These effects can be simulated at a global scale by MAGICC (curves in figure). Thus, at the time of equivalent doubling of 1765 CO_2 (2030), the equilibrium warming relative to 1765 is 2.5°C (point A in figure), whilst the realized warming is only 1.8°C (point B).



BOX 3
SOCIO-ECONOMIC SCENARIOS USED BY THE IPCC AND THE DERIVATION OF CONSISTENT CLIMATIC AND ENVIRONMENTAL SCENARIOS

Six emissions scenarios were prepared for the 1992 IPCC Supplementary Report (IS92 a-f) (IPCC, 1992a). These have since been reviewed and retained for the 1995 IPCC assessment. The six scenarios represent a range in emissions estimates based on different assumptions of GNP, population growth rate, energy use, land use and other socio-economic factors that determine emissions levels. The two most important of these 'socio-economic scenarios', population and GNP, are listed in the Table for 2100. The other assumptions and a regional breakdown of projections are contained in IPCC (1992a).

A system of simple models named MAGICC (Model for the Assessment of Greenhouse-gas Impacts and Climate Change) has been developed at the Climatic Research Unit, University of East Anglia (Hulme *et al.*, 1995a, in press) for estimating different effects of the IPCC (and other) emissions scenarios (see Figure). It incorporates all of the important state-of-the-art knowledge as reported by the IPCC (IPCC, 1990a; 1992a), including a CO_2-fertilization feedback and negative forcings due to sulphate aerosols and stratospheric ozone depletion. The emissions are converted to atmospheric concentrations by gas models, and the concentrations are converted into radiative forcing potential for each gas. The net radiative forcing is then computed and input into a simple upwelling-diffusion energy-balance climate model. This produces global estimates of mean annual temperature and further ice melt and thermal expansion models are used to compute sea level change. The estimates are time-dependent with a time horizon up to 2100. Sub-models of MAGICC have been widely used by the IPCC, and the system is continually being updated to reflect improved scientific knowledge. However, it should be noted that an important weakness of MAGICC is its inability to account for regionally-specific processes such as stratospheric ozone depletion and sulphate forcing, which are highly dependent on complex atmospheric chemistry.



A number of environmental scenarios that have been generated by MAGICC for each of the six IPCC emissions scenarios are also shown in the Table: the atmospheric concentration of CO_2, global mean annual temperature change (by 2100) assuming the mid-range climate sensitivity, and global sea level rise (middle, upper and lower estimates). Note that MAGICC has also been employed, in conjunction with general circulation models, to derive more detailed climate scenarios based on emissions scenario IS92a to assist in the 1995 IPCC Working Group II review of impacts of climate change (cf. Appendix 1, Box A2).

	1990	Scenario for 2100					
Names of IPCC Scenarios		IS92a	IS92b	IS92c	IS92d	IS92e	IS92f
Population (billion)[1]	5.252	11.3	11.3	6.4	6.4	11.3	17.6
Economic growth rate (annual GNP)[1]	-	2.3%	2.3%	1.2%	2.0%	3.0%	2.3%
CO_2 concentration (ppmv)[2]	355	733	710	485	568	986	848
Global mean annual temperature change (°C)[2,3]	0	2.47	2.40	1.53	1.91	2.84	2.92
Range (°C).[2,4]	–	1.62–3.75	1.57–3.66	0.97–2.44	1.23–2.99	1.89–4.26	1.93–4.40
Sea level rise (cm)[2,3]	0	45	45	33	38	50	51
Range (cm)[2,5]	–	14–85	13–85	7–68	10–76	17–92	17–95

[1] Leggett *et al.* (1992). [2] Based on 'best estimate' assumptions given in Wigley and Raper (1992) with CO_2 fertilization feedback included, but using an updated version of MAGICC (May 1993) giving different values from those reported by Wigley and Raper. [3] Assumes a mid-range climate sensitivity of 2.5°C (cf. Section 6.5.3). [4] Values for low (1.5°C) and high (4.5°C) climate sensitivity. [5] Subjective 10% and 90% confidence levels.

BOX 4
CASE STUDY: AN INTEGRATED ASSESSMENT OF IMPACTS OF CLIMATE CHANGE ON THE AGRICULTURAL ECONOMY IN EGYPT

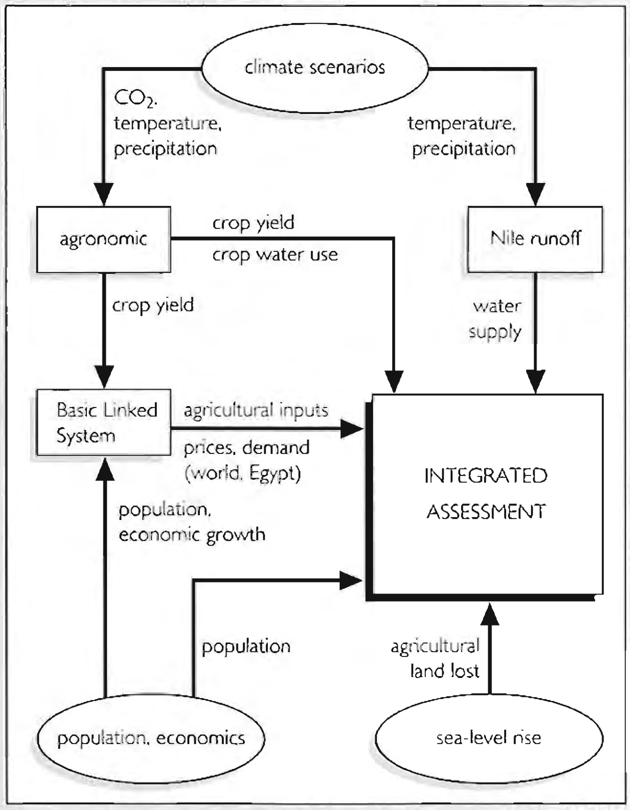
Background: agriculture in Egypt is restricted to the fertile lands of the narrow Nile valley from Aswan to Cairo and the flat Nile Delta north of Cairo. Together this comprises only 3 per cent of the country's land area. Egypt's entire agricultural water supply comes from irrigation, solely from the Nile River. In 1990, agriculture (crops and livestock) accounted for 17 per cent 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.

Methods: the assessment was part of an international study of climate change impacts on world food supply and trade (Rosenzweig and Parry, 1994), forming one component of a coordinated international programme of climate change impact studies (Strzepek and Smith, in press). A number of submodels were used to estimate the different sectoral impacts of climate change (see Figure). A digital elevation model of the Nile Delta was developed for determining land loss due to sea level rise. A physically-based water balance model of the Nile Basin was used to evaluate river runoff. This was linked to a simulation model of the High Aswan dam complex to determine impacts on Lake Nasser yields. Process-based agronomic models (incorporating direct effects of elevated CO_2) were used to estimate crop yields and crop water requirements, and cropping patterns under different climatic scenarios were determined using the Egyptian food supply and trade model, one component of an international food trade model, the Basic Linked System (BLS), which was run at a global level.

Results from the BLS and other submodels were then taken directly, or aggregated using expert judgement, to provide inputs to an Egyptian Agricultural Sector Model (EASM-CC). This is an integrated model of the agricultural economy incorporating effects on water, land, crops, livestock and labour. One output of the model is the annual consumer-producer surplus, an economic measure of social welfare.

Testing of methods: each of the submodels used in the study was validated against local data. Further, an elaborate comparative analysis was undertaken to select an appropriate hydrological model from a number of candidate models. Each of the linked national or regional models in the BLS has been tested in its region of origin, while the complete model was initialised with 1980 data from the Food and Agriculture Organization and run through to 1990, model parameters being tuned for the 1980s period to obtain the 'best fit' for 1990.



Scenarios: the current baseline adopted for the socio-economic projections was 1990 and the climatological baseline, 1951-1980. The time horizon of the study, 1990-2060, was largely dictated by the climate change projections. Socioeconomic scenarios for a future world in 2060 were developed for population (estimated from UN/World Bank projections to more than double, assuming current growth rates) and economic growth (based upon growth rates assumed in the world food supply and trade study).

The climatic scenarios were based on three equilibrium 2 x CO_2 GCM experiments (each displaying results close to the

continued ...

ing specific technologies that are on the horizon and their probable adoption rates, or by a combination of these.

6.5 Projecting Future Climate

In order to conduct experiments to assess the impacts of climate change, it is first necessary to obtain a quantitative representation of the changes in climate themselves. No method yet exists of providing confident predictions of future climate. Instead, it is customary to specify a number of plausible future climates. These are termed 'climatic scenarios', and they are selected to provide information that is:

- Straightforward to obtain and/or derive.
- Sufficiently detailed for use in regional impact assessment.
- Simple to interpret and apply by different researchers.
- Representative of the range of uncertainty of predictions.
- Spatially compatible, such that changes in one region are physically consistent with those in another region and with global changes.
- Mutually consistent, comprising combinations of changes in different variables (which are often correlated with each other) that are physically plausible.

Several types of climatic scenario have been used in previ-

... continued

upper end of the 1.5-4.5°C range of global mean annual temperature projections given by the IPCC) and a fourth 'low-end' scenario (in the middle of this range), based on transient model outputs. Each scenario comprised values of mean monthly changes in temperature, precipitation and solar radiation. Values from the appropriate GCM grid box were applied as adjustments to local daily or monthly climatological observations for the baseline period. The scenarios were assumed to apply in 2060, and to coincide with a CO_2 level of 555 ppmv, broadly similar to the IPCC IS92a projection (cf. Box 2).

Sea level rise associated with changing temperatures was estimated to be 37 cm between 1990 and 2060. This estimate is derived from a one metre global sea level rise by 2100, the same scenario as that used in the IPCC Common Methodology (IPCC, 1991b; cf. Box 6) but at the high end of recent estimates (see Box 3). This was added to a predicted 38 cm subsidence of the Nile Delta, giving a relative sea level rise of 75 cm by 2060.

Impacts: impacts were estimated as the difference between simulations for 2060 without climate change, based on projections of population, economic growth, agricultural production, commodity demand, land and water resources and water use (Base 2060), and simulations with changed climate according to the four climatic scenarios.

The Table provides a summary of the impacts of the four scenario climates on each sector together with the integrated impacts on economic welfare (the consumer-producer surplus). The agricultural water productivity index is an aggregate measure of impacts on agriculture: total agricultural production (tonnes) divided by total agricultural water use (cubic metres). The results illustrate how impacts on individual sectors are affected by impacts on other sectors. For example, under the GISS scenario, despite an 18 per cent increase in water resources, the 5 per cent loss of land and 13 per cent reduction in agricultural water productivity leads to a 6 per cent reduction in economic welfare. The results also demonstrate how individual sectoral assessments may give a misleading view of the overall impact, which is better reflected in the integrated analysis. For instance, under the 'low-end' scenario, while sectoral impacts are mainly positive, the integrated impact is actually a 10 per cent decline in economic welfare. This is because the rest of the world performs better than Egypt under this scenario, Egypt loses some of its competitive advantage for exports and thus the trade balance declines.

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 for the UKMO scenario. They achieve a modest 7–8 per cent 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 (in press)

Table. A comparison of sectoral with integrated impacts for the four climatic scenarios (per cent change from 2060 Base results).

	Sectoral impacts				Integrated impact
Climatic scenario	Land area	Food demand	Agricultural water productivity index	Water resources	Consumer-producer surplus
UKMO[1]	–5	–3	–45	–13	–23
GISS[2]	–5	–1	–13	+18	-6
GFDL[3]	–5	–1	–36	–78	–52
'Low-end'	–5	0	+10	+14	–10

[1] United Kingdom Meteorological Office model (Wilson and Mitchell, 1987)

[2] Goddard Institute for Space Studies model (Hansen et al., 1983)

[3] Geophysical Fluid Dynamics Laboratory model (Manabe and Wetherald, 1987)

ous impact studies. These fall into three main classes: synthetic scenarios, analogue scenarios and scenarios from general circulation models.

6.5.1 Synthetic scenarios

Synthetic scenarios describe techniques where particular climatic elements are changed by a realistic but arbitrary amount (often according to a qualitative interpretation of climate model predictions for a region). Adjustments might include, for example, changes in mean annual temperature of ± 1, 2, 3°C, etc. or changes in annual precipitation of ± 5, 10, 15 per cent, etc. relative to the baseline climate. Adjustments can be made independently or in combination.

Given their arbitrary nature, these are not scenarios in the strict sense, but they do offer useful tools for exploring system sensitivity in impact assessments. In particular, synthetic scenarios can be used to obtain valuable information on:

The sensitivity of the exposure unit to climate change, which can be expressed, for example, as a percentage change in response per unit change in climate relative to the baseline (see Box 5).

Thresholds or discontinuities of response that might occur under a given magnitude or rate of change. These may represent

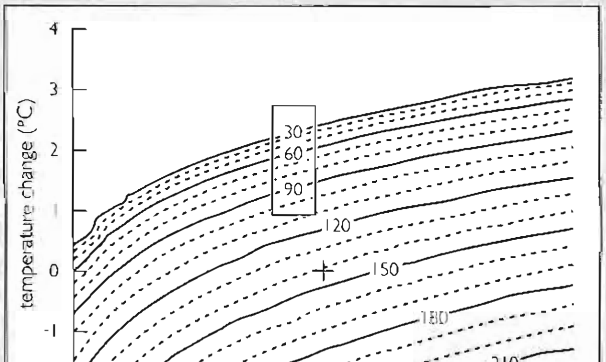
BOX 5
SENSITIVITY STUDIES AND RESPONSE SURFACES

One of the problems with adopting any single climatic scenario is that it represents only one of an infinite number of plausible future conditions. Even the more common practice of specifying a range of scenarios is limited in that first, the range may be modified in the light of new knowledge and second, the full range of projections for one variable may not coincide with the full range for another. Thirdly the number of scenarios used may not allow the identification of critical thresholds and non-linearities in the response of an exposure unit to changing climate. This latter point is especially pertinent with respect to the Framework Convention on Climate Change, which requires that levels of 'dangerous' climate change be identified.

One method of embracing a range of future climates is to develop response surfaces that depict (usually in two or three dimensions) the response of an exposure unit to all relevant and plausible combinations of climatic forcings. There are numerous derived variables of practical importance such as soil moisture, runoff, frost frequency, accumulated temperature or flood frequency and return periods, that depend in a non-linear fashion on more fundamental climatological variables such as temperature, precipitation, cloud cover and windspeed (Pittock, 1993).

The figure shows a response surface for snowcover duration, as simulated by an impact model, as a function of changes in temperature and precipitation for a location near Falls Creek in Victoria, Australia (Whetton *et al.*, 1992). The '+' symbol marks the duration for the present climate (no change) and the rectangle represents durations possible for a range of future climates given in regional scenarios produced for 2030.

Clearly, alternative climate change scenarios (e.g., for more distant time horizons, or representing updated knowledge) can readily be applied to a plot of this kind. Moreover, the response surface clearly indicates those combinations of temperature and precipitation change that would be required to produce a given (perhaps critical) response (e.g., a critical threshold of snow duration below which investment in snow removal equipment for transportation could not be economically justified).



levels of change above which the nature of the response alters (e.g., warming may promote plant growth, but very high temperatures cause heat stress), or responses which have a critical impact on the system (e.g., windspeeds above which structural damage may occur to buildings).

Tolerable climate change, which refers to the magnitude or rate of climate change that a modelled system can tolerate without major disruptive effects (sometimes termed the 'critical load'). This type of measure is potentially of value for policy, as it can assist in defining specific goals or targets for limiting future climate change (cf. Section 8.3.2).

6.5.2 *Analogue scenarios*

Analogue scenarios are constructed by identifying recorded climatic regimes which may serve as analogues for the future climate in a given region. These records can be obtained either from the past (temporal analogues), or from another region at the present (spatial analogues).

Temporal analogues are of two types: palaeoclimatic analogues based on information from the geological record, and instrumentally-based analogues selected from the historical observational record, usually within the past century. Both have been used to identify periods when the global (or hemispheric) temperatures have been warmer than they are today. Other features of the climate during these warm periods (e.g., precipitation, air pressure, windspeed), if available, are then combined with the temperature pattern to define the scenario climate. Palaeoclimatic analogues are based on reconstructions of past climate from fossil evidence such as plant or animal remains and sedimentary deposits. Three periods have received particular attention: the Mid-Holocene (5–6000 years Before Present), the Last (Eemian) Interglacial (125,000 BP) and the Pliocene (3–4 million BP) (e.g., see Budyko, 1989). Instrumentally-based analogues identify past periods of observed global-scale warmth as an analogue of a GHG-induced warmer world. Maps are constructed of the differences in regional temperature (and other variables) during these periods relative either to long term averages, or to similarly identified cold periods (e.g., see Lough *et al.*, 1983). The main problem with both these types of analogue concerns the physical mechanisms and boundary conditions giving rise to the warmer climate. Aspects of these were almost certainly different in the past from those involved in greenhouse gas induced warming.

Nevertheless, there may be value in identifying weather anomalies from the historical record that can have significant short-term impacts (such as droughts, floods and cold spells). A change in future climate could mean a change in the frequency of such events. For example, several studies have used the dry 1930s period in central North America as an analogue of possible future conditions (Warrick, 1984; Williams *et al.*, 1988; Rosenberg, 1993). Another important anomaly in many regions is the El Niño phenomenon. Changes in the frequency of this event could have significant impacts in many sectors. An extension of this idea is to select 'planning scenarios' (Parry and Carter, 1988), representing not the most extreme events, but events having a sufficient impact and frequency to be of concern (for example, a 1-in-10 year drought event) or consecutive events, whose combined effect may be greater than the sum of individual anomalies.

Spatial analogues require the identification of regions today having a climate analogous to the study region in the future (for an example, see Section 4.3.4). This approach is severely restricted, however, by the frequent lack of correspondence between other non-climatic features of two regions that may be important for a given impact sector (e.g., day length, terrain, soils or economic development).

Given these weaknesses, the use of analogue scenarios to represent future climate is not generally recommended (IPCC, 1990a, p. xxv), although there may be certain applications where they can be used in conjunction with physically-based predictions. Some examples of these are given in Appendix 1.

6.5.3 Scenarios from general circulation models

Three dimensional numerical models of the global climate system (including atmosphere, oceans, biosphere and cryosphere) are the only credible tools currently available for simulating the physical processes that determine global climate. Although simpler models have also been used to simulate the radiative effects of increasing greenhouse gas concentrations, only general circulation models, possibly in conjunction with nested regional models (see Appendix 1), have the potential to provide consistent and physically consistent estimates of regional climate change, which are required in impact analysis.

General Circulation Models (GCMs) produce estimates of climatic variables for a regular network of grid points across the globe. Results from about 20 GCMs have been reported to date (e.g., see IPCC, 1990a and 1992a). However, these estimates are uncertain because of some important weaknesses of GCMs. These include:

- Poor model representation of cloud processes.
- A coarse spatial resolution (at best employing grid cells of some 200 km horizontal dimension in model runs for which outputs are widely available to impact analysis).
- Generalized topography, disregarding some locally important features.

BOX 6

CASE STUDY: EFFECTS OF CLIMATE CHANGE ON COASTAL ENVIRONMENTS OF THE MARSHALL ISLANDS

Problem: for many low-lying coastal areas of the world, the effects of accelerated sea level rise (ASLR) associated with global climate change may result in catastrophic impacts in the absence of adaptive response strategies. Even in the absence of climate change, however, the combined pressures of growth and development will require organized adaptive response strategies to cope with an increased vulnerability of populations and economies to storms, storm surges and erosion. The Republic of the Marshall Islands consists of 34 atolls and islands in the Pacific Ocean with majority elevations below 2–3 metres above mean sea level. A vulnerability analysis case study for Majuro Atoll was conducted to provide a first order assessment of the potential consequences of ASLR during the next century.

Method: the study followed a common methodology outlined by IPCC (1991b). That methodology follows, in some respects, the general framework identified by the seven steps described in these Guidelines. However, it did not examine the comparison between future projections 'with' and 'without' climate change. Moreover, the socioeconomic impacts of the policy options were not considered explicitly. The study was concerned only with the effects of ASLR (inundation, flooding, groundwater supplies), leaving the integration of frequency and intensity of extreme events, changes in currents and tides, increased temperature and changes in rainfall patterns for the future, when regional models can simulate such changes.

Testing of method: the study included a multi-disciplinary team made up of in-country experts, regional assistance from the South Pacific Regional Environment Programme and a consulting firm which conducted oceanographic/engineering studies. The methodology proved very useful in identifying potential impacts to atolls and adaptation responses. Reliance on existing information and lack of other information placed some limitations on the study, but qualitative data obtained during the study permitted meaningful extrapolations.

Scenarios: ASLR of 1.0 m by the year 2100 was used to assess the worst case impact to shoreline communities. Three scenario cases were considered (as specified by the Common Methodology): (1) ASLR=0 for zero sea level rise, (2) ASLR=1 for 0.3m (1.0 ft.) rise, and (3) ASLR=3.3 for a 1 m (3.3 ft.) rise. Subsidence/uplift or regional variability were not taken into account due to lack of information. The effects were considered for both the ocean and lagoon side of the atoll and for four major study areas representing most environmental conditions of the atoll nation.

Impacts: the potential effects of ASLR include: (1) an approximate 10–30 per cent shoreline retreat with a dry land loss of 160 acres out of 500 acres on the most densely populated part of the atoll; (2) a significant increase in severe flooding by wave runup and overtopping with ASLR=3.3 resulting in flooding of half of the atoll from even normal yearly runup events; (3) flood frequency increases dramatically; (4) a reduction of the freshwater lens area which is important during drought periods; (5) a potential cost of protecting a relatively small portion of the Marshall Islands of more than four times the current GDP, (6) a loss of arable land resulting in increased reliance on imported foods.

Policy options: the study considered, though did not formally evaluate, the options of protection (including structural considerations), accommodation (including land elevation and adaptive economic activities for flooded areas), a retreat strategy to the highest elevations on the atoll. and a no-response strategy (including a continuation of ad hoc and crisis response measures currently used to address flooding problems). The major recommendations included the need to develop and implement integrated coastal zone management, which would incorporate ASLR response planning and begin the process of developing a baseline of understanding of the natural and human systems likely to be affected by climate change.

Source: Hotthus *et al.* (1992)

- Problems in the parameterization of sub-grid scale atmospheric processes such as convection and soil hydrology.
- A simplified representation of land-atmosphere and ocean-atmosphere interactions.

As a result, GCM outputs, though physically plausible, often fail to reproduce even the seasonal pattern of present-day climate observed at a regional scale. This naturally casts some doubt on the ability of GCMs to provide accurate estimates of future regional climate. Thus GCM outputs should be treated, at best, as broad-scale sets of possible future climatic conditions and should not be regarded as predictions.

GCMs have been used to conduct two types of experiment for estimating future climate: equilibrium-response and transient-response experiments.

Equilibrium-response experiments: the majority of experiments have been conducted to evaluate the equilibrium response of the global climate to an abrupt increase (commonly, a doubling) of atmospheric concentrations of carbon dioxide. Clearly, such a step change in atmospheric composition is unrealistic, as increases in GHG concentrations (including CO_2) are occurring continuously, and are unlikely to stabilize in the foreseeable future. Moreover, since different parts of the global climate system have different thermal inertias, they will approach equilibrium at different rates and may never approximate the composite equilibrium condition modelled in these simulations.

A measure that is widely used in the intercomparison of various GCMs, is the climate sensitivity parameter. This is defined as the global mean equilibrium surface air temperature change that occurs in response to an equivalent doubling of the atmospheric CO_2 concentration. Values of the parameter obtained from climate model simulations generally fall in the range 1.5–4.5°C (IPCC, 1992a). Knowledge of the climate sensitivity can be useful in constructing climate change scenarios from GCMs (see Appendix 1).

Transient-response experiments. Recent work has focused on fashioning more realistic experiments with GCMs, specifically, simulations of the transient-response of climate to GHG-induced forcing. The early simulations of this kind considered the transient response of climate to an instantaneous equivalent doubling of CO_2—so-called 'switch-on' experiments. More recently, simulations have been made of the climate response to a time-dependent increase in greenhouse gases (IPCC, 1990a; 1992a). Transient simulations offer several advantages over equilibrium-response experiments. First, in the recent experiments, the specifications of the atmospheric perturbation are more realistic, involving a continuous, time dependent, change in GHG concentrations. Second, the representation of the oceans is more realistic, more recent simulations coupling atmospheric models to dynamical ocean models. Third, transient simulations provide information on the rate as well as the magnitude of climate change, which is of considerable value for impact studies. Fourth, the most recent transient simulations have also discriminated between the climatic effects of regional sulphate aerosol loading (a negative forcing) and global GHG forcing (Taylor and Penner, 1994).

The interpretation of transient simulations is complicated, however, by two important problems associated with the coupling of atmospheric and ocean models. First, the models commonly exhibit drift in the control simulation, such that the global mean temperature at the end of the simulation deviates from that at the start. This may be an expression of natural climatic variability, or a result of poor initialization of the ocean model or errors in the coupling of the ocean and atmosphere models. Second, transient simulations exhibit the so-called 'cold start' problem (Hasselmann *et al.*, 1993). This refers to the assumption that the climate is in equilibrium at the start of a simulation, with GHG concentrations representative of conditions in recent decades. However, this is not the case, as there has been a considerable build-up of GHGs since pre-industrial times, and the recent climate is certainly not in equilibrium. Thus, for the first few decades of a simulation, global warming is strongly inhibited by the inertia of the ocean-atmosphere system. One result of this is that it becomes very difficult to assign calendar dates to the climate changes simulated, because although the timing of GHG forcing is consistent with projections, the timing of the climate response is not. A method of constructing transient climatic scenarios that sidesteps this problem is illustrated in Appendix 1 (Box A2).

Ongoing work is attempting to address the cold start problem, by simulating the climate response to GHG concentrations during the past century. This type of simulation has the useful additional feature of allowing comparisons to be made between the modelled behaviour of the climate and the climate actually observed during the instrumental period.

Additional problems with transient simulations include the inability of current ocean models adequately to resolve boundary currents and deep convection, and their poor performance in reproducing the El Niño/Southern Oscillation (ENSO) phenomenon.

Information from GCMs. The following types of information are available from GCMs for constructing scenarios:

- Outputs from a 'control' simulation, which assumes recent GHG concentrations, and an 'experiment' which assumes future concentrations. In the case of equilibrium-response experiments, these are values from multiple-year model simulations for the control and 2 x CO_2 equilibrium conditions. Transient-response experiments provide values for the control equilibrium conditions and for each year of the transient model run (e.g., 1990 to 2100).
- Values of surface or near-surface climatic variables for model grid boxes characteristically spaced at intervals of several hundred kilometers around the globe.
- Values of air temperature, precipitation (mean daily rate) and cloud cover, which are commonly supplied for use in impact studies. Data on radiation, windspeed, vapour pressure and other variables are also available from some models.
- Data averaged over a monthly time period. However, daily or hourly values of certain climatic variables, from which the monthly statistics were derived, may also be stored for a number of years within the full simulation periods.

Some alternative procedures for constructing regional climatic scenarios from GCM information are detailed in Appendix 1.

6.6 Projecting Environmental Trends with Climate Change

Projections must be made for each of the environmental variables or characteristics of interest in the study and included in the description of environmental trends in the absence of climate change. These projections are made using the climate projections and the biophysical models selected for the study (as described in Section 4.2.1). Because all changes in environmental conditions not due to climate factors should already have been incorporated in the development of the environmental trends in the absence of climate change, the only changes in the trends to be incorporated here are those due solely to climate change.

Future changes in climate can be expected to modify some of the environmental trends outlined in Section 6.3. Furthermore, there are likely to be a set of additional environmental changes that are directly related to the changes in climate themselves. The two factors most commonly required in assessments are greenhouse gas concentrations and sea level rise.

Projections of greenhouse gas concentrations are important for assessing effects first, on radiative forcing of the climate, second, on depletion of stratospheric ozone (e.g., CFCs) and third, on plant response (e.g., CO_2 and tropospheric ozone). In applying them, however, they should be consistent with the projected climate changes (see Section 6.2.2, above). Scenarios for CO_2 concentrations are given in Box 3.

Sea level rise is one of the major impacts projected under global warming. Global factors such as the rate of warming, expansion of sea water, and melting of ice sheets and glaciers all contribute to this effect (see Box 3). However, local conditions such as coastal land subsidence or isostatic uplift should also be taken into account in considering the extent of sea level changes and their regional impacts. In most assessments, the vulnerability of a study region to the effects of sea level rise will be apparent (e.g., in low lying coastal zones; see Box 6). Less obvious are some inland locations which may also be affected (for example, through sea water incursion into groundwater). The magnitude of future sea level rise is still under discussion, but the estimates given in Box 3 (which are consistent with the other changes shown in the Box) may serve as a useful basis for constructing scenarios.

Other factors that are directly affected by climate include river flow, runoff, soil characteristics, erosion and water quality. Projections of these often require full impact assessments of their own, or could be included as interactive components within an integrated assessment framework (see Section 4.2.3).

6.7 Projecting Socio-economic Trends with Climate Change

The changes in environmental conditions that are attributable solely to climate change serve as inputs to economic models that project the changes in socio-economic conditions due to climate change over the study period. All other changes in socio-economic conditions over the period of analysis are attributable to non-climatic factors and should have been included in the estimation of socio-economic changes in the absence of climate change.

Socio-economic factors that influence the exposure unit may themselves be sensitive to climate change, so the effects of climate should be included in projections of those. In some cases this may not be feasible (e.g., it is not known how climate change might affect population growth) and trends estimated in the absence of climate change would probably suffice (see Section 6.4). In other cases, projections can be adjusted to accommodate possible effects of climate (for example, there are quantifiable effects on human health of the interaction between local climate and atmospheric pollution and toxic waste disposal in many urban areas, the causes of which are closely associated with emissions and bi-products of fossil fuel combustion.).

There are also many human responses to climate change that are predictable enough to be factored-in to future projections. These are often accounted for in model simulations as feedbacks or 'autonomous adjustments' to climate change and are considered in Section 8.2.

A final factor to consider in projecting socio-economic trends under a changing climate is the effect that various policies designed to mitigate climate change might themselves have on the future state of the economy and society. For example, polices to reduce fossil fuel consumption through higher energy prices might alter the pattern of economic activity, thus modifying the possible impacts of any remaining (unmitigated) changes in climate that occur.

STEP 5: ASSESSMENT OF IMPACTS

7

Impacts are estimated as the differences over the study period between the environmental and socio-economic conditions projected to exist without climate change (the future baseline), and those that are projected with climate change. This definition can be extended to include consideration of adaptation in the estimation of impacts with climate change. Up to now, few climate impact studies have paid adequate attention to adaptation. Further, many studies have assumed a fixed baseline, often failing to recognize that conditions in the future will be quite different from those at present, even in the absence of climate change. In practice, however, construction of the future baseline is often fraught with difficulties relating to the projection of highly uncertain socio-economic and environmental scenarios (cf. Section 6), and a fixed baseline at least offers a ready reference for sensitivity testing. Moreover, there are certain impact studies, particularly those involving biophysical systems, that are fully justified in using a fixed baseline (e.g., hydrological studies of pristine river catchments). These different approaches to impact assessment are illustrated in Box 7.

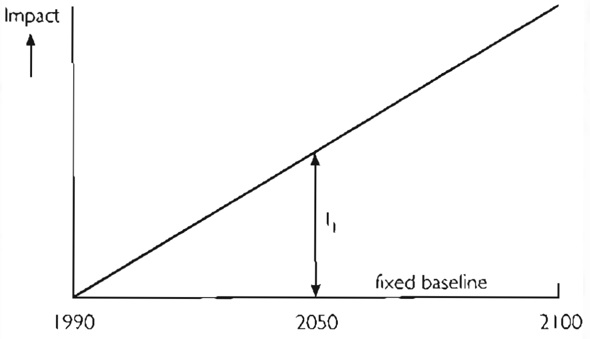
BOX 7
DIFFERING APPROACHES TO THE ASSESSMENT OF IMPACTS

The three figures illustrate schematically how differing degrees of realism in assessing impacts result from alternative assumptions about the baseline and from consideration of various types of adaptation. In Figure (a), impacts in the year 2050 (I_1) are portrayed as the cumulative effects of future climate change on an exposure unit, assuming a fixed baseline (i.e., no concomitant changes in the environmental, technological, societal and economic conditions relative to the present). This unrealistic, though readily applicable representation of the future is characteristic of many early climate impact assessments.

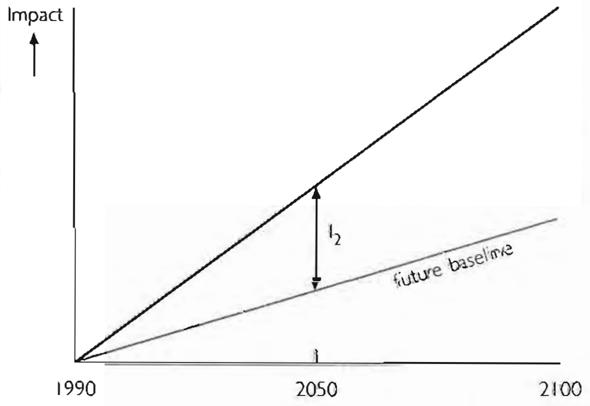
Figure (b) shows how more realism is introduced if impacts of future climate change are evaluated relative to a future baseline without climate change. The impact relative to the future baseline may be greater or, as is shown in Figure (b), less than the impact relative to the fixed baseline (I_2).

However, this approach still ignores the many adjustments and adaptations that would occur either in expectation of or in response to impacts of climate change. These are shown in Figure (c), which distinguishes between two types of adaptation: autonomous adjustment, which is implemented immediately (often unconsciously) as part of the normal package of measures available to organisms or systems for coping with climatic variability; and deliberate adaptation, which involves conscious actions to mitigate or exploit the effects of climate change. In most cases (as in Figure (c)), the objective of adaptation is to reduce the negative impacts of climate change (I_3 and I_4, respectively).

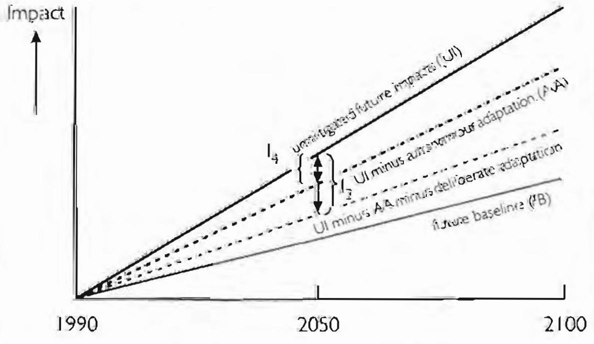
(a) Impacts of climate change relative to a fixed baseline



(b) Impacts of climate change relative to a future baseline



(c) Impacts of climate change relative to a future baseline following adaptation



The evaluation of results obtained in an assessment is likely to be influenced in part by the approach employed, and in part by the required outputs from the research. Some of the more commonly applied techniques of evaluation are described below.

7.1 Qualitative Description

An evaluation may rely solely on qualitative or semi-quantitative assessments, in which case qualitative description is the common method of presenting the findings. The success of such evaluations usually rests on the experience and interpretative skills of the analyst, particularly concerning projections of possible future impacts of climate (see, for example, Box 8). The disadvantages of subjectivity in this 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).

BOX 8
CASE STUDY: HEALTH IMPACTS OF ENVIRONMENTAL CHANGES IN HONDURAS

Background: in the past two decades the landscape of Honduras, a mountainous, tropical nation in Central America with 5.5 million inhabitants, has been transformed through overgrazing, monoculture agriculture and deforestation. In the southern region, soil dessication and erosion caused by intensive agriculture has altered the hydrological cycle, and mean temperatures have risen. Deforestation in central and northern Honduras has affected water basins and water availability. These meteorological and ecological changes have already affected the distribution of vector-borne diseases.

Problem: to examine the role of climate in influencing the distribution, abundance and transmission of vector-borne diseases (VBDs) in Honduras.

Method: the assessment was qualitative, based on expert judgement.

Testing of method: the method involved the empirical compilation of available data on recent trends in climate, land use, pesticide use, population density and prevalence of VBDs, and their geographical and temporal integration.

Scenarios: the study considered qualitative scenarios of climatic warming along with increased climatic instability, including more frequent droughts and floods, and all trends that are already being observed. Short term trends in other environmental and socio-economic factors were also examined in evaluating potential health risks.

Impacts: attention was paid to the current status and trends in a number of common VBDs, which act both directly and indirectly on humans.

Malaria: in southern Honduras, changes in land use and subsequent soil dessication and erosion during the past two decades have disrupted the hydrological cycle, leading to a recorded increase in median annual temperature in the order of 5–10°C between the early 1970s and late 1980s. This temperature increase has rendered the region too hot for anopheline mosquitoes, and the incidence of malaria has fallen. However, the concomitant aridification of the region has forced people to move away to the cities, plantations and assembly farms further north. Large areas of north-east tropical rainforest have been cleared, and migrants concentrated there tend to be non-immune to malaria. The indiscriminate use of pesticides in banana, pineapple and melon plantations has led to widespread anopheline resistance. In 1987, 20,000 cases of malaria were registered in Honduras; in 1993, 90,000 cases were recorded, of which 85 per cent were in northern regions.

Chagas' disease: 'Kissing bugs' (*Rhodnius prolixis* and *Triatoma dimitata*) are the chief vectors of Chagas' disease, and opossums, rats, armadillos, cats and dogs are among its reservoirs. Massive environmental changes such as deforestation, have altered all components in the life cycle and, deprived of habitat, sustenance and blood meals, reservoirs and bugs alike move to peri-urban areas. Chagas' (a chief cause of heart disease) is expected to increase under higher temperatures due to a shortening of insect generation time, the stimulation of blood meal seeking and an increasing frequency of active parasites, all of which amplify vector abundance and transmission.

Other VBDs: Dengue fever is increasing as *Aedes spp.* breeding sites swell in peri-urban areas. The advance of *Ae aegypti* (another vector whose maturation and generation are accelerated by warmth), plus the spread of the cold-hardy *Ae albopictus*, are increasing concern throughout Latin America, and yellow fever is in resurgence.

Indirect effects through nutrition: the common bean *(Phaseolus vulgaris)* is the principal source of protein in the diet of the poor in Latin America. Whitefly *(Bemisia tabaci)* has recently emerged as a serious vector of geminiviruses, including the bean golden mosaic geminivirus (BGMV) which has devastated bean crops in some years. Whitefly outbreaks have been exacerbated in recent years by frequent and severe droughts. Over 60 per cent of Honduran children under 10 years are malnourished, and the loss of the staple crops to vector-borne plant pathogens further stunts growth and development, reduces immunity and increases the burden of communicable illness.

Adaptation options: Intervention to control VBDs with insecticides and medication have time-limited effectiveness, and can increase vulnerability by eliminating predators of pests and selecting resistant strains. Vaccines in development hold some promise. However, anticipatory adjustments and improved management of ecosystems (forests, watersheds, mangroves) are options that may enhance the resilience to climatic stresses and improve resistance against the redistribution of opportunistic species.

Source: Almendares *et al.*, (1993)

BOX 9 CROSS IMPACTS ANALYSIS

Figure I. An interaction matrix for forest impacts (after Martin and Lefebvre, 1993)

Variable Names	Climate Change	CO_2 Enrichment	Forest microclimate	Fire	Pathogens	Tree birth	Tree growth	Tree death	Forest area	Nutrient cycling	Trace gas emissions	Chemistry	Aquatic ecosystems	Wildlife	Forest products industry	Fisheries	Recreation	Economics	*Row sum (driving power)*
Climate Change			1	1		1	1	1					1	1			1		8
CO_2 Enrichment	1		1				1	1					1						5
Forest microclimate				1	1	1	1	1		1	1	1	1	1			1		11
Fire					1	1	1	1	1	1	1			1			1		9
Pathogens						1	1	1											3
Tree birth									1					1	1	1			4
Tree growth				1		1			1	1	1			1	1		1		8
Tree death				1		1			1	1	1		1	1	1		1		9
Forest area	1			1							1			1	1		1		6
Nutrient cycling						1	1	1			1		1	1					6
Trace gas emissions												1							1
Chemistry	1					1	1	1											4
Aquatic ecosystems						1											1		2
Wildlife						1	1	1		1	1						1		6
Forest products industry						1	1	1										1	4
Fisheries													1					1	2
Recreation						1	1	1					1	1				1	6
Economics																			0
Column sum (dependency)	3	0	2	5	2	12	10	10	4	5	7	2	7	9	4	1	9	3	

Cross impacts analysis (Holling, 1978) is a method of highlighting and classifying the relationships between key elements of a system. It entails identifying the pertinent variables of the system, and entering these into an interaction matrix, which represents the relationships between the different variables. If one variable exerts a direct influence on the other variable, an entry is made in the appropriate cell of the matrix. The entry can simply indicate presence or absence of an influence (a special case of cross impacts analysis termed structural analysis), or it can be assigned a quantitative weight to indicate the strength of the influence. Additionally, some measure of uncertainty in the relationship may also be given (e.g., see Clark, 1986). By summing the cell values by rows and columns, a measure is obtained of the driving power or influence of a variable (row sums) and dependency of a variable (column sums).

An example of a cross impacts (structural) analysis for impacts of climate change on forests is given in Figure I (Martin and Lefebvre, 1993). Only the presence or absence of an influence are indicated. For example, climate change is shown to influence forest microclimate, fire, tree birth, tree growth, tree death, aquatic ecosystems, wildlife and recreation: a total driving power (row sum) of 8. Similarly, pathogens are influenced by forest microclimate and fire, giving a total dependency (column sum) of 2.

Variables can now be categorized into four types: autonomous variables (weak drivers and weakly dependent), result variables (weak drivers and strongly dependent), relay variables (strong drivers and strongly dependent) and forcing variables (strong drivers and weakly dependent). These can readily be distinguished by plotting the row and column totals on a driving power/dependency graph (Figure II). In this example, forest microclimate appears to be more of a forcing variable than climate change from the standpoint of the forest. Moreover, by these criteria, tree growth and tree death should constitute good indicators of climate change and could be usefully monitored to determine the future of the forest.

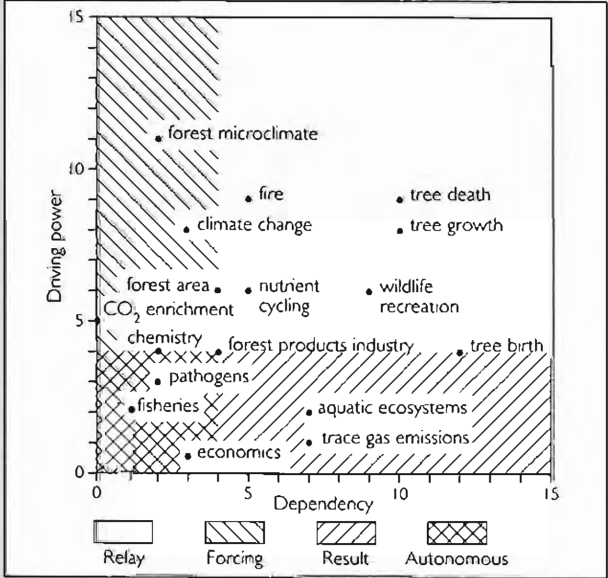
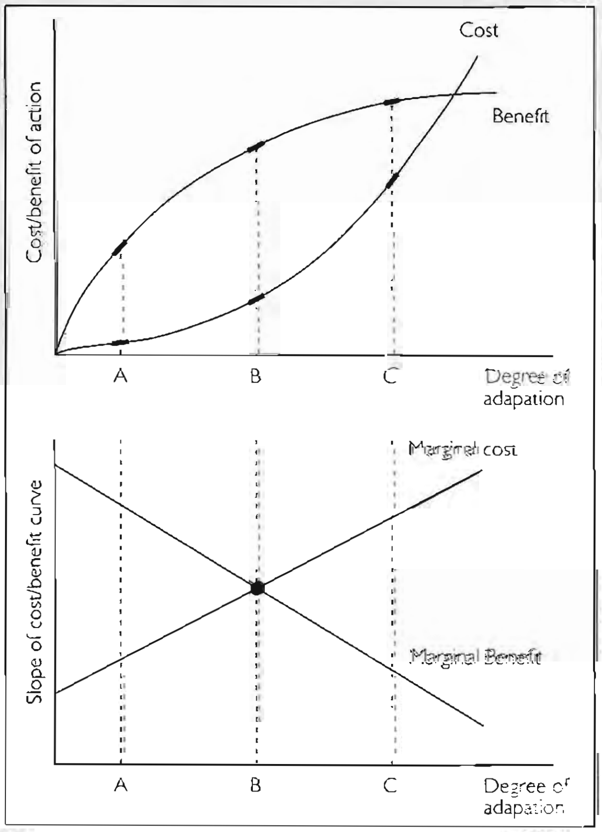


Figure II. Outcomes of the forest impacts structural analysis (after Martin and Lefebvre, 1993)

BOX 10
COST-BENEFIT ANALYSIS

Cost-benefit analysis has the specific objective of evaluating an anticipated decision or range of decision responses. For example, in considering the costs and benefits of an adaptation strategy, a cost-benefit analysis might seek to evaluate a question facing a decision maker: 'Do the benefits of a given level of adaptation outweigh the costs of its implementation?' The benefits of this action are the avoided damages (i.e., costs) of impacts of climate change (evaluated, for instance, using models of the type described in Section 4.2.2).

The problem can be illustrated in a simple diagram (see figure). In the upper graph, the degree of adaptation is expressed as two lines: one representing the costs of adaptation and the other the benefits (avoided costs) accruing from this action. Both lines show increases with increasing levels of adaptation, but the growth in costs accelerates, while the growth in benefits diminishes. Characteristically, the costs of minimal adaptation are small while the benefits are high (e.g., at point A), but as the level of adaptation increases, so the additional or marginal costs increase, while the marginal benefits decline. These are the slopes of the two lines in the upper graph, plotted as straight lines in the lower graph. Economic analysis generally concludes that the optimal result is where the marginal cost and marginal benefit of the change are equal (point B on the graph). To the left of point B further action is beneficial, because the additional (marginal) benefits secured exceed the additional (marginal) costs. Further adaptation beyond point B produces an unfavourable cost-benefit ratio (e.g., at point C) and is therefore not justified.



A more formal method of organizing qualitative information on impacts of climate change, cross impacts analysis, is illustrated in Box 9.

7.2 Indicators of Change

A potentially useful method of evaluating both the impacts of climate change and the changes themselves is to focus on regions, organisms or activities that are intrinsically sensitive to climate. For example, climate change might affect the altitude at which certain temperature-limited vector-borne diseases are found, and high altitude sites in Kenya, Rwanda, Costa Rica and Argentina have been suggested as potential foci for monitoring both of the vectors themselves, and of the populations at risk (Haines *et al.*, 1993). Similarly, changes in plant behaviour may indicate that certain critical thresholds of temperature change have been approached or exceeded. For instance, an increasing frequency of events where plants fail to flower may suggest that the chilling (vernalization) requirements of the plant have not been fulfilled. Another example is low-lying coastal zones at risk from inundation due to rising sea level, and the vulnerable populations located in such regions.

7.3 Compliance to Standards

Some impacts may be characterized by the ability to meet certain standards which have been enforced by law. The standards thus provide a reference or an objective against which to measure the impacts of climate change. For example, the effect of climate change on water quality could be gauged by reference to current water quality standards.

7.4 Costs and Benefits

Perhaps the most valuable results that can be provided to policy makers by impact assessments are those which express impacts as potential costs or benefits. Methods of evaluating these range from formal economic techniques such as cost-benefit analysis to descriptive or qualitative assessments.

Cost-benefit analysis is often employed to assess the most efficient allocation of resources (see Box 10). This is achieved through the balancing or optimization of 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 a common metric. Thus, for example, where monetary values are ascribed, this should be 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 also varies from country to country, should be explicitly considered in the calculations.

Formal cost-benefit analysis proceeds on the basis of applying a single money metric for costs and benefits as far as is possible and credible. In the context of global warming, the relevant costs are the costs of mitigation and adaptation. These will tend to be expressed in terms of marketed resources such as labour and capital costs. The benefits of mitigation and adapta-

BOX 11 CASE STUDY: EFFECTS OF CLIMATE CHANGE ON NATURAL TERRESTRIAL ECOSYSTEMS IN NORWAY

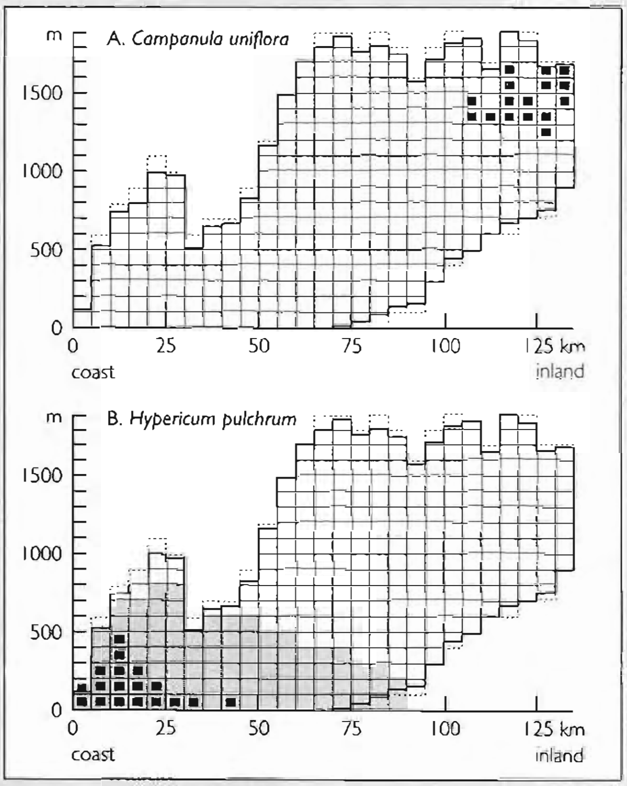
Problem: the objectives of this assessment were to examine the probable patterns of ecological change in Norway under a changed climate regime, with a particular emphasis on identifying plant species and communities sensitive to or at risk from climate change.

Methods: in part descriptive, based on expert judgement, and in part using correlative models of species distribution. All methods examined the potential impacts of climate change as defined in a specific climatic scenario for Norway.

Testing of methods/sensitivity: correlative models are based on the spatial coincidence of vegetation species and climatic variables under present-day climate. They are very simple to apply, but have the disadvantage that they do not provide an ecophysiological explanation of the observed plant distributions, although they usually represent hypotheses about which factors control or limit those distributions. The models can really only be tested against palaeoecological evidence of plant distributions from previous cool or warm periods, where the contemporary climatic information is derived from independent sources (e.g., insect evidence).

Scenarios: a seasonal scenario for an equivalent doubling of CO_2 was used, based on a subjective composite of results from several GCMs for the Norwegian region.

Impacts: the effects of climate change on species distribution were estimated using a narrow west-east transect through central Norway, giving altitude on the vertical axis and distance from the Atlantic coast on the horizontal axis. Dashed boxes indicate variations in altitude at site locations within the transect. Figures A and B illustrate the sensitivity of two species: *Campanula uniflora* (a rare alpine and continental species) and *Hypericum pulchrum* (a frost sensitive coastal species) to the climate changes described by the scenario. Solid squares indicate the current and shaded squares the predicted distribution of a species. The analysis suggests that rare northern or Alpine species may be threatened by extinction (Figure A), both due to shifts in climate and to changes in snow cover and runoff. Temperate and oceanic zone species would be favoured under the changed climatic regime (Figure B), but their colonization could be delayed by anthropogenic or natural barriers.



Source: Holten and Carey (1992)

tion are expressed in terms of avoided warming damages. In turn, these damages may show up in terms of market values—lost crops, forest damage etc., and in non-market values—changes in human health, changes in amenity and biodiversity, for example. As far as what counts in assessing damages, the distinction between market and non-market values is immaterial: both contribute to human well-being, which is the ultimate yardstick of cost-benefit assessments. In practice, both types of value raise complex issues. Market values may not, for example, represent the true value of resources to a given economy, e.g., in the presence of taxes or subsidies or if environmental costs are neglected. In this case, they have to be adjusted to secure their 'shadow' values which measure the cost of the damage to society as a whole. Non-market values have to be elicited by direct and indirect methods such as contingent valuation, hedonic property and wage models, travel cost measures, etc. The resulting estimates should, like shadow market values, reflect the underlying willingness of individuals to pay for the commodity, asset or service that is at risk.

There is extensive economic literature on both the methodologies for valuing non-market damages, and on empirical estimates (for an overview, see Pearce, 1993).

7.5 Geographical Analysis

One common feature of the different approaches to climate impact assessment is that they all have a geographical dimension. Climate and its impacts vary over space, and this pattern of variation is likely to change as the climate changes. These aspects are of crucial importance for policy makers operating at regional, national or international scale, because changes in resource patterns may affect regional equity, with consequent implications for planning.

Thus the geographical analysis of climate changes and their impacts, where results are presented as maps, has received growing attention in recent years. This trend has been paralleled by the rapid development of computer-based geographical information systems (GIS), which can be used to store, analyse, merge and depict spatial information.

The applications of GIS in climate impact analysis include:

- Depicting patterns of climate (past, present or projected).
- Using simple indices to evaluate the present-day regional potential for different activities based on climate and other environmental factors (e.g., crop suitability, energy demand, recreation, water resources). The indices can then be compared with observed patterns of each activity as a validation test.

- Mapping changes in the pattern of potential induced by a given change in climate. In this way the extent and rate of shift in zones of potential can be evaluated for a given change in climate.
- Identifying regions of particular sensitivity and vulnerability to climate, which may merit more detailed examination (for example, regions where, on the basis of the map analysis, it may be possible, under a changed climate, to introduce new crop species).
- Considering impacts on different activities within the same geographical region, so as to provide a compatible framework for comparison and evaluation (e.g., to consider the likely competing pressures on land use from agriculture, recreation, conservation and forestry under a changed climate).

A simple ecological example is given in Box 11. As computer power improves, the feasibility of conducting detailed modelling studies at a regional scale has been enhanced. The main constraint is on the availability of detailed data over large areas, but sophisticated statistical interpolation techniques and the application of stochastic weather generators to provide artificial climatological data at a high time resolution, may offer partial solutions.

7.6 Dealing with Uncertainty

Uncertainties pervade all levels of a climate impact assessment, including the projection of future GHG emissions, atmospheric GHG concentrations, changes in climate, future socio-economic conditions, potential impacts of climate change and the evaluation of adjustments. There are two methods which attempt to account for these uncertainties: uncertainty analysis and risk analysis.

7.6.1 Uncertainty analysis

Uncertainty analysis comprises a set of techniques for anticipating and preparing for the impacts of uncertain future events. It is used here to describe an analysis of the range of uncertainties encountered in an assessment study. These arise from two sources, here referred to as 'errors' and 'unknowns'.

Errors may arise from several sources, including measurement error, paucity of data and inadequate parameterization or assumptions. Unknowns include alternative scenarios, or the omission of important explanatory variables. The maximum range of uncertainty is the product of the individual uncertainties. The upper and lower bounds of these may be highly improbable, so more useful alternatives are confidence limits (e.g., 5 or 95 percentiles), which can be computed by studying the probability of uncertainties propagating, using methods such as Monte Carlo analysis (for energy and GHG emissions examples, see Edmonds *et al.*, 1986 and de Vries *et al.*, 1994; for a health impacts example, see Martens *et al.*, 1994; for an agricultural example, see Brklacich and Smit, 1992). These percentiles are often used as upper and lower estimates of an outcome, with the mean or median outcome used as the 'best' or 'central' estimate. The quantification of uncertainty arising from inadequate parameterizations or assumptions is more problematic, however, as probabilities cannot readily be assigned to different choices.

7.6.2 Risk analysis

Risk analysis deals with uncertainty in terms of the risk of impact. Risk is defined as the product of the probability of an event and its effect on an exposure unit. It has been argued that future changes in average climate are likely to be accompanied by a change in the frequency of extreme or anomalous events, and it is these that are likely to cause the most significant impacts (Parry, 1990). Thus there is value in focusing on the changing risk of climatic extremes and of their impacts. This approach can then be helpful in assessing the potential risk of impact relative to predefined levels of acceptable or tolerable risk. It is important to stress, however, that while occurrence probabilities of hypothetical climatic events are relatively straightforward to compute, it is not generally possible to ascribe any degree of confidence to probabilities of future impacts.

In those disciplines that inherently deal with probabilities, frequencies and statistical information to characterize natural hazards (floods, storms, waves, earthquakes, streamflow) and design criteria for control structures, the application of risk and uncertainty analysis is a central feature of decision-making. Extensions of commonly used methods that have evolved for dealing with historical climatic variability can be employed for climate change impact studies, especially in the important areas of hydrology, water management and shore protection (Stakhiv *et al.*, 1991; 1993).

Another form of risk analysis—decision analysis—is used to evaluate response strategies to climate change. It can be used to assign likelihoods to different climatic scenarios, identifying those response strategies that would provide the flexibility, at the least cost (minimizing expected annual damages), that best ameliorates the anticipated range of impacts (for a water resources example, see Fiering and Rogers, 1989).

A method for evaluating responses to rare and extreme hydrological events—multiobjective risk partitioning—has been developed by Haimes and Li (1991), which combines both risk and uncertainty of individual events with a decision tree framework, in order to identify solutions that best accommodate the range of uncertainty.

STEPS 6 AND 7: ASSESSMENT OF AUTONOMOUS ADJUSTMENTS AND EVALUATION OF ADAPTATION STRATEGIES

8

Impact experiments are usually conducted to evaluate the effects of climate change on an exposure unit in the absence of any responses which might modify these effects. Two broad types of response can be identified: mitigation and adaptation (Figure 5).

8.1 Mitigation and Adaptation

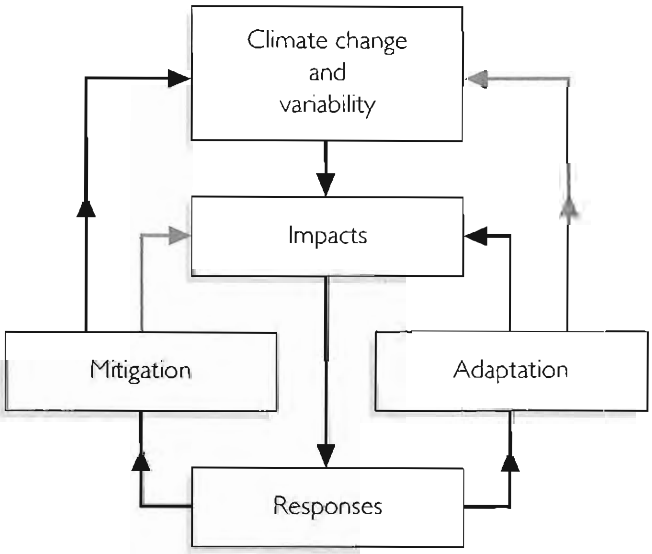
Mitigation or 'limitation' attempts to deal with the causes of climate change. It achieves this through actions that prevent or retard the increase of atmospheric greenhouse gas (GHG) concentrations, by limiting current and future emissions from sources of GHGs (e.g., fossil fuel combustion, intensive agriculture) and enhancing potential sinks for GHGs (e.g., forests, oceans). In recent years there has been a heavy focus on mitigation as a major strategy for coping with the greenhouse problem. However, it seems likely that realistic policies of mitigation will be unable fully to prevent climate changes, and that alternative adaptive measures are needed.

Adaptation is concerned with responses to both the adverse and positive effects of climate change. It refers to any adjustment, whether passive, reactive or anticipatory, that can respond to anticipated or actual consequences associated with climate change. Many policies of adaptation make good sense in any case, since present-day climatic variability (in the form of extreme climatic events such as droughts and floods) already causes significant damage in different parts of the world. Adaptation to these events can thus help to reduce damage in the short term, regardless of any longer-term changes in climate.

While mitigation and adaptation are complementary responses, as both are needed, the evaluation of mitigation policies is outside the scope of these Guidelines. For more information on this topic, the reader is directed to parallel work by Working Group III of the Intergovernmental Panel on Climate Change.

Yet the identification and evaluation of adaptation options is an essential component of impact assessment. In this section, a basic distinction is drawn between system responses to climate change that are automatic or built-in (termed autonomous adjustments), and responses that require deliberate policy decisions, described as adaptation strategies. While there are some overlaps between these two types of adaptation, they are allocated separate steps in the assessment framework (Figure 4) in recognition of the different treatment they usually receive in assessment studies.

Figure 5. Pathways of response: mitigation and adaptation. Black lines indicate direct effects or feedbacks; grey lines depict secondary or indirect effects (after Smit, 1993)



8.2 Assessment of Autonomous Adjustments

Most ecological, economic or social systems will undergo some natural or spontaneous adjustments in the face of a changing climate. These 'autonomous' adjustments are likely to occur in response both to gradual changes in average climate (which themselves may be barely imperceptible relative to background climatic variability) as well as to more drastic shifts in climate, for example, those associated with a change in dominant atmospheric circulation patterns. What is much less certain, however, is what forms these adjustments will take and what costs they will incur. Clearly, in order to obtain credible estimates of impacts, there is a need to account for these autonomous adjustments in the assessment process (Smit, 1993; Rosenberg, 1992).

Within the broad class of autonomous adjustments it may be instructive to distinguish three groups according to their 'degree of spontaneity': inbuilt, routine and tactical adjustments.

8.2.1 Inbuilt adjustments

Inbuilt adjustments, sometimes referred to as physiological adjustments, are the unconscious or automatic reactions of an exposure unit to a climatic perturbation. Some of these are easy to identify (for example, the automatic response of a plant to drought conditions is to reduce transpiration water loss by closing its stomata), and can be accounted for in models that describe the system. Others are more difficult to detect (for instance, the ability of long-lived organisms such as trees to acclimate to a slowly changing climate). These may require the implementation of some controlled experiments to determine the nature of the adjustment mechanisms (for example, by transplanting tree species between different climatic regimes to investigate the processes of acclimation in a changed environment; see Beuker, 1994).

8.2.2 Routine adjustments

Routine adjustments refer to everyday, conscious responses to variations in climate that are part of the routine operations of a system. For example, as the climate changes, the growing season for crop plants would also change, and crop performance might be improved by shifting the sowing date. In some crop growth models the sowing date is determined by climate (e.g., the start of the rainy season or the disappearance of snow cover), so it is selected automatically to suit the conditions. Here, the model is performing internally an adjustment that a farmer might do instinctively or routinely.

8.2.3 Tactical adjustments

Tactical adjustments imply a level of response over and above the adjustments that are made routinely in the face of climatic variability. Such adjustments might become necessary following a sequence of anomalous climatic events, which indicate a shift in the climate. For example, a run of years with below-average rainfall in a semi-arid region may persuade farmers that cultivation of a drought-resistant crop like sorghum is more reliable than a drought-sensitive crop like maize, in spite of its lower yield capacity than maize in favourable conditions. Adjustments of this type require a behavioural change, but can still be accommodated internally within the system. There are numerous examples of assessments that consider these small-scale, low cost adjustments (e.g., the MINK study, see Box 13; and a study of world food supply, Rosenzweig and Parry, 1994).

In moving towards a more interventionist type of adjustment, however, the distinction between autonomous adjustments and adaptation starts to become blurred. For instance, it is not always a straightforward task to separate out autonomous tactical adjustments that are directly related to climate change from adjustments that are made to changing external conditions, which are themselves an adaptive response to climate change (such as government assistance to farmers to cope with adverse climatic conditions). The evaluation of these 'exogenous' adaptations is examined in the following section.

8.3 Steps in the Evaluation of an Adaptation Strategy

In this section, types of adaptation are described and procedures presented for identifying, classifying and evaluating available options for decision making. For more information on adaptation strategies, Chapter 6 of the 1990 IPCC Response Strategies report (IPCC, 1991a) provides a good overview of the range of issues and ideas that should be considered in developing a coherent approach. Moreover, several countries (including Australia, Canada, and the USA) are actively pursuing the development of protocols for the assessment of adaptation to climate change.

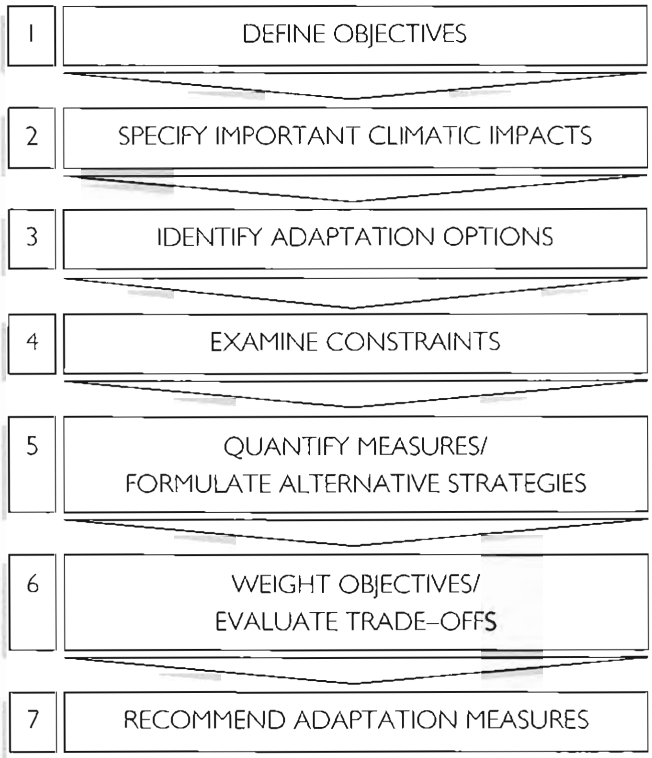
At present there are no generally accepted procedures for formulating national and regional policies for adaptation to climate change, one of the reasons being that the assessment process involves value judgements, which can be both subjective and controversial. Nevertheless, formal evaluation procedures do exist to address analogous problems as part of the planning process in many developed countries. By drawing on the experiences gained in formulating those planning guidelines, a broad framework for the evaluation of adaptation strategies to cope with climate change can be identified. As with the general framework for assessing climate impacts, the framework for developing adaptation strategies also comprises seven steps (Figure 6).

8.3.1 Defining the objectives

Any analysis of adaptation must be guided by some agreed goals and evaluation principles. It is not sufficient merely to state that adverse impacts should be avoided, reduced or eliminated. Two examples of general *goals* commonly propounded by international institutions and conventions are: (i) the promotion of sustainable development, and (ii) the reduction of vulnerability. However, these are so broad that they are open to many different interpretations, so specific objectives need to be defined that complement the goals.

Objectives are usually derived either from public involvement, from stated public preferences, by legislation, through an interpretation of goals such as those described above, or any combination of these. They represent desired targets which can be evaluated using specified criteria and constraints. Table 2 illustrates three possible objectives that might be selected to achieve each of the two different goals described above, and the evaluation criteria that can be used to measure their success. Most of these are quantitative measures (e.g., income, employment); others like biodiversity can be quantified, but not in economic terms.

Figure 6. Development of an adaptation strategy



A common, shared set of evaluation principles and decision rules is an important aspect of analysis. The scientific and technical part of the climate impact assessment provides most of the information concerning physical effects and direct social and economic impacts on the main resource-dependent sectors. The options to ameliorate or modify the adverse primary impacts all have their own economic, social and environmental benefits and costs. It is not always apparent what these are, since they differ among resource use sectors and the public.

Virtually all forms of cost-benefit analysis follow the basic decision rule that for any action, project, programme or strategy, the benefits must exceed the costs, however they are measured. Benefits are measured relative to a set of desired targets or planning objectives, which reflect a notion of what needs to be achieved. Those objectives can further be quantified by conventional measures of relative worth, termed evaluation criteria (e.g., income, employment, change in habitat acreage, population at risk, etc.). Constraints may also be part of an evaluation framework, defining a set of bounds that are considered acceptable (for example, a 100-year return period event or a minimum habitat size for a species based on per capita water availability).

8.3.2 Specifying the climatic impacts of importance

This step involves an assessment, following the methods outlined elsewhere in this report, of the possible impacts of climate variability or change on the exposure unit. Where climatic events are expected that will cause damage, these need to be specified in detail so that the most appropriate adaptation options can be identified. Where beneficial climatic events are anticipated, these should be examined, both in their own right and because they may help to compensate for negative effects. Details include the magnitude and regional extent of an event, its frequency, duration, speed of onset and seasonality (i.e., timing during the year). In the case of long-term climate change, impacts should be considered relative to those that would be expected to occur in the absence of climatic change. Moreover, since there is often great scientific uncertainty attached to projections, it may be useful to express possible changes in terms of the probability of their occurrence and/or as changes in the recurrence frequency of events observed in the historical climatological record.

One general approach for identifying the exposure units at risk from climate variability is vulnerability assessment. Vulnerability can be defined as the degree to which an exposure unit is disrupted or adversely affected as a result of climatic events. It follows that vulnerable systems, activities or regions are likely to be those most in need of planned adaptation.

The approach can be illustrated with reference to a 'common methodology' that has been developed for the national-scale assessment of coastal zone vulnerability to sea level rise (IPCC 1991b, 1994; cf. Box 6). One of the main objectives of the common methodology is to inform national decision makers about the vulnerability of the coastal zone, the possible problems a country may face due to a changing climate and sea level and, if necessary, the types of assistance that are most needed to overcome these problems. The identification of critical levels of vulnerability and critical levels of climate change is likely to be important in the determination of what constitutes 'dangerous' levels of climate change (a term used in Article 2 of the UN Framework Convention on Climate Change). A proposed six step process of determination is outlined in Figure 7.

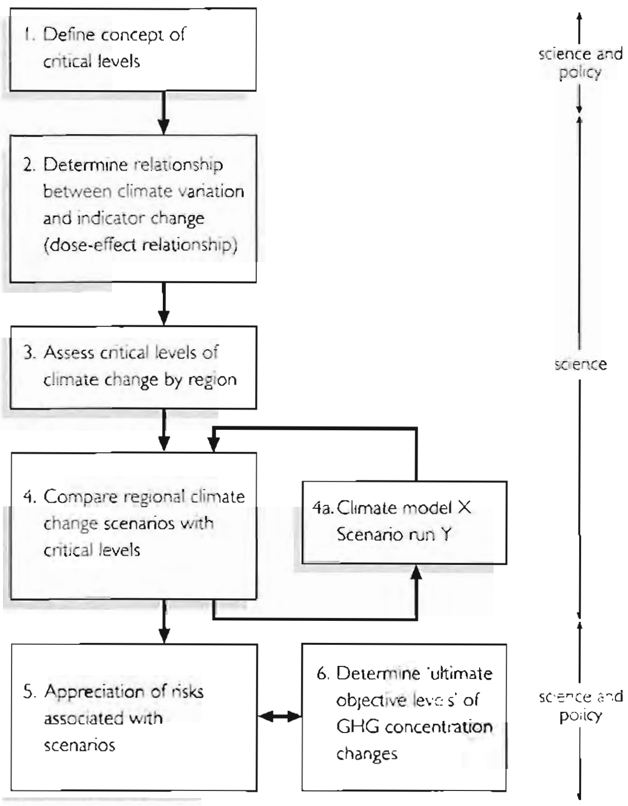


Figure 7. A six step approach to the ultimate objective of the Climate Convention (after Swart and Vellinga, 1994)

8.3.3 Identifying the adaptation options

The main task of assessment involves the compilation of a detailed list of possible adaptive responses that might be employed to cope with or take advantage of the effects of climate. The list can be compiled by field survey and by interviews with relevant experts, and should consider all practices currently or previously used, possible alternative strategies that have not

Table 2. An example of a multiple criteria evaluation framework, in this case, for water resources management (Stakhiv, 1994)

OVERALL GOAL	SPECIFIC OBJECTIVE	EVALUATION CRITERIA
SUSTAINABLE DEVELOPMENT	1 Regional economic development	Income Employment
	2 Environmental protection	Biodiversity Habitat areas Wetland types
	3 Equity	Distribution of employment Minority opportunities
REDUCE VULNERABILITY	1 Minimize risk	Population at risk Frequency of event
	2 Minimize economic losses	Personal losses Insured losses Public losses
	3 Increase institutional response	Warning time Evacuation time

been used, and newly created or invented strategies. Information is needed on the frequency with which particular actions are taken, in what circumstances and by whom. The effectiveness of different actions, their cost and the reasons for their use or otherwise should also be recorded. It is useful to note here that there are abundant cases to demonstrate that existing policies and practices may actually increase the impacts of present-day climatic variability. For example, agricultural support payments, subsidized insurance and damage cooperation payments may encourage higher risk taking among farmers and increase the total costs to society. These are cases of maladaptation that should be identified at an early stage of assessment. This step also requires a consideration of the likely impact on adaptation strategies of technological change.

Six generic types of behavioural adaptation strategy for coping with negative effects of climate have been identified by Burton *et al.* (1993):

- *Prevention of loss*, involving anticipatory actions to reduce the susceptibility of an exposure unit to the impacts of climate (e.g., controlled coastal zone retreat to protect wetland ecosystems from sea level rise and its related impacts).
- *Tolerating loss*, where adverse impacts are accepted in the short term because they can be absorbed by the exposure unit without long term damage (e.g., a crop mix designed to minimize the maximum loss, to ensure a guaranteed minimum return under the most adverse conditions).
- *Spreading or sharing loss*, where actions distribute the burden of impact over a larger region or population beyond those directly affected by the climatic event (e.g., government disaster relief).
- *Changing use or activity*, involving a switch of activity or resource use from one that is no longer viable following a climatic perturbation to another that is, so as to preserve a community in a region (e.g., by employment in public relief works).
- *Changing location*, where preservation of an activity is considered more important than its location, and migration occurs to areas that are more suitable under the changed climate (e.g., the re-siting of a hydro-electric power utility due to a change in water availability).
- *Restoration*, which aims to restore a system to its original condition following damage or modification due to climate (for example, an historical monument susceptible to flood damage). This is not strictly an adaptation to climate, as the system remains susceptible to subsequent comparable climatic events.

Table 3. Characteristics of selected coping strategies by smallholders for drought in central and eastern Kenya[a] (after Akong'a *et al.*, 1988)

		Effectiveness			Constraints					
Response/ coping strategy	Prevalence	Normal	Moderate drought	Severe drought	Recovery	Labour	Capital	Constraints 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 labour	M–H	H	H	H	+	+	–	–	+	–
Migrant wage labour	M	H	H	H	–	+	–	–	+	–
Permanent employment	M	H	H	H	+	+	–	–	+	–
Local business	L	M	M	L	0	+	+	–	+	–
Cash crop[c]	M	H	M	L	+	+	+	+	+	+
Sell capital assets	M	H	M	L	–	–	–	–	–	+
Livestock sales	H	H	M–H	M–L	–	–	–	–	+	–
Remittances/donations										
Relatives/friends	M–H	M	H	H	+	–	–	–	–	–
Government and others[d]	M–H	?	H	H	?	–	–	–	+	–
Loans/credits	L	H	H	H	+	–	+	–	+	–

Key:	Prevalence/Effectiveness			Recovery/Constraints		
	H	=	> 50%/High	–	=	negative, i.e., impedes recovery/is a constraint
	M–H	=	30–50/Mod. high	+	=	positive, i.e., aids recovery/is not a constraint
	M	=	15–30/Moderate	0	=	neutral, i.e., no effect on recovery
	L	=	0–15/Low	?	=	uncertain or variable

[a] Consensus agreement by 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 altitudinal 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.

There are, of course, many cases where climate changes can be positive. Here the strategies involve capitalizing on opportunities.

Different criteria can be used for organizing the information. For instance, detailed tables have been used to catalogue traditional adjustment mechanisms for coping with inter-annual climatic variability in self-provisioning societies (Jodha and Mascarenhas, 1985; Akong'a *et al.*, 1988). Table 3 illustrates a classification system for displaying smallholder coping strategies for drought in central and eastern Kenya and a qualitative effectiveness ranking for different measures.

Other methods of cross-tabulation have been employed in formal procedures of resource management. For example, alternative water resource adaptation measures in the United States are commonly analysed according to both the type of measure and its strategic scope. Four groupings of strategy have been identified (Stakhiv, 1993):

- Long range strategies, generally pertinent to issues involving mean changes in climate (e.g., river basin planning, institutional changes for water allocation).
- Tactical strategies, concerned with mid-term considerations of climatic variability (e.g., flood proofing, water conservation measures).
- Contingency strategies, relating to short-term extremes associated with climatic variability (e.g., emergency drought management, flood forecasting).
- Analytical strategies, embracing climatic effects at all scales (e.g., data acquisition, water management modelling).

Numerous options exist for classifying adaptive measures, but generally, regardless of the resource of interest (e.g., forestry, wetlands, agriculture, water) the prospective list should include management measures that reflect:

- Structural/infrastructural measures.
- Legal/legislative changes.
- Institutional/administrative/organizational measures.
- Regulatory measures.
- Education.
- Financial incentives, subsidies.
- Research and development.
- Taxes, tariffs, user fees.
- Market mechanisms.
- Technological changes.

It is worth noting that society in general, and each resource use sector separately, already contends with contemporary climatic variability and the wide range of natural hazards (e.g., floods, droughts, storm surges and hurricanes) and the variety of opportunities (e.g., a benign period of weather; an unbroken 'snow season'; a mild winter) this brings. As a first approximation, it is probably fair to assume that most of the current measures employed in resource management to deal with climatic variability will be equally feasible, even if not comparatively cost-effective, under a different climatic regime. It follows, therefore, that the adaptation measures which ought to be selected now are those which are beneficial for reasons other than climate change and, for the most part, can be justified by current evaluation criteria and decision rules. This is sometimes referred to as the 'no regrets' strategy

8.3.4 Examining the constraints

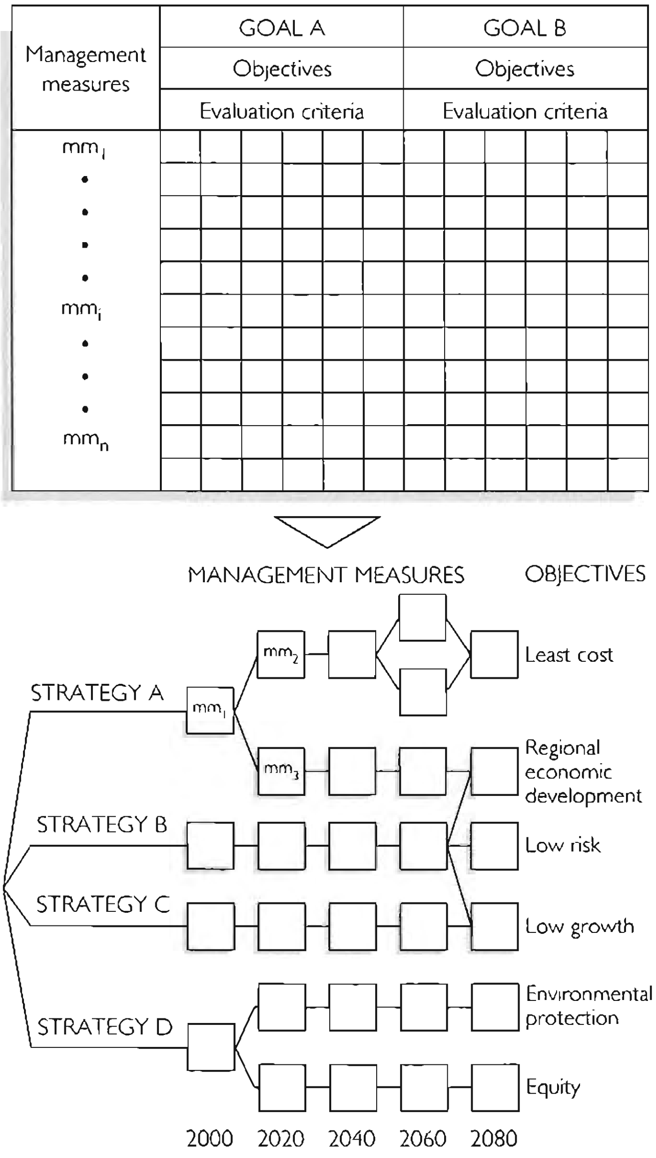
Many of the adaptation options identified in the previous step are likely to be subject to legislation, influenced by prevailing social norms related to religion or custom, or constrained physically (such as the landward retreat from an eroding coast) or biologically (e.g., genetic material for plant breeding to adapt to changing climate). This may encourage, restrict or totally prohibit their use. Thus, it is important to examine closely, possibly in a separate study, what these constraints are and how they might affect the range of feasible choices available.

8.3.5 Quantifying the measures and formulating alternative strategies

The next step is to assess the performance or degree of fulfilment of each management measure with respect to the stated objectives. It may be possible, if appropriate data and analytical tools exist, to use simulation models to test the effectiveness of different measures under different climate scenarios. Historical and documentary evidence, survey material or expert judgement are some other alternative sources of this information. Uncertainty analysis and risk assessment are also considered at this stage (see Section 7.6).

Management measures can be ranked according to their responsiveness to individual objectives and criteria as a way of

Figure 8. Some procedures for strategy formulation—top: multicriteria analysis of individual management measures; bottom: multiobjective strategy formulation.



assessing their robustness, effectiveness and resilience relative to other comparable measures. The second step in such analysis would be to assess the performance of each management measure across all the objectives, recognizing that some of the objectives conflict with one another (e.g., in Table 2, regional economic development often conflicts with environmental protection). This step is a prelude to developing strategies which maximize the level of achievement of some objectives while maintaining baseline levels of progress towards the remaining objectives. In order to assess which options are better suited for certain strategies, multicriteria analysis provides a formal, useful and replicable method of evaluation (Figure 8, top). One of the important aspects to consider at this stage is the quantification of achievable rates of adaptation and their additional costs. The faster the need for adaptation, the more it is likely to cost per annum.

An example of testing the feasibility of one line of adaptation to drought risk in Saskatchewan, Canada is given in Box 12. A more extensive range of adaptations has been tested for the central USA (see Box 13).

8.3.6 Weighting objectives and evaluating trade-offs

The adaptation strategies that emerge from the foregoing analysis each relate to specific objectives (Figure 8, bottom). Even if all objectives are directed to the same general goal, however, it is very likely that many will conflict with one another. This step of the analysis, therefore, is the key evaluation step, where each objective must be weighted according to assigned preferences and then comparisons made between the effectiveness of different strategies in meeting these objectives. For instance, for coastal responses to accelerated sea level rise, there could be a 'pure' retreat option, consisting exclusively of regulatory measures, taxes, incentives and legal and institutional measures spread out over a period of time. Also, a pure protection option might be considered, consisting of structural measures and better organized monitoring, warning and evacuation plans.

The key aspect of this step of evaluation is that all the component measures that comprise a strategy are compared against the same set of objectives and criteria, so that decision makers, policy makers and the public can see the relative range of benefits and costs for each strategy as well as the distribution of impacts among the sectors and population (equity). Only then can trade-offs among objectives and between management measures be undertaken. A wide variety of methods and models are available for such multicriteria analyses (e.g., Goicoechea *et al.*, 1982; Chankong and Haimes, 1983).

A standard impact accounting system for evaluating the effectiveness of different planning strategies is used operationally in federal projects in the United States. This evaluates

BOX 12
CASE STUDY: POTENTIAL IMPACTS OF CLIMATE CHANGE ON AGRICULTURE IN SASKATCHEWAN, CANADA

Background: the province of Saskatchewan in Canada has about 40 per cent of Canada's farmland and it accounts for about 60 per cent of Canada's wheat production, most of which is exported. About one eighth of internationally traded wheat originates from Saskatchewan.

Problem: to evaluate the possible impacts of future climate change on Saskatchewan agriculture, assuming the same technology and economic circumstances as in the 1980s.

Methods: four different types of predictive model were linked hierarchically: crop growth, farm simulation, input-output and employment models. These provided estimates of regional crop yields, income and economic activity at the farm level, commodity use relationships between sectors of the provincial economy, and provincial employment. The effects of changed climate, described by climatic scenarios, were then traced through from changes in crop yield to effects on regional employment.

Testing of methods/sensitivity: each of the models had been tested and calibrated based on climatic or economic data from recent years. In addition, the sensitivity of the crop growth model to arbitrary changes in climatic input variables was also investigated to ascertain its suitability for evaluating the effects of climate change.

Scenarios: three types of climatic scenario were examined: one historical anomaly scenario (the drought year 1962), one historical analogue scenario (the dry period 1933–37) and one GCM-based 2 x CO_2 scenario. The climatological baseline was 1951–80. Future changes in other environmental and socio-economic factors were not considered.

Impacts: under present climatic conditions, Saskatchewan can expect occasional extreme drought years with wheat yields reduced to as little as one-quarter of normal, with large effects on the agricultural economy and on provincial GDP and large scale losses in employment. Occasional periods of consecutive years with drought can lead to average yield reductions of one-fifth and substantial losses of farm income and employment. Under the GCM-based 2 x CO_2 scenario, with increased growing season temperatures combined with increased precipitation but higher potential evapotranspiration, wheat yields would also decline, by average levels similar in magnitude to an extreme period under present climate, with comparable economic impacts. The frequency of drought or severe drought is estimated to triple relative to the baseline under this scenario.

Adjustments. one potential adaptive response to climate change was tested: the switching of 10 per cent of the cropped area from spring wheat to winter wheat. It was estimated that yield losses in drought years would be significantly lower with such an adaptation, but that the reverse would be true in normal years. Thus this adaptation would be favoured if climate shifted towards warmer and drier conditions in the future.

Source: Williams *et al.* (1988)

BOX 13
CASE STUDY: THE MINK PROJECT AN INTEGRATED REGIONAL ASSESSMENT

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. Except for pockets of forestry on the Ozark Plateau of southeast Missouri, and grassland on sand dunes in north central Nebraska, the region is fairly coherent, with flat or rolling topography used predominantly for agriculture.

Problem: to study how climate change might affect the current and future functioning of regional-scale economies.

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. For forests, a succession model (FORENA) that simulates the annual development of individual trees within a mixed species forest was used. This allows the effects of climate change on both forest growth and species composition to be evaluated. Both EPIC and FORENA were modified to account for the direct effects of CO_2 on photosynthesis and water use. Several approaches were used to estimate regional water resources: changes in evapotranspiration and irrigation requirements were modelled using EPIC. Regional water supply was estimated using empirical relationships between present and past streamflows. Impacts on the energy sector drew on the modelling and interpretations from the other three sectors and on an analysis of how heating and air conditioning requirements are affected by changing temperature. Finally, the economy-wide effects of changes in productivity of the above resource sectors were studied using IMPLAN, a regional input-output model. IMPLAN describes the interaction between 528 industries in the MINK region.

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. FORENA had been validated previously for conditions in the eastern United States, and results were also compared with observed forest behaviour under drought conditions in Missouri. A sensitivity study was conducted on the response of forest biomass to changes in temperature and precipitation. 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 the year 2030, along with an increase in CO_2 concentration of 100 ppm (to 450 ppm). Four sets of conditions were investigated: (1) the current baseline, which referred to the economic situation in the early 1980s, with 1951–1980 as the climatological baseline; (2) climate change imposed on the current baseline; (3) a baseline description of the economic structure of the region in the future without climate change (including population, economic activity and personal income); and (4) imposition of climate change on the future baseline (including feedbacks between sectors, such as the projected extent of irrigated agriculture given scenarios of future water supply).

Impacts: in the MINK region of 2030 with a climate like that of the 1930s the main results of the study are: (1) 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 irriga-

continued . . .

the effects of different plans on a set of four basic objectives or impact categories:

- National economic development (monetary).
- Environmental quality (significant environmental resources and their ecological, cultural and aesthetic attributes).
- Regional economic development (distribution of regional economic activity in terms of regional income and employment).
- Other social effects (including urban and community impacts, life, health and safety factors, displacement, long-term productivity, energy requirements and energy conservation).

All impacts and adaptation measures are evaluated according to these four categories. Selection of preferred strategies thus requires the determination of trade-offs between the categories.

8.3.7 Recommending adaptation measures

The results of the evaluation process should be compiled in a form that provides policy advisers and decision makers with information on the best available adaptation strategies. This should include some indication of the assumptions and uncertainties involved in the evaluation procedure, and the rationale used (e.g., decision rules, key evaluation principles, national and international support, institutional feasibility, technical feasibility) to narrow the choices.

8.4 Points to Consider in Developing an Adaptation Strategy

It may be helpful to note some of the practical requirements involved in conducting an adaptation assessment of the type proposed above. These include: institutional requirements, data requirements, analytical tools and cost.

8.4.1 Institutional requirements

The formal procedures described above, which are routinely and successfully used in a variety of resource management settings in many developed countries, do, however, require an institutional and information infrastructure as prerequisites. This implies that there is an organizational, administrative and legal structure in place that is capable of carrying out the procedures in a uniform

... continued

tion from west to east). (2) Impacts on forestry would not be fully felt by 2030, but in the long term they would be severe. There is little potential for adaptation to the climate change unless the production of wood for biomass fuel makes adaptation economically justifiable. However, forestry is a very small part of the MINK economy. (3) Impacts on water resources would be major and severe. The quality and quantity of surface waters would diminish, water-based recreation would suffer losses and navigation would become uneconomic on the Missouri. 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. (4) Only about 20–25 per cent of the region's current energy use would be sensitive to a 1930s-type climate, and any impacts of climate would be eased by adjustments within the energy sector so that the effect on the regional economy would be minor. (5) 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 per cent), the regional economic impacts of the climate change would be small. This is because agriculture, while important relative to other regions of the US, 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 1984–87 crop production in MINK by 17 per cent. The CO_2 effect would reduce the loss to 8 per cent, and on-farm adjustments would reduce it further to 3 per cent. In the forestry sector a number of management options were investigated using the FORENA model (e.g., the suitability of pine plantations and various thinning strategies), but none was considered appropriate as a response to climate change in the region. Rather, barring major public intervention, only reactive measures to forest decline such as salvage cutting were judged likely. Qualitative assessments were made of possible adjustments in water use (e.g., water conservation, a shift of emphasis from navigation to hydropower production, recreation and water supply on the Missouri River) and in energy production and use (e.g., energy-saving water pumping and irrigation practices, improved energy-use efficiency and adoption of new or existing technologies for improving electric conversion efficiency and reducing cooling water requirements).

Policy options: although the MINK study did not seek to provide specific recommendations to policy makers for how to cope with climate change in this region, one important conclusion was that the relevant policy issue at the regional scale is not one of climate change abatement (which can only be dealt with at national and international level), but rather one of optimal adjustment to climate change. An important assumption of the study was that markets play a major role in inducing adjustments needed for adequate response to climate change. However, some important elements are not commonly considered in economic terms (e.g., the quality of aquatic habitats is projected to decline in the MINK region). These should necessarily fall within the ambit of public policy. Moreover, the study also speculated on possible policy shifts, which could have more far-reaching implications for the MINK region (e.g., the removal of subsidies for irrigation agriculture under sharply increased water scarcity or subsidization of plantation forestry as a method of capturing atmospheric carbon and of energy production).

Source: Rosenberg (1993)

and replicable manner. Moreover, some of the analytical tools employed are both sophisticated and resource intensive to develop and operate.

It is clear that some of these prerequisites are likely to be lacking in less developed countries, due to the limited resources available. However, alternative 'low cost' procedures are available that could be applied in many regions. Additional capabilities could then be built up over time, if desired. The framework outlined above is therefore a general one, which is applicable to a wide range of situations and capabilities in different regions.

8.4.2 Data requirements

Data requirements can vary considerably, depending on the scope of the study. Biological and physical information such as climatological, hydrological and agricultural production data, is likely to be more readily available than socio-economic information, though not necessarily in the form required. It is very likely, however, that original socio-economic data will have to be collected as part of the analysis. This can prove to be quite expensive in terms of time, money and human resources, as it may require surveys of the population where adaptive actions are being considered. An alternative is expert judgement, but this should be blended with a knowledge of social values and priorities or there is a danger that local perceptions and understandings may be overlooked in the assessment.

8.4.3 Analytical tools

As has already been indicated, a number of aspects of the analysis can be enhanced with the use of models. These can vary from formalized methods of qualitative assessment (e.g., Delphi analysis of expert judgement) to advanced quantitative assessment models (many of which are described elsewhere in this report). Many of these types of model are available as software packages for a personal computer. However, aside from their cost (which need not be excessive), and the considerable complexity often entailed in linking model inputs and outputs, data availability is likely to impose the greatest constraint on model use in many regions.

8.4.4 Cost

The cost of conducting a study of adaptation to climate change can vary widely. A detailed study can easily cost several hundred thousand US dollars, although useful results can be obtained from small-scale studies costing in the range 50,000 to 100,000 US dollars.

8.4.5 Policy exercises

One possible method of evaluating policy adjustments is the policy exercise. Policy exercises combine elements of a modelling approach with expert judgement, and were originally advocated as a means of improving the interaction between scientists and policy makers. Senior figures in government, industry and finance are encouraged to participate with senior scientists in 'exercises' (often based on the principles of gaming), whereby they are asked to judge appropriate policy responses to a number of given climatic scenarios. Their decisions are then evaluated using impact models (Brewer, 1986; Toth, 1989). The method has been tested in a number of recent climate impact assessments in South-East Asia (Parry *et al.*, 1992).

8.4.6 Sensitization seminars

A less formal method of communicating the important research issues to policy makers is through organized meetings on climate change and its possible effects. If these are targeted at policy makers and other stakeholders, they can be very effective vehicles for influencing attitudes and, ultimately, policy.

ORGANIZATION OF RESEARCH AND COMMUNICATION OF RESULTS

9

9.1 The Framework in Practice

The foregoing sections present a set of guidelines for potential practitioners on alternative approaches and tools that they might consider adopting in undertaking a climate impact and adaptation assessment. The scope of these guidelines is very broad, though the methods described are often detailed. By way of synthesis, therefore, this concluding section reviews the analytical framework developed in the report, and suggests a four stage method for applying the framework in practice.

9.1.1 The Seven Step Framework

The guidelines have been arranged in a seven-step analytical framework that aims to capture the major components of an assessment study (cf. Figure 4). The framework is able to accommodate the wide range of methods followed in a large number of previous assessments, as is demonstrated in some of the boxed examples in this report. However, it should not be regarded as a definitive approach to assessment. There are other assessments that follow perfectly valid alternative analytical methods (for example, studies where the main focus is on adaptation to climate change). Nonetheless, while the logical order of analysis may be different in these studies, most of the basic tools and methods that are actually applied are embraced in these Guidelines.

While this report has sought to be as comprehensive as possible, it should not be inferred that all the seven steps or all procedures within each step should be applied in any one assessment. Applying the former may not be necessary or appropriate; applying the latter would simply not be feasible. Each assessment study has its own unique requirements, focus and objectives, and these are probably served by only a small subset of the approaches described. Furthermore, there are certainly aspects that are not covered in the Guidelines—the field is large, and methods of climate impact assessment are developing rapidly—and their exclusion here should not preclude their use in future assessments.

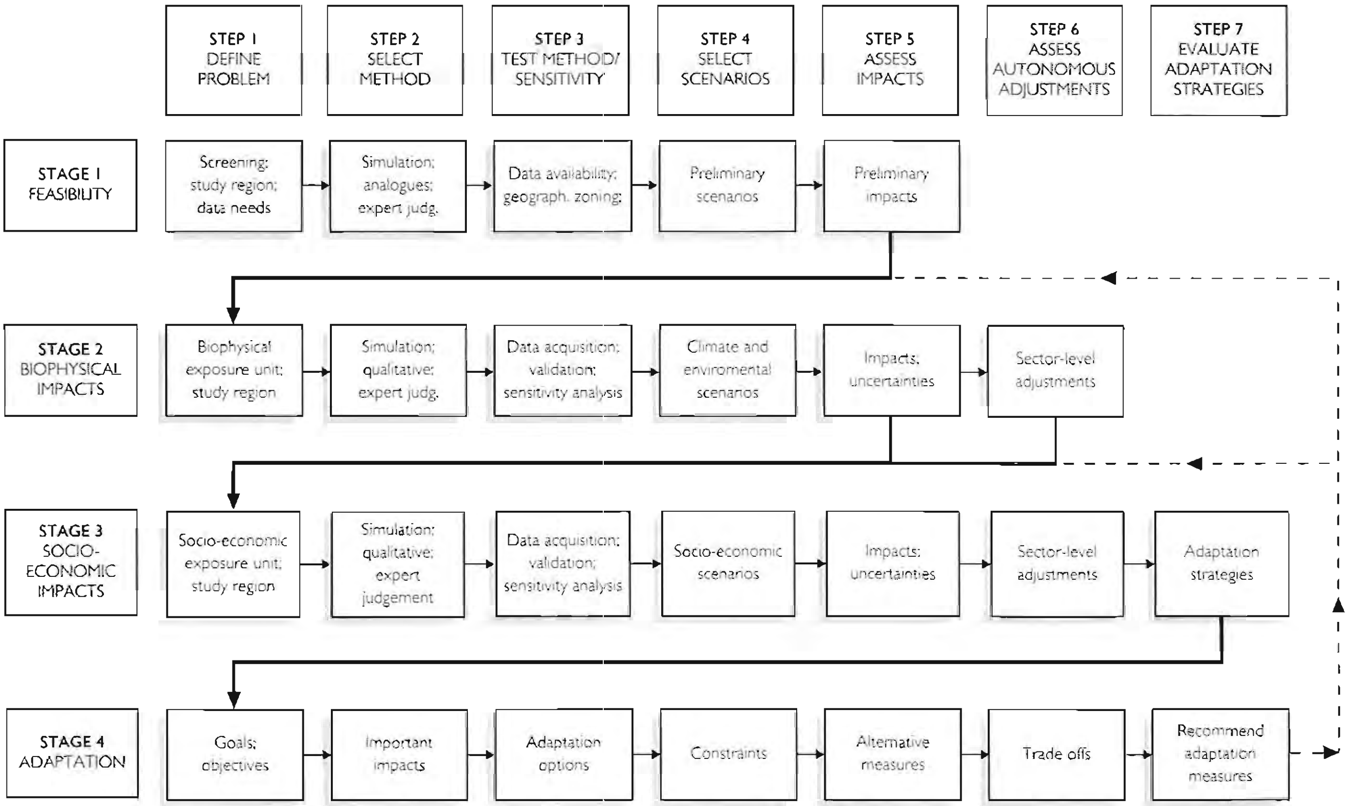
9.1.2 A four stage method for conducting assessments

The observation was made in Section 2.4 that the procedures contained in each of the seven general steps are themselves sometimes arranged in a multi-step framework which parallels the seven steps. This is not surprising, when one considers how most assessments are actually conducted in practice. Few studies proceed monotonically through all the necessary steps without repeating at least some iterations. For example, where the outputs of one impact model are used as the inputs for another, similar procedures for, *inter alia*, data acquisition, model testing, parameter selection, fixing of assumptions and scenario development, must occur when applying each model.

In all, four main stages of iteration can be identified through which an assessment may need to proceed (Figure 9):

- Feasibility.
- Assessment of biophysical impacts.
- Assessment of socio-economic impacts.
- Evaluation of adaptation options.

Figure 9. A four stage method for conducting climate change impact and adaptation assessments



These stages are depicted as rows in Figure 9. The columns represent broadly comparable steps, with some of the alternative procedures at each step listed in the boxes. Thick arrows show the linkages between stages and thin arrows link the steps. Dashed lines represent reiterations that may be required to repeat an analysis under a new set of assumptions.

This kind of 'walk-through' method can offer a useful template for conducting assessment studies at the national level. Following this approach, the United Nations Environment Programme is currently preparing non-expert Workbooks based on the Technical Guidelines described here. When completed, the IPCC Technical Guidelines and UNEP Workbooks will form a complementary pair of guides: the former primarily for researchers and the latter for non-experts.

9.2 Organization of Research

The effective organization of research is a key element in most climate impact studies, but especially so in large, multi-disciplinary projects. Two aspects are important to consider: the coordination of research, and research collaboration.

9.2.1 Coordination

Experience suggests that the executive responsibility for coordinating research activities is usually best assigned to a single location, group or person. Overall guidance is sometimes provided by a panel of experts or steering committee, including the coordinator. Subordinate responsibilities can be delegated to other researchers, but the structure should preserve a framework of accountability.

Several tasks can be identified that should normally be the responsibility of the coordinator, involving the planning of the research, identification of stakeholders, selection of common approaches, initiation of studies and monitoring of the research.

Planning of the research. Regardless of the nature of the study, the source of funding or the client being served, it is necessary, at an early stage of preparation, to formulate a research plan. This usually comprises a statement of the research objectives, a description of the main tasks, the research methods, the intended outputs, a preliminary schedule and the estimated cost. A research plan can serve several functions:

- It provides a framework for initiating the research and making preliminary arrangements for elements such as excursions and meetings.
- It is helpful for identifying resource requirements such as staff, working space, equipment and data.
- It can be distributed to other experts for comments and advice.
- It can be used as a working document for discussing possible research collaboration, additional funding, publication or other cooperation.

Identification of stakeholders. The most successful impact studies are often those which involve a broad cross-section of the community in the study region. Thus, a valuable element of study design is the identification of important 'stakeholders'. Some possible stakeholders to consider are listed here:

- Policy makers, who commission the impact assessments in order to obtain information that can be used to guide policy.
- Experienced climate impact researchers, who are familiar with the issues and the analytical methods. It may be primarily their responsibility to formulate the methods, gather and collate the data, and analyse and report the results of the study.
- Other researchers, who may have no experience in climate impact assessment, but may possess local knowledge, analytical tools or data that could be valuable in an impact assessment.
- Government officials and local advisers, who may be able to assist by supplying data, exercising judgement or identifying key regions or persons.
- Persons of regional influence, such as village elders, industrial executives and landowners, who might be able to provide advice, resources, access or other assistance to the study.
- Communicators, such as teachers, newspaper editors and radio and television producers, who can describe the research to the community.
- Other members of the community, whose cooperation may be required in conducting surveys, field experiments and other research activities.

Common approaches. The coordinator may also bear responsibility for enforcing some commonality of approach in research. This ensures that the results of an assessment are readily comparable, both within the project, and relative to other projects. It may entail, for example, the adoption of standard scenarios, use of standard projection periods, and consistency in the reporting of results. Consistency is especially important in cases where results from one part of the study are used as inputs to another.

Initiation of studies. As a preliminary stage of research, some projects carry out pilot studies to explore the feasibility of the methods (Section 5.1). In some cases, pilot studies may have to be conducted as a prerequisite for the receipt of funding or of development loans. Other projects may hold a meeting of researchers, to exchange ideas, forge new links, agree on the workplan, allocate tasks, and decide a schedule. Where research is being conducted at multiple sites or in different countries, another option is for coordinators to travel to meetings at each centre. This has the advantage of exposing the coordinator to a wider range of researchers, to local conditions and to local problems. Finally, in some projects, particularly commissioned studies, where the goals are clear and deadlines tight, it may be sufficient to despatch guidelines to the participants so that they can begin work immediately.

Monitoring of the research. It is often a contractual requirement for projects to provide funding agencies with regular reports on progress. Although these reports do not always receive close scrutiny from funding bodies, they are a useful method of assessing progress, achievements, and financial status. They can also form a basis for the publication of results. It is common for international projects to receive a mid-term review by independent experts, where researchers are required to present their work, justify their methods and report preliminary results. Even if this is not a formal requirement, a mid-term review can be a valuable aid to project coordinators, as a means of assessing progress to date, and future goals.

9.2.2 Collaboration

Collaboration in conducting an assessment can be required at up to four levels: between researchers, between stakeholders, nationally and internationally.

Collaboration between researchers. Climate impact assessment is interdisciplinary, involving the collaboration of researchers who, in many cases, may not have worked together before. The identification of researchers who understand the goals of the research, and are willing to work together, often under tight time constraints, can be a major undertaking in the planning and execution of many assessment studies. The effectiveness of collaboration may also be influenced by the working environment. At one extreme, some international projects purposefully bring together researchers to work at a single site. At the other extreme, studies may be conducted with no direct contact between researchers. A useful framework for interdisciplinary and interjurisdictional collaboration at a regional scale is provided by Integrated Regional Impact Assessment (see Section 2.3.3, above). Studies have been aided considerably in recent years by the establishment of international networks of researchers, common databases and newsletters.

Collaboration between stakeholders. The involvement of other stakeholders in the assessment process has many advantages but also some drawbacks. Local knowledge and experience can be very useful in conducting the study, mobilising resources, interpreting results and in gaining regional acceptance of the results and recommendations. In addition, the monitoring of a project by funding agencies can be helpful in focusing the goals of the research. However, policy makers should beware of jeopardizing the integrity of the research by excessive participation, whilst researchers should ensure that their work meets the needs of policy as much as possible.

National programmes. Under the auspices of the World Climate Programme (WCP), many countries have now organized their own national climate programmes. Within these programmes most have made provision for climate impact studies, and have set up committees for directing research and channelling funding through national scientific bodies and government departments. Examples of countries with national programmes include: Australia, Canada, Finland, Hungary, Netherlands, Japan, Switzerland, UK and USA.

Internationally, there are different levels of cooperation and organization. Some important activities at global scale include:

- The World Climate Impact Assessment and Response Strategies Studies Programme (WCIRP), which is run by the United Nations Environment Programme (UNEP), is one component of the WCP. Projects receiving funding from UNEP are generally international in scope, and innovative in content.
- The United Nations Regional Economic Commissions, which liaise with national meteorological services in assessing the socio-economic and population impacts of climatic variability and change.
- The Intergovernmental Panel on Climate Change (IPCC) Working Group II (Impacts), which was established by WMO and UNEP for reviewing research on the impacts of future climate change.
- The International Geosphere-Biosphere Programme (IGBP) of the International Council of Scientific Unions (ICSU), which has a number of elements devoted to climate change and its impacts. Its function is to promote international collaboration in research. Funding is provided by national governments.
- The Human Dimensions of Global Environmental Change Programme (HDP) of the International Social Science Council (ISSC), which has a similar structure to the IGBP, but whose focus is on socio-economic aspects of environmental change.
- The Scientific Committee on Problems of the Environment (SCOPE), which is also organized by ICSU, prepares state-of-knowledge surveys on major environmental issues.
- The Man and the Biosphere Programme of the United Nations Educational, Scientific and Cultural Organization (UNESCO).
- The Organization of Economic Cooperation and Development (OECD).

9.3 Communication of Results

An effective impact assessment is usually characterized by the establishment of good communication between researchers and other interest groups. Four lines of communication are important for researchers: with other researchers, with policy makers, with private enterprise and with the public.

9.3.1 Communication among researchers

Two issues are of critical importance in communicating and evaluating research results among researchers: the reporting of results and peer review.

Reporting of results. There is a burgeoning literature on the possible effects of future climate, but as yet there has been little attempt to coordinate or standardize either the approaches used or the reporting of results. It is critical that the methodology, assumptions and results of studies are transparent. A number of important requirements for reporting results are listed here:

- Methods of assessment should be detailed in full.
- Information from climate models used in scenario construction should be correctly interpreted and original sources accurately cited.
- The major assumptions of a study need to be outlined and substantiated.
- Impact models should be properly tested, fully documented or cited, and accessible to other researchers so that results are easily reproducible.
- All results should be accompanied by estimates of their attendant uncertainties.

Peer review. The peer review of results is a vital element ensuring the quality control of published research. Proper vetting by expert reviewers is the only means by which non-specialists are able to evaluate the quality and significance of research.

Most reputable scientific journals subject submitted papers to a rigorous review process. However, there are some cases where, given the interdisciplinary nature of the research, specialist review cannot be offered for some elements of a study. Therefore, researchers bear some responsibility for ensuring that all their methods and models are exposed to such a review process from appropriate experts. Indeed, many large projects organize their own review process, whereby specialists are asked to provide formal reviews of results prior to final publication.

9.3.2 Communication with policy makers

Much climate impacts research seeks to answer questions that impinge on or are specifically defined by policy. Thus, communication between policy makers and researchers is essential, the former demanding of the latter solutions to problems and the latter alerting the former to issues of importance and requesting the resources to research them.

One of the major problems of communication between researchers and policy makers is the need to convey the considerable uncertainties attached to future estimates, while demonstrating that there is a problem to be addressed. Moreover, the recent upsurge of interest in environmental issues has led to a rapid increase in the demands on researchers to communicate results directly to policy makers (e.g., through government hearings). Since many of the goals of policy makers are short-term, there may be advantages in presenting research results in the form of the types of impacts likely to be experienced in the early stages of a more general climatic change. Such results could usefully be expressed, for example, in terms of the risk of certain events occurring that are of immediate concern (e.g., drought or coastal flooding). Nonetheless, there are still major issues that should be addressed over a longer time perspective (for example, potential impacts such as extinctions, that are irreversible, or more tangible planning questions such as construction of dams or coastal defences).

9.3.3 Communication with private enterprise

The private sector is a key player in influencing climate policy, both as a significant contributor to GHG emissions and as an end-user of climate as a resource. Besides wielding considerable political and economic influence, some sectors, such as insurance, are greatly concerned about the possible impacts of climate change and sea level rise on their activities. Moreover, in many countries engineering consultant firms are key players in the preparation of climate assessments, often as part of larger environmental impact assessments of proposed developments.

9.3.4 Communication with the public

Ultimately, most policy makers are answerable to the public, and public opinion plays an important role in determining policy. It is important, therefore, that the public is kept well-informed about progress in research. Effective communication is thus vital, and it is brought about partly through education but primarily via the mass media. While researchers have a responsibility to communicate their work in a clear and concise manner to the public, the media also bears a great responsibility for accurate reporting of the research. Unfortunately, there has been a tendency by some to report only the most dramatic or controversial aspects of climatic change and its impacts, rather than to present a more balanced view. Researchers should be wary of checking thoroughly any material which is to be communicated to the public in this way.

REFERENCES

ACCIS (1990). *Directory of United Nations Databases and Information Services*. 4th Ed. United Nations.

Ackerman, T.P. and Cropper, W.P. (1988). Scaling global climate projections to local biological assessments. *Environment*, **30**, 31–34.

Adams, R.M., Rosenzweig, C., Peart, R.M., Ritchie, J.T., McCarl, B.A., Glyer, J.D., Curry, R.B., Jones, J.W., Boote, K.J. and Allen, L.H., Jr. (1990). Global climate change and U.S. agriculture. *Nature*, **345(6272)**, 219–222.

Akong'a, J., Downing, T.E., Konijn, N.T., Mungai, D.N., Muturi, H.R. and Potter, H.L. (1988). The effects of climatic variations on agriculture in central and eastern Kenya. In Parry, M.L., Carter, T.R., and Konijn, N.T. (eds). *The Impact of Climatic Variations on Agriculture, Volume 2. Assessments in Semi-Arid Regions*. Kluwer, Dordrecht, The Netherlands, pp. 121–270.

Alcamo, J. (ed.). (1994). *IMAGE 2.0: Integrated Modelling of Global Climate Change*. Kluwer, Dordrecht, The Netherlands, 321 pp. (reprinted from *Wat. Air Soil Pollut.*, **76**).

Almendares, J., Sierra, M., Anderson, P.K. and Epstein, P.R. (1993). Critical regions, a profile of Honduras. *Lancet*, **342**, 1400–1402 (reprinted in *Health and Climate Change*, Lancet, London, 1994, pp. 29–31).

Arnell, N.W., Brown, R.P.C. and Reynard, N.S. (1990). *Impact of Climatic Variability and Change on River Flow Regimes in the UK*. Report No. 107, Institute of Hydrology, Wallingford, UK, 154 pp.

Bardossy, A. and Plate, E.J. (1992). Space-time model for daily rainfall using atmospheric circulation patterns. *Water Resources Research*, **28**, 1247–1260.

Beier, J. (1991). *Global Change Data Sets: Excerpts from the Master Directory*. National Aeronautic and Space Administration (NASA), USA.

Bergthorsson, P., Bjomsson, H., Dyrmundsson, 0., Gudmundsson, B., Helgadottir, A., and Jomnundsson, J.V. (1988) . The Effects of Climatic Variations on Agriculture in Iceland. In Parry, M.L., Carter T.R. and Konijn N.T. (eds). *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*. Kluwer, Dordrecht, The Netherlands, pp. 381–509.

Beuker, E. (1994). Long-term effects of temperature on the wood production of *Pinus sylvestris* L. and *Picea abies* (L.) Karst. in old provenance experiments. *Scand. J. For. Res.*, **9**, 34–45.

Binkley, C. (1988). A Case Study of the Effects of CO_2-Induced Climatic Warming on Forest Growth and the Forest Sector: B. Economic Effects on the World's Forest Sector. In Parry, M.L., Carter T.R. and Konijn N.T. (eds). *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*. Kluwer, Dordrecht, The Netherlands, pp. 197–218.

Boer, G.J., Arpe, K., Blackburn, M., Deque, M., Gates, W.L., Hart, T.L., Le Treut, H., Roeckner, E., Sheinin, D.A., Simmonds, I., Smith, R.N.B., Tokioka, T., Wetherald, R.T. and Williamson, D. (1991). *An Intercomparison of the Climates Simulated by 14 Atmospheric General Circulation Models*. CAS/JSC Working Group on Numerical Experimentation Report No. 15, WMO/TDNo. 425, World Meteorological Organization, Geneva, 37 pp.

Bonan, G.B. (1993). Do biophysics and physiology matter in ecosystem models? *Climatic Change*, **24**, 281–285.

Brewer, G.D. (1986). Methods for synthesis: policy exercises. In Clark W.C. and Munn R.E. (eds). *Sustainable Development of the Biosphere*. Cambridge University Press, pp. 455–473.

Brklacich, M. and Smit, B. (1992). Implications of changes in climatic averages and variability on food production opportunities in Ontario, Canada. *Climatic Change*, **20**,1–21.

Buck, R.J., Favis-Mortlake, D.T. and Downing, T.E. (in press). Parsimonious statistical emulation of a complex crop simulation model—an application for climate change impact assessment. *Climate Research*.

Budyko, M.I. (1989). Empirical estimates of imminent climatic changes. *Soviet Meteorology and Hydrology*, **No. 10**, 1–8.

Bultot, F., Coppens, A., Dupriez, G.L., Gellem D. and Meulenberghs, F. (1988). Repercussions of a CO_2 doubling on the water cycle and on the water balance—a case study for Belgium. *Journal of Hydrology*, **99**, 319–347.

Burtis, M.D. (1992). *Catalog of Data Bases and Reports*. ORNL/CDIAC-34/R4, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, USA.

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

Burton, I. and Cohen, S.J. (1992). *Adapting to Global Warming: Regional Options*. Paper presented at the International Conference on Impacts of Climatic Variations and Sustainable Development in Semi-Arid Regions (ICID), Fortaleza, Brazil, 27 January–1 February, 1992.

Carter, T.R., Parry, M.L., Nishioka, S. and Harasawa, H. (1992). *Preliminary Guidelines for Assessing Impacts of Climate Change*. Environmental Change Unit, University of Oxford, United Kingdom and Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 28 pp.

Chankong, V. and Haimes, Y. (1983). *Multiobjective Decision Making: Theory and Methodology*. Elsevier, New York, 406 pp.

CIA (1972). *World Databank II*, Central Intelligence Agency, Washington, D.C., USA.

Clark, W.C. (1986). Sustainable development of the biosphere: themes for a research program. In: Clark, W.C. and Munn, R.E. (eds). *Sustainable Development of the Biosphere*. Cambridge University Press, pp. 5–48.

Cline, W. (1992). *The Economics of Global Warming*. Institute for International Economics, Washington, D.C.

Cohen, S.J. (1991). Possible impacts of climatic warming scenarios on water resources in the Saskatchewan River sub-basin, Canada. *Climatic Change,* **19**, 291–317.

Cohen, S.J. (ed.) (1993). *Mackenzie Basin Impact Study. Interim Report #1*. Environment Canada, Edmonton, 163 pp.

Croley, J.E. II (1990). Laurentian Great Lakes double-CO_2 climate change hydrological impacts. *Climatic Change,* **17**, pp. 27–47.

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

CRU (1992). *Development of a Framework for the Evaluation of Policy Options to deal with the Greenhouse Effect: A Scientific Description of the ESCAPE model, Version 1.1, May 1992.* Climatic Research Unit, Norwich, UK, 126 pp.

Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B.D. and Sausen, R. (1992). Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Clim. Dynamics,* **7**, 55–69.

Department of the Environment (1991). *The Potential Effects of Climate Change in the United Kingdom.* United Kingdom Climate Change Impacts Review Group, HMSO, London, 124 pp.

Downing, T.E. (1992). Climate change and vulnerable places: global food security and country studies in Zimbabwe, Kenya, Senegal and Chile. *Research Report No. 1,* Environmental Change Unit, University of Oxford, 54 pp.

ECMWF (1993). *The Description of the ECMWF/WCRP Level III-A Global Atmospheric Data Archive,* European Centre for Medium Range Weather Forecasting, Shinfield, Reading, UK.

Edmonds, J.A., Reilly, J.M., Gardner, R.H. and Brenken, A. (1986). *Uncertainty in Future Global Energy Use and Fossil Fuel CO_2-emissions 1975 to 2075.* TR036, DOE3/Nbb–0081 Dist. Category UC–11, National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia.

Edmonds, J.A., Pitcher, H.M., Rosenberg, N.J. and Wigley, T.M.L. (1993). Design for the Global Change Assessment Model GCAM. Paper presented at the *International Workshop on Integrated Assessment of Mitigation, Impacts and Adaptation to Climate Change,* 13–15 October 1993, International Institute for Applied Systems Analysis, Laxenburg, Austria, 7 pp.

EPRI (1994). The Evaluation of Regional Climate Simulations. Summary Report of IPCC WGI/MECCA Workshop, Macquarie University, NSW, Australia, February 1994. Electric Power Research Institute, Palo Alto, CA USA.

Fankhauser, S. (1993). The social costs of greenhouse gas emissions: an expected value approach. Paper presented at the *International Workshop on Integrated Assessment of Mitigation, Impacts and Adaptation to Climate Change,* 13–15 October 1993, International Institute for Applied Systems Analysis, Laxenburg, Austria, 26 pp.

FAO (1978). Report on the Agro-Ecological Zones Project. Volume 1, Methodology and Results for Africa. *World Soil Resources Report,* **48**. Food and Agriculture Organization, Rome, Italy.

FAO (1992a). CROPWAT. A computer program for irrigation planning and management. *FAO Irrigation and Drainage Paper 46,* Food and Agriculture Organization, Rome, 126 pp.

FAO (1992b). *AGROSTAT-PC, Computerized Information Series: User Manual, Population, Land Use, Production, Trade, Food Balance Sheets, Forest Products.* Food and Agriculture Organization, Rome.

FAO (1993). *Agriculture: Towards 2010.* Report C93/24, Food and Agriculture Organization, Rome. 320 pp. plus appendices.

FAO/UNESCO (1971–1981, various dates). *Soil Map of the World. Volumes 1–10.* Food and Agriculture Programme and United Nations Educational, Scientific and Cultural Organization, Paris.

Farhar-Pilgrim, B. (1985). Social analysis. In Kates, R.W., Ausubel, J.H. and Berberian M. (eds.). *Climate Impact Assessment: Studies of the Interaction of Climate and Society.* SCOPE 27, Wiley, Chichester, pp. 323–350.

Fiering, M.B. and Rogers, P.P. (1989). *Climate Change and Water Resource Planning Under Uncertainty.* Research Report prepared for the US Corps of Engineers, Institute for Water Resources, Washington, D.C.

Frederick, K.D. (1993). Paper 4. Climate change impacts on water resources and possible responses in the MINK region. *Climatic Change,* **24**, 83-115.

Fritz, J. (1990). *A Survey of Environmental Monitoring and Information Management Programmes of International Organizations.* United Nations Environment Programme, Nairobi.

Gadgil, S., Huda, A.K.S., Jodha, N.S., Singh, R.P. and Virmani, S.M. (1988). The effects of climatic variations on agriculture in dry tropical regions of India. In Parry, M.L., Carter T.R. and Konijn, N.T. (eds). *The Impact of Climatic Variations on Agriculture. Volume 2. Assessments in Semi-Arid Regions.* Kluwer, Dordrecht, The Netherlands, pp. 495–578.

Geign, S.C. van de, Goudriaan, J. and Berendse, F. (eds) (1993). Climate change; crops and terrestrial ecosystems. *Agrobiologische Thema's 9,* CABO-DLO, Centre for Agrobiological Research, Wageningen, The Netherlands, 144 pp.

Giorgi, F. (1990). Simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate,* **3**, 941–963.

Giorgi, F. and Mearns, L.O. (1991). Approaches to the simulation of regional climate change: a review. *Rev. Geophys.*, **29**, 191-216.

Giorgi, F., Marinucci, M.R. and Visconti, G. (1992). A 2 x CO_2 climate change scenario over Europe generated using a limited area model nested in a general circulation model. 2. Climate change scenario. *J. Geophys. Res.*, **97(D9)**, 10011–10028.

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

Grove, J.M. (1988). *The Little Ice Age*. Methuen, London, 498 pp.

Goicoechea, A., Hansen, D. and Duckstein, L. (1982). *Multiobjective Decision Analysis with Engineering and Business Applications*. Wiley, New York, 520 pp.

Haimes, Y.Y. and Li, D. (1994). Multiobjective risk partitioning for rare hydrologic events. In Haimes, Y.Y., Moser, D. and Stakhiv, E. (eds). *Risk-Based Decision Making in Water Resources VI*. Proc. Engineering Foundation Conference, American Society of Civil Engineers, New York, NY.

Haines, A., Epstein, P.R. and McMichael, A.J. (1993). Global health watch: monitoring impacts of environmental change. *Lancet*, **342**, 1464–1469.

Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R. and Travis, L. (1983). Efficient three-dimensional global models for climate studies: Models I and II. *Mon. Wea. Rev.*, **111**, 609–662.

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

Haxby, W.F. *et al.* (1983). Digital images of combined oceanic and continental data sets and their use in tectonic studies. *EOS Transactions of the American Geophysical Union*, **64**, 995–1004.

Hicks, A.J. (1993). *Directory of Organizations and Institutes Active in Environmental Monitoring*. United Nations Environment Programme, Nairobi.

Holdridge, L.R. (1947). Determination of world plant formations from simple climatic data. Science, **105**, 367–368.

Holling, C.S. (ed.)(1978). *Adaptive Environmental Assessment and Management*. Wiley, Chichester, 377 pp.

Holten, J.I. and Carey, P.D. (1992). *Responses of Climate Change on Natural Terrestrial Ecosystems in Norway*. NINA Forskningsrapport 29, Norwegian Institute for Nature Research, Trondheim, Norway, 59

Hotthus, P., Crawford, M., Makroro, C. and Sullivan, S. (1992). Vulnerability assessment for accelerated sea level rise case study: Majuro Atoll, Republic of the Marshall Islands, *SPREP Reports and Studies Series* No. 60, Apia, Western Samoa, 107 pp.

Hulme, M. (1994). Validation of large-scale precipitation fields in general circulation models. In Desbois, M., and Dèsalmand, F. (eds). *Global Precipitation and Climate Change*. NATO ASW Proceedings, Springer-Verlag, Berlin, pp. 387–405.

Hulme, M., Wigley, T., Jiang, T., Zhao, Z-c., Wang, F., Ding, Y., Leemans, R. and Markham, A. (1992). *Climate Change due to the Greenhouse Effect and its implications for China*. World Wide Fund for Nature, Gland, Switzerland, 57 pp.

Hulme, M., Raper, S. and Wigley, T. M. L. (1995a, in press). An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy*.

Hulme, M., Conway, D., Jones, P.D., Jiang, T., Barrow, E.M. and Turney, C. (1995b, in press). A 1961–90 climatology for Europe for climate change modelling and impact applications. *Int. J. Climatology*.

Hutchinson, M.F. (1987). Methods of generating weather sequences. In Bunting, A.H. (ed.) *Agricultural Environments: Characterization, Classification and Mapping*. CAB International, Wallingford, UK, pp. 149–157.

IBSNAT (1989). *Decision Support System for Agrotechnology Transfer Version 2.1 (DSSAT V2.1)*, International Benchmark Sites Network for Agrotechnology Transfer, Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu.

IPCC (1990a). *Climate Change: The IPCC Scientific Assessment*. Houghton, J.T., Jenkins, G.J., and Ephraums, J.J. (eds). Report of Working Group I of the Intergovernmental Panel on Climate Change, Cambridge University Press, 364 pp.

IPCC (1990b). *Climate Change: The IPCC Impacts Assessment*. Tegart, W.J.McG., Sheldon, G.W. and Griffiths, D.C. (eds). Report prepared for IPCC by Working Group II, Australian Government Publishing Service, Canberra, 210 pp.

IPCC (1991a). *Climate Change: The IPCC Response Strategies*. Island Press, Washington, D.C.

IPCC (1992a). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Houghton, J.T., Callander B.A. and Varney S.K. (eds). Cambridge University Press, 200 pp.

IPCC (1992b) *Climate Change 1992: the Supplementary Report to the IPCC Impacts Assessment*. Tegart, W.J. McG., Sheldan, G.W. and Griffiths, D.C. (eds). Report prepared for IPCC Working Group II, Australian Government Publishing Service, Canberra.

IPCC (1994). *Preparing to meet the Coastal Challenges of the 21st Century*. Conference Report, World Coast Conference 1993. Nordwijk, The Netherlands.

Johda, N.S. and Mascarenhas, A.C. (1985). Adjustment in self-provisioning societies. In Kates, R.W., Ausubel, J.H. and

Berberian, M. (eds). *Climate Impact Assessment: Studies of the Interaction of Climate and Society.* SCOPE 27, Wiley, Chichester, pp. 437–464.

Jones, P.D., Raper, S.C.B., Bradley, R.S., Diaz, H.F., Kelly, P.M. and Wigley, T.M.L. (1986a). Northern Hemisphere surface air temperature variations 1851-1984. *J. Clim. Appl. Met.*, **25**, 161–179.

Jones, P.D., Raper, S.C.B. and Wigley, T.M.L. (1986b). Southern Hemisphere surface air temperature variations 1851–1984. *J. Clim. Appl. Met.*, **25**, 1213–1230.

Karl, T.R., Wang, W-C., Schlesinger, M.E., Knight, R.W. and Portman, D.A. (1990) . A method of relating general circulation model simulated climate to the observed local climate. Part I: seasonal studies. *J. Climate*, **3**, 1053–1079.

Kates, R.W. (1985). The interaction of climate and society. In Kates, R.W., Ausubel, J.H. and Berberian, M. (eds). *Climate Impact Assessment: Studies of the Interaction of Climate and Society.* SCOPE 27, Wiley, Chichester, pp. 3–36.

Köppen, W. (1931). *Gründe der Klimakunde.* Walter de Gruyter, Berlin.

Kutzbach, J.E. and Guetter, P.J. (1986). The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. *J. Atmos. Sci.*, **43**, 1726–1759.

Lamb, H.H. (1977). *Climate: Present, Past and Future. Volume 2: Climatic History and the Future.* Methuen, London, 835 pp.

Leemans, R. and Cramer, W.P. (1991). The IIASA database for mean monthly values of temperature, precipitation, and cloudiness on a global terrestrial grid. *IIASA Research Report*, **RR-91-18**, International Institute for Applied Systems Analysis, Laxenburg, Austria, 62 pp.

Leggett, J., Pepper, W.J. and Swart, R.J. (1992). Emissions scenarios for the IPCC: an update. In Houghton, J.T., Callander, B.A. and Varney S.K. (eds). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge University Press, pp. 69–95.

Liverman, D. (1986). The response of a global food model to possible climate changes: A sensitivity analysis. *J. Climatol.*, 6, 355–373.

Lorenz, E.N. (1968). Climate determinism. *Meteorological Monographs*, **8(30)**, 1–3.

Lough, J.M., Wigley, T.M.L. and Palutikof, J.P. (1983) . Climate and climate impact scenarios for Europe in a warmer world. *J. Clim. Appl. Meteorol.*, 22, 1673–1684.

Lovell, C.A.K. and Smith, V.K. (1985). Microeconomic analysis. In Kates, R.W., Ausubel, J. H. and Berberian, M. (eds). *Climate Impact Assessment: Studies of the Interaction of Climate and Society.* SCOPE 27, Wiley, Chichester, pp. 293–321.

McGregor, J.L. and Walsh, K.J. (1993). Nested simulations of perpetual January climate over the Australian region. *J. Geophys. Res.*, **98(D12)**, 23283–23290.

McGregor, J.L., Walsh, K.J. and Katzfey, J.J. (1993). Nested modelling for regional climate studies. In Jakeman, A.J., Beck, M.B. and McAleer, M.J. (eds) *Modelling Change in Environmental Systems.* John Wiley, pp. 367–386.

McKenney, M.S. and Rosenberg, N.J. (1991). *Climate Data Needs from GCM Experiments for Use in Assessing the Potential Impacts of Climate Change on Natural Systems.* Climate Resources Program, Resources for the Future, Washington, D.C., 19 pp.

McWilliams, B.E. (ed.) (1991). *Climate Change: Studies on the Implications for Ireland.* Department of the Environment, Stationery Office, Dublin, 193 pp.

Magalhães, A.R. and Neto, E.B. (eds) (1989). *Socio-economic Impacts of Climatic Variations and Policy Responses in Brazil.* UNEP/SEPLAN-CE, Fortaleza, Ceará, Brazil (unpublished).

Manabe, S. and Wetherald, R.T. (1987). Large scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. *J. Atmos. Sci.*, **44**, 1211–1235.

Manabe, S., Stouffer, R.J., Spelman, M.J. and Bryan, K. (1991). Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part 1: Annual mean response. *J. Climate*, **4**, 785–818.

Manabe, S., Spelman, M.J. and Stouffer, R.J. (1992). Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part 2: Seasonal response. *J. Climate*, **5**, 105–126.

Manne, A.S. and Richels, R.G. (1992). *Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits.* Cambridge MA, MIT Press.

Manne, A., Mendelsohn, R. and Richels, R. (1993). MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Paper presented at the *International Workshop on Integrated Assessment of Mitigation, Impacts and Adaptation to Climate Change*, 13–15 October 1993, International Institute for Applied Systems Analysis, Laxenburg, Austria, 38 pp.

Martens, W.J.M., Rotmans, J. and Niessen, L.W. (1994). *Climate Change and Malaria Risk: An Integrated Modelling Approach.* RIVM Report No. 461502003, National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands, 37 pp.

Martin, P. and Lefebvre, M. (1993). 9 to 5. 9 approaches to tackle 5 aspects of climate change. *Climatic Change*, **25**, 421–438.

Matthews, E. (1983). Global vegetation and land use: new high-resolution data bases for climate studies. *J. Appl. Clim. Meteor.*, **22**, 473–487.

Matthews, E. (1985). *Atlas of archived vegetation, land-use and seasonal albedo data sets.* NASA Technical Memorandum No. 86199, National Aeronautics and Space Administration, New York, 23 pp.

Matthews, E. and Fung, I. (1987). Methane emission from natural wetlands. *Global Biogeochemical Cycles*, **1**, 61–86.

Mearns, L.O. and Rosenzweig, C. (1994). Use of a nested regional climate model with changed daily variability of precipitation and temperature to test related sensitivity of dynamic crop models. *Preprints of the AMS Fifth Symposium on Global Change Studies, January 23–28 1994*, American Meteorological Society.

Mikami, T. (ed.) (1992). *Proceedings of the International Symposium on Little Ice Age Climate*. Department of Geography, Tokyo Metropolitan University, Hachioji, Japan, 342 pp.

Morita, T., Matsuoka, Y., Kainuma, M., Harasawa, H. and Kai, K. (1993). AIM—Asian-Pacific Integrated Model for Evaluating Policy Options to reduce GHG Emissions and Global Warming Impacts. Paper presented at the *International Workshop on Integrated Assessment of Mitigation, Impacts and Adaptation to Climate Change,* 13–15 October 1993, International Institute for Applied Systems Analysis, Laxenburg, Austria, 26 pp.

Murphy, J.M. (1994). Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part I: Control climate and flux correction. *J. Climate* (in press).

Murphy, J.M. and Mitchell, J.F.B. (1994). Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part II: Spatial and temporal structure of the response. *J. Climate* (in press).

National Defense University (NDU) (1978). *Climate Change to the Year 2000*. Washington, D.C., Fort Lesley J. McNair.

National Defense University (NDU) (1980). *Crop Yields and Climate Change to the Year 2000. Vol. 1*. Washington, D.C., Fort Lesley J. McNair.

Nordhaus, W.D. (1992). The DICE Model: Background and Structure of a Dynamic Integrated Climate Economy Model of the Economics of Global Warming. *Cowles Foundation Discussion Paper, No. 1009*, New Haven, Connecticut.

Ninh, N.H., Glantz, M.H. and Hien, H.M. (eds) (1991). *Climate Related Impact Assessment in Vietnam*. Center for Natural Resources Management and Environmental Studies, University of Hanoi, Vietnam and National Center for Atmospheric Research, Boulder, Co., USA (unpublished).

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.

OECD (1990). *Main Economic Indicators—Historical Statistics, 1969-1988*. 766 pp.

OECD Environment Committee (1991). *Climate Change: Evaluating the Socio-Economic Impacts*. 109 pp.

Olson, J., Watts, J.A. and Allison, L.J. (1985). *Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database*. Carbon Dioxide Information and Analysis Center, Oak Ridge, Tennessee, USA.

Parry, M.L. (1978). *Climatic Change, Agriculture and Settlement*. Dawson, Follkestone, 214 pp.

Parry, M.L. and Carter, T.R. (1988). The assessment of effects of climatic variations on agriculture: aims, methods and summary of results. In Parry, M.L., Carter, T.R. and Konijn, N.T. (eds). *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*. Kluwer, Dordrecht, The Netherlands, pp. 11–95.

Parry, M.L., Carter, T.R. and Konijn, N.T. (eds) (1988a). *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*, Kluwer, Dordrecht, The Netherlands, 876 pp.

Parry, M.L., Carter, T.R. and Konijn, N.T. (eds) (1988b). *The Impact of Climatic Variations on Agriculture. Volume 2. Assessments in Semi-Arid Regions*, Kluwer, Dordrecht, The Netherlands, 764 pp.

Parry, M.L. (1990). *Climate Change and World Agriculture*, Earthscan, London, 210 pp.

Parry, M.L., Blantran de Rozari, M., Chong, A.L. and Panich, S. (1992). *The Potential Socio-Economic Effects of Climate Change in South-East Asia*. United Nations Environment Programme, Nairobi, 126 pp.

Pearce, D. W. (1993) *Economic Values and the Natural World*, Earthscan, London

Pearman, G.I. (ed.) (1988) *Greenhouse: Planning for Climate Change*. CSIRO, Melbourne.

Peck, S.C. and Teisberg, T.J. (1992). CETA: A model for Carbon Emissions Trajectory Assessment. *The Energy Journal*, **13(1)**, 55–77.

Pfister, C. (1984). *Das Klima der Schweiz und Seine Bedeutung in der Geschichte von Bevolkenung und Landwirtschaft*. 2 volumes. Haupt, Bern.

Pitovranov, S.E. (1988). The assessment of impacts of possible climate changes on the results of the IIASA RAINS sulfur deposition model in Europe. *Wat. Air Soil Pollut.*, **40**, 95–119.

Pittock, A.B. (1993). Climate scenario development. In Jakeman, A.J., Beck, M.B. and McAleer, M.J. (eds). *Modelling Change in Environmental Systems*. John Wiley, pp. 481–503.

Riebsame, W.E. (1988). *Assessing the Social Implications of Climate Fluctuations: A Guide to Climate Impact Studies*. United Nations Environment Programme, Nairobi, 82 pp.

Robinson, J. (1985). Global monitoring and simulations. In Kates, R.W., Ausubel, J.H. and Berberian, M. (eds). *Climate Impact Assessment: Studies of the Interaction of Climate and Society*. SCOPE 27, Wiley, Chichester, pp. 3–36.

Robock, A., Turco, R.P., Harwell, M.A., Ackerman, T.P., Andressen, R., Chang, H-S. and Sivakumar, M.V.K. (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. (1992). Adaptation of agriculture to climate change. *Climatic Change*, **21**, 385–405.

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

Rosenzweig, C. and Parry, M.L. (1994). Potential impact of climate change on world food supply. *Nature*, **367**, 133–38.

Rotmans, J. (1990). *IMAGE: an Integrated Model to Assess the Greenhouse Effect.* Kluwer, Dordrecht.

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

Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B. (1990). Developing climate scenarios from equilibrium GCM results. *Report No. 47*, Max-Planck-Institut-für-Meteorologie, Hamburg, 29 pp.

Scheraga, J.D., Leary, N., Goettle, R., Jorgenson, D. and Wilcoxen, P. (1993). Macroeconomic modelling and the assessment of climate change impacts. In Kaya, Y., Nakicenovic, N., Nordhaus, W.D. and Toth, F.L. (eds). Costs, Impacts and Possible Benefits of CO_2 Mitigation. *IIASA Collaborative Paper*, **CP-93-2**, pp. 107–132.

Scott, M.J. (1993). Impacts of Climate Change on Human Settlements: Guidelines for Assessing Impacts. Draft Mimeo submitted to the *UNEP-Canada Workshop on Impacts and Adaptation to Climate Variability and Change*, Toronto, Canada, 29 November–3 December 1993, 3 pp.

Smit, B. (1991). Potential future impacts of climatic change on the Great Plains. In Wall, G. (ed.) *Symposium on the Impacts of Climatic Change and Variability on the Great Plains.* Department of Geography Publication Series, Occasional Paper No. 12, University of Waterloo, Canada.

Smit, B (1993). (Ed.) *Adaptation to Climatic Variability and Change.* Report of the Task Force on Climate Adaptation, The Canadian Climate Program. Occasional Paper No. 19, Department of Geography, University of Guelph, 53 pp.

Smith, J.B. and Tirpak, D.A. (1990). *The Potential Effects of Global Climate Change on the United States.* Report to Congress, United States Environmental Protection Agency, Washington, D.C.

Smith, M. (1992). *Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements.* Land and Water Development Division, Food and Agriculture Organization, Rome, 60 pp.

Stakhiv, E.Z., Ratick, S.J. and Du, W. (1991). Risk-cost aspects of sea level rise and climate change in the evaluation of shore protection projects. In: Ganoulis, J. (ed.). *Water Resources Engineering Risk Assessment.* NATO ASI Series. Springer-Verlag, Berlin, pp. 311–335.

Stakhiv, E.Z. (1993). Water resources planning and management under climate uncertainty. In: Ballentine, T.M. and Stakhiv, E.Z. (eds). *Proceedings of the First National Conference on Climate Change and Water Resources Management*, IWR Report 93-R-17, Institute of Water Resources, US Army Corps of Engineers, Washington, D.C., IV–20–IV–35

Stakhiv, E.Z. (1994). Water resources planning of evaluation principles applied to ICZM. In: Proc. *Preparatory Workshop on Integrated Coastal Zone Management and Responses to Climate Change.* World Coast Conference 1993, New Orleans, Louisiana.

Stewart, T.R. and Glantz, M.H. (1985). Expert judgement and climate forecasting: A methodological critique of *Climate Change to the Year 2000. Climatic Change*, **7**, 159–183.

Strain, B.R. and Cure, J.D. (eds) (1985). *Direct Effects of Increasing Carbon Dioxide on Vegetation.* DOE/ER–0238, United States Department of Energy, Office of Energy Research, Washington D.C., 286 pp.

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

Strzepek, K.M., Onyeji, S.C., Saleh, M. and Yates, D. (in press). An assessment of integrated climate change impact on Egypt. In Strzepek, K.M. and Smith, J. (eds). *As Climate Changes: International Impacts and Implications.* Cambridge University Press, Cambridge.

Swart, R.J. and Vellinga, P. (1994). The 'ultimate objective' of the framework convention on climate change requires a new approach in climate change research. *Climatic Change*, **26**, 343–349.

Swartzman, G.L. and Kaluzny, S.P. (1987). *Ecological Simulation Primer.* Macmillan, New York, 370 pp.

Tarpley, J.D. (1991). The NOAA global vegetation index project—a review. *Palaeogeog., Palaeoclim., Palaeoecol.*, **90**, 189–194.

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

TSU (1994). *Climatic Scenarios and Socioeconomic Projections for IPCC WGII Assessment.* IPCC WGII Technical Support Unit, Washington, D.C, 12 pp. plus appendices and diskettes.

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, 43 pp.

United Nations (1991). *World Population Prospects, 1990.* Population Studies No. 120, New York.

United Nations (1992). *World Population Prospects: The 1992 Revision*, New York.

UNEP (1987). *World Directory of Environmental Expertise,* INFOTERRA. United Nations Environment Programme, Nairobi.

UNEP (1992). *World Atlas of Desertification*. Edward Arnold, London.

UNEP (1993). *Environmental Data Report, 1993–94*. United Nations Environment Programme, Blackwell, Oxford.

Viner, D. and Hulme, M. (1992). *Climate Change Scenarios for Impact Studies in the UK: General Circulation Models, Scenario Construction Methods and Applications for Impact Assessment*. Report for the UK Department of the Environment, Climatic Research Unit, University of East Anglia, Norwich, 70 pp.

Viner, D. and Hulme, M. (1994). *The Climate Impacts LINK Project: Providing Climate Change Scenarios for Impacts Assessment in the UK*. Report for the UK Department of the Environment, Climatic Research Unit, Norwich, 24 pp.

Vinnikov, K.Ya. and Groisman, P.Ya. (1979). An empirical model of present-day climate change. *Meteorol. Gidrolog.*, **1979, No. 3**, 25–36 (in Russian).

Vloedbeld, M. and Leemans, R. (1993). Quantifying feedback processes in the response of the terrestrial carbon cycle to global change: the modeling approach of IMAGE-2. *Wat. Air Soil Pollut.*, **70**, 615–628.

de Vries, H.J.M., Olivier, J.G.J., van den Wijngaart, R.A., Kreileman, G.J.J. and Toet, A.M.C. (1994). Model for calculating regional energy use, industrial production and greenhouse gas emissions for evaluating global climate scenarios. *Wat. Air Soil Pollut.*, **76**, 79–131.

Warrick, R.A. (1984). The possible impacts on wheat production of a recurrence of the 1930s drought in the U.S. Great Plains. *Climatic Change*, **6**, 5–26.

Warrick, R.A., Barrow, E.M. and Wigley, T.M.L. (eds). (1993). *Climate and Sea Level Change: Observations, Projections and Implications*. Cambridge University Press, Cambridge.

Whetton, P.H., Hennessy, K.J., Pittock, A.B., Fowler, A.M. and Mitchell, C.D. (1992). Regional impact of the enhanced greenhouse effect on Victoria. *Annual Report 1991-92*. CSIRO Division of Atmospheric Research, Commonwealth Scientific and Industrial Research Organization, Mordialloc, 64 pp.

WHO (1990). Global estimates for health situation assessments and projections 1990. *WHO/HST/90.2*, Division of Epidemiological Surveillance and Health Situation and Trend Assessment, World Health Organization, 61 pp.

Whyte, A.V.T. (1985). Perception. In Kates, R.W., Ausubel, J.H. and Berberian, M. (eds). *Climate Impact Assessment: Studies of the Interaction of Climate and Society*. SCOPE 27, Wiley, Chichester, pp. 403–436.

Wigley, T.M.L. and Raper, S.C.B. (1992). Implications for climate and sea level of revised IPCC emissions scenarios. *Nature*, **357**, 293-300.

Wigley, T.M.L., Jones, P.D., Briffa, K.R. and Smith, G. (1990). Obtaining sub-grid-scale information from coarse-resolution general circulation model output. *J. Geophys. Res.*, **95(D2)**, 1943–1954.

Wilks, D.S. (1988). Estimating the consequences of CO_2-induced climate change on North American grain agriculture using general circulation model information. *Climatic Change*, **13**, 19–42.

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

Williams, G.D.V., Fautley, R.A.Jones, K.H., Stewart, R.B., and Wheaton, E.E. (1988). Estimating Effects of Climatic Change on Agriculture in Saskatchewan, Canada. In Parry, M.L., Carter, T.R. and Konijn, N.T. (eds). *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions*., Kluwer, Dordrecht, The Netherlands, pp. 219–379.

Wilson, C.A. and Mitchell, J.F.B. (1987). A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean. *J. Geophys. Res.*, **92(13)**, 315–343.

WMO (1985). *Report of the WMO/UNEP/ICSU- SCOPE Expert Meeting on the Reliability of Crop-Climate Models for Assessing the Impacts of Climatic Change and Variability*. WCP–90, World Meteorological Organization, Geneva, 31 pp.

WMO (1988). *Water Resources and Climatic Change: Sensitivity of Water Resource Systems to Climate Change and Variability*. WCAP-4, World Meteorological Organization, Geneva.

World Bank (1991). *World Development Report, 1991*. Oxford University Press, New York.

WRI (1992). *World Resources, 1992-1993. A Guide to the Global Environment. Toward Sustainable Development*. World Resources Institute, Oxford University Press, New York, 385 pp.

Yin, Y. and Cohen, S.J. (1994). Identifying regional goals and policy concerns associated with global climate change. *Global Environmental Change*, **4(3)**, 246–260.

Zobler, L. (1986). A world soil file for global climate modelling. *NASA Technical Memorandum 87802*, National Aeronautics and Space Administration, New York.

APPENDIX 1: APPROACHES FOR DEVELOPING CLIMATIC SCENARIOS FROM GCM INFORMATION

A1

Some standard methods of scenario construction are outlined below. Most impact assessments relying on GCM outputs for scenarios have adopted one of the alternatives described. For further details, readers are referred to the examples cited. Useful reviews of climatic scenario development are provided by Giorgi and Mearns (1991) and Pittock (1993).

A1.1 Equilibrium changes

Two methods are commonly used for computing the change in climate between the modelled control and 2 x CO_2 conditions for each grid box: by calculating the difference or 'delta' (i.e., 2 x CO_2 minus control), or the ratio (i.e., 2 x CO_2 divided by control) between pairs of values. The former method is usually preferred for considering temperature changes and the latter for precipitation changes. Note that if ratios are applied to temperatures, data should be converted from the relative Celsius scale to the absolute Kelvin scale (0°C = 273.15K).

A1.2 Scaling to the baseline

Since GCM outputs are not generally of a sufficient resolution or reliability to estimate regional climate even for the present-day (i.e., via the control run), it is usual for baseline observational data to be used to represent the present-day climate. These are then adjusted to represent the 2 x CO_2 climate, either by adding the deltas or multiplying the ratios described above (Box A1). The method implicitly assumes, therefore, that any systematic errors in the control run are also present in the experiment. A further note of caution concerns the application of precipitation ratios derived from GCM outputs to baseline precipitation in dry regions. If the GCM indicates that precipitation increases due to a shift in circulation, this increase expressed as a percentage has little effect when multiplied by the low baseline value, producing an unrealistic scenario. In such cases, the discretionary use of differences rather than ratios might be appropriate.

A1.3 Transient changes

The procedure for constructing transient scenarios is somewhat different. Firstly, the problem of drift in the control run (see Section 6.5.3) makes the selection of an averaging period problematic. Some workers use the full control period for averaging, others a period at the beginning, and still others a period in the control run corresponding to the equivalent period in the perturbation run.

Second, the requirements for scenario information from transient model outputs are either for discrete or continuous estimates. Discrete estimates provide values for time slices in the future (for example, decadal averages of change relative to the control). Continuous estimates refer to year-by-year values throughout the projection period. A simple method of scenario construction, developed for use in deliberations by IPCC Working Group II (TSU, 1994) is described in Box A2.

A1.4 Missing variables

In the absence of information on changes in certain climatic variables important for impact assessment, values of these variables are usually fixed at baseline levels. Given the sometimes strong correlations between variables under present-day climate, this procedure should be adopted with caution. An alternative involves invoking these statistical relationships to adjust missing variables according to changes in predicted variables.

A1.5 Time resolution

It is usually assumed that monthly adjustments made to climatic variables can be applied equally to data at shorter, within-month time steps. In the absence of information about the year-to-year variability of climate, it is further assumed that this remains the same under the scenario climate as during the baseline period. Recently, methods have been reported that make use of the daily data that are available from a limited number of GCM simulations. The statistical properties of these data can be used to generate stochastic weather data sets suitable as inputs to impact models.

A1.6 Sub-grid-scale data

One of the major problems faced in applying GCM projections to regional impact assessments is the coarse spatial scale of the estimates. Typically, GCM data are available at a horizontal grid point resolution of, at best, some 200 kilometers. Several methods have been adopted for developing regional GCM-based scenarios at sub-grid scale:

(1) The study area baseline is combined with the scenario anomaly of the nearest centre of a grid box (e.g., Bultot *et al.*, 1988; Croley, 1990). This has the drawback that sites which are in close mutual proximity but fall in different grid boxes, while exhibiting very similar baseline climatic characteristics, may be assigned a quite different scenario climate.

(2) The scenario anomaly field is objectively interpolated, and the baseline value (at a site or interpolated) is combined with the interpolated scenario value (e.g., Parry and Carter, 1988; Cohen, 1991). This overcomes the problem in (1), but introduces a false precision to the estimates.

(3) Experiments are conducted with regional 'fine mesh' climate models, which use inputs from GCMs and are then run (nested) at a higher spatial resolution (e.g., see the review by McGregor *et al.*, 1993). This is a physically-based method of accounting for important local forcing factors such as surface type and elevation, which GCMs are unable to resolve. A number of model runs have been conducted for regions in Europe and North America (e.g., Giorgi *et al.*, 1992) and Australia (e.g., McGregor and Walsh, 1993), and at least one (agricultural) impact study has been reported based on the outputs from a nested model (Mearns and Rosenzweig, 1993).

(4) Statistical relationships are established between observed climate at local scale and at the scale of GCM grid boxes. These relationships are used to estimate local adjustments to the baseline climate from the GCM grid box values (e.g., Wilks, 1988; Karl *et al.*, 1990; Wigley *et al.*, 1990). A variant of this approach relates local climate to objective measures of historical circulation types and then determines a scenario climate on the basis of the circulation type computed from GCM predictions (e.g., Bardossy and Plate, 1992). A weakness of both of these methods is that they assume that the relationships between sub-grid scale and large-scale climate will not change under GHG forcing.

A1.6 Composite scenarios

A number of studies have combined the anomaly fields from several scenarios (e.g., GCMs, historical) into one scenario using either dynamical/empirical reasoning (e.g., Pearman, 1988; Ackerman and Cropper, 1988; Robock *et al.*, 1993) or averaging (e.g., Santer *et al.*, 1990). Composite scenarios of this type are not generally realistic at a global scale, as they are based on a range of source scenarios, each having different assumptions and regional parameterizations. However, they have become useful in impact assessment both because they are relatively simple to apply and because they can provide information on between-model uncertainty of projections (Viner and Hulme, 1992).

A1.7 Scaling GCM outputs to global projections

It has become common to use simple climate models rather than GCMs to estimate the effects on future global temperatures of alternative GHG emission scenarios (IPCC, 1990a, 1992a). Their attractiveness as policy tools makes it desirable to use these scenarios in impact studies. However, since only global estimates are provided they cannot be used directly in regional assessments. A method of overcoming this problem makes use of GCM information in conjunction with the global estimates, whereby the GCM estimates of regional changes are scaled according to the ratio between the GCM estimate of global temperature change and that provided in the simple scenario (for example, for a doubling of CO_2). An example of how this technique can be used in developing transient scenarios is shown in Box A2.

A1.8 Selecting models

Many GCM simulations have been conducted in recent years, and it is not easy to choose suitable examples for use in impact assessments. In general, the more recent simulations are likely to be more reliable as they are based on recent knowledge, and they tend to be of a higher spatial resolution than earlier model runs. The IPCC has undertaken a GCM intercomparison exercise, which should provide useful information on model reliability and uncertainties (EPRI, 1994). It is strongly recommended that recent reviews of GCMs be consulted before selection. The National Center of Atmospheric Research, Boulder, Colorado, USA has been acting as a clearing house for GCM data from different modelling groups. In addition, the Model Evaluation Consortium for Climate Assessment (MECCA) at Macquarie University, New South Wales, Australia has developed a prototype compact disc, MECCA CD, which contains data from GCMs and a protocol for their distribution and use.

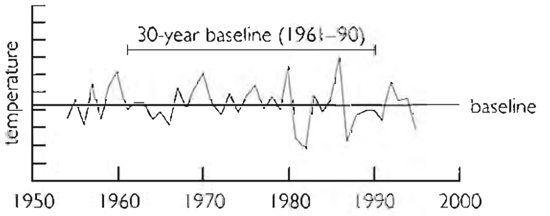
BOX A1
SCENARIOS FROM EQUILIBRIUM GCM OUTPUTS

To illustrate how equilibrium GCM outputs are commonly used to develop climatic scenarios, let us consider that the climatic variable of interest is June surface air temperature at a site, S. A long time series of mean June temperatures is available from a meteorological station at the site (Figure (a)). GCM estimates of monthly mean temperature for a model grid point adjacent to or interpolated to site S have been obtained for an equilibrium 2 x CO2 simulation, accompanied by estimates for a control simulation assuming present-day atmospheric greenhouse gas (GHG) concentrations (Figure (b)).

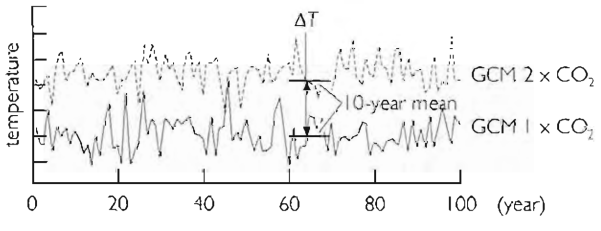
The climatological baseline is selected as the most recent standard 30-year averaging period for which observations are available (1961–1990; Figure (a)). Note that this period encompasses notable extreme events and some cyclicity at a decadal time scale.

The GCM estimates for the control and equilibrium 2 x CO2 simulations are shown in Figure (b) as annual values of mean June temperature. Climate modellers usually provide model results only for a period during which the global mean annual temperature approximates equilibrium (often a 10-year period). A similar period is also selected from late in the control run, as it often takes several decades for the modelled 1 x CO2 atmosphere to equilibriate. The difference between the mean equilibrium control and mean equilibrium 2 x CO2 temperature is then computed, and this is applied as an adjustment to each annual baseline value of June temperature at site S (Figure (c)).

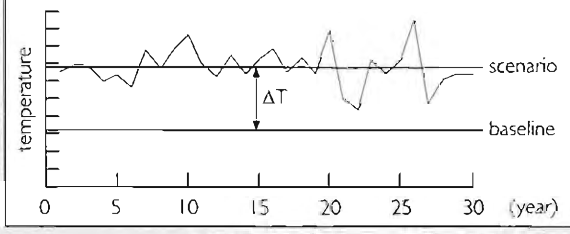
(a) Observed temperature



(b) GCM equilibrium simulations



(c) 2 x CO_2 scenario



BOX A2
SCENARIOS FROM TRANSIENT GCM OUTPUTS

A simple method of constructing scenarios based on transient GCM outputs has been developed at the Climatic Research Unit, UK for use in the IPCC WG II Second Assessment (TSU, 1994). The method is adapted from ideas originally proposed by Santer *et al.* (1990), and links information on the regional pattern of climate change from transient GCM simulations with output from a set of simple models which determine the global temperature response to given assumptions about future greenhouse gas emissions and concentrations (MAGICC).

MAGICC is described elsewhere in this report (Box 3). In order to obtain time dependent regional scenarios from the global mean temperature changes estimated by MAGICC, information is required from transient runs with GCMs. Results from three coupled ocean-atmosphere GCM experiments have been used in this exercise: the UK Hadley Centre model (UKTR; Murphy, 1994, Murphy and Mitchell, 1994), the Max Planck Institute, Hamburg model (ECHAM1-A; Cubasch *et al.*, 1992) and the Geophysical Fluid Dynamics Laboratory, Princeton model (GFDL89; Manabe *et al.*, 1991, 1992). Each model has been run over different time horizons and with slightly different assumptions about GHG concentrations.

All models are affected by the cold start problem (cf. Section 6.5.3), making it difficult to assign dates to the transient climate changes projected with these models. To overcome this, the time development of mean annual global temperature change was obtained using MAGICC, which starts with a pre-industrial climate and accounts for the GHG and sulphate aerosol forcing up to 1990. The model was run for the IS92a emissions scenario (including sulphates) assuming the mid-range climate sensitivity (2.5°C). The mean annual global temperature change was computed for the years 2020 and 2050 as 0.53°C and 1.16°C, respectively. These values have been used to identify the decades in three transient GCM runs where the global mean annual temperature changes are equivalent (see Table I). In addition to overcoming the cold start problem, this method also harmonizes the different radiative forcing scenarios used in each experiment.

To construct the scenarios, differences (or ratios) have been computed between the mean climate during the identified decades and equivalent decades in the control run simulation. These differences (ratios) can then be used as adjustments to the climatological baseline following the methods described in Appendix 1, Section A1.2.

It should be stressed that the levels of warming shown in Table I are mean annual global averages and represent only the mid-range climate sensitivity as determined by MAGICC. They are illustrative of the differences in seasonal and geographical pattern of climate change between the three GCMs, and are not intended to embrace the range of uncertainties attributable to different climate sensitivities, to alternative GHG emissions scenarios or to less tangible sources of error. For example, for a high emissions scenario (e.g., IS92f) combined with high climate sensitivity (4.5°C) the corresponding values of global warming for 2020 and 2050 are 0.81°C and 1.91°C, respectively. For a low emissions scenario (e.g., IS92c) and low climate sensitivity (1.5°C), the respective values are 0.34°C and 0.65°C. Therefore, the adoption of alternative assumptions would yield quite different regional scenarios.

An additional limitation of the approach is that the pattern of change derived from the GCMs does not reflect the likely pattern attributable to sulphate forcing (sulphates are treated only at a global scale by MAGICC). Transient experiments with GCMs which include both GHG and sulphate forcing have only recently been completed (Taylor and Penner, 1994).

Notwithstanding their limited range of representativeness, the scenarios described above still exhibit large inter-regional and between-model differences. To illustrate this, three locations have been arbitrarily selected to represent temperate (Beijing), semi-arid (Bulawayo) and oceanic (Havana) environments. Table II shows winter and summer temperature and precipitation changes estimated by the three GCMs for 2020 and 2050 at the nearest GCM grid boxes to these locations.

Table I. Ten-year periods in the three transient GCM simulations assumed to be equivalent to the decades centred around 2020 and 2050 in the MAGICC model simulations (with increase in global mean surface air temperature of 0.53°C and 1.16°C, respectively, relative to 1990). Source: TSU (1994).

YEAR	Equivalent years in GCM GFDL89	 ECHAM1-A	 UKTR
2020	18–27	35–44	24–33
2050	36–45	48–57	49–58

continued ...

... continued

Table II. Model-simulated changes in seasonal (December to February–DJF; June to August–JJA) temperature and precipitation at grid boxes representing three contrasting sites: Beijing, Bulawayo and Havana. Values are from transient GCM simulations and represent mean climate in 2020 and 2050 following procedures described in the text. Source of data: TSU (1994).

GCM	Change in climate by 2020				Change in climate by 2050			
	Temperature (°C)		Precipitation (%)		Temperature (°C)		Precipitation (%)	
	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA
	Beijing, China (39.93°N, 116.28°E)							
GFDL89	0.4	0.5	-18	+9	2.8	1.1	-5	0
UKTR	1.5	1.0	+82	+20	2.5	1.5	+70	+28
ECHAM1-A	0.7	0.4	-20	+15	1.0	1.5	+5	-13
	Bulawayo, Zimbabwe (20.15°S, 28.62°E)							
GFDL89	-0.1	0.2	+1	+6	1.7	1.6	-7	+32
UKTR	0.3	0.1	+34	+84	2.0	2.0	+27	+77
ECHAM1-A	0.6	0.9	-1	-21	1.0	2.1	+14	-45
	Havana, Cuba (23.17°N, 82.35°W)							
GFDL89	0.7	0.7	+11	+17	0.9	0.9	+7	-8
UKTR	0.8	0.7	+28	+14	1.0	1.2	-10	-12
ECHAM1-A	0.7	0.5	-13	-3	0.3	0.7	+10	-19

APPENDIX 2: A SELECTION OF CLIMATE IMPACT ASSESSMENTS, SHOWING THE STUDY REGION, SECTORS CONSIDERED, CLIMATIC SCENARIOS ADOPTED AND ANALYTICAL METHODS EMPLOYED

A2

REGION	SECTORS	CLIMATIC SCENARIOS	APPROACH	STUDY METHODS	REFERENCE
Globe	Agr. For. Wat. Ene	GCM Equilibrium $2 \times CO_2$	Parallel sectoral assessments	Modelling	Strzepek and Smith (in press)
Globe	Agr. For. Eco. Ene	GCM Equilibrium $2 \times CO_2$	Integrated	Modelling	Alcamo, 1994
Globe	Hea	GCM Equilibrium $2 \times CO_2$	Sectoral	Modelling	Martens *et al.*, 1994
Brazil	Agr. Ene. Ind. Hea. Urb. Wat	Temporal analogue	Parallel sectoral assessments	Modelling; qualitative	Magalhães and Neto, 1989
China	Sea. Eco. Agr. Ene	GCM Equilibrium $2 \times CO_2$ (Composite)	Parallel sectoral assessments	Modelling	Hulme *et al.*, 1992
Iceland, Finland, Canada, N. USSR, Japan	Agr	GCM Equilibrium $2 \times CO_2$; temporal analogue	Sectoral	Modelling	Parry *et al.*, 1988a
Indonesia, Malaysia & Thailand	Sea. Wat. Agr. Coa. Fis	GCM Equilibrium $2 \times CO_2$	Parallel sectoral assessments	Modelling	Parry *et al.*, 1992
Ireland	Agr. For. Eco. Wat. Sea. Fis	Expert judgement	Parallel sectoral assessments	Expert judgement; modelling	McWilliams, 1991
Japan	Wat. Agr. For. Fis. Eco. Coa. Ene. Urb. Hea	Various	Parallel sectoral assessments	Expert judgement; modelling	Nishioka *et al.*, 1993
Kenya, Brazil, Ecuador, India, S. USSR, Australia	Agr	Temporal analogue	Sectoral	Modelling; empirical survey	Parry *et al.*, 1988b
Missouri, Illinois, Nebraska, Kansas, USA (MINK)	Agr. For. Ene	Temporal analogue	Integrated	Modelling	Rosenberg, 1993
UK	Sea. Eco. Agr. For. Coa. Wat. Ene. Ind. Tra. Fin. Rec	GCM Equilibrium $2 \times CO_2$ (Composite)	Parallel sectoral assessments	Expert judgement; modelling	Department of the Environment, 1991
USA	Sea. Agr. For. Wat	GCM Equilibrium $2 \times CO_2$	Parallel sectoral assessments	Modelling	Smith and Tirpak, 1990
Vietnam	Agr. Hea. Ene. For. Fis.	Expert judgement, temporal analogue??	Parallel sectoral assessments	Modelling; qualitative	Ninh *et al.*, 1991
Zimbabwe, Kenya, Senegal, Chile	Agr	Expert judgement	Sectoral	Modelling	Downing, 1992

Agr: agriculture For: forestry Ene: energy supply and demand Wat: water resources Sea: sea level rise Coa: coastal zone Eco: natural ecosystems
Fis: fisheries Ind: industry Urb: urban areas Fin: financial sector Hea: human health Tra: transport Rec: recreation and tourism

APPENDIX 3: ABBREVIATIONS, ACRONYMS AND CHEMICAL FORMULAE

A3

AIM	Asia-Pacific Integrated Model
ASLR	Accelerated Sea Level Rise
BaU	Business-as-Usual
BGMV	Bean Golden Mosaic Virus
CO_2	Carbon Dioxide
CEC	Commission of the European Communities
CEOS-IDN	Commission on Earth Observing System-International Data Network
CETA	Carbon Emissions Trajectory Assessment Model
CFC	Chlorofluorocarbon
CGE	Computable General Equilibrium (models)
CH_4	Methane
CRU	Climate Research Unit
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
DICE	Dynamic Integrated Climate Economy
DMI	Dynamic Macroeconomic Interindustry (models)
ECHAM 1-A	Max Planck Institute for Meteorology ECMWF Hamburg model Version 1-a
EPIC	Erosion-Productivity Impact Calculator
ESCAPE	Evaluation Strategies to Address Climate Change by Adapting to and Preventing Emissions
FAO	Food and Agriculture Organization
GCAM	Global Change Assessment Model
GCM	General Circulation Model
GDP	Gross Domestic Product
GEMS	Global Environmental Monitoring System (UNEP)
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GIS	Geographical Information Systems
GNP	Gross National Product
GRID	Global Resource Information Database (UNEP)
HDP	Human Dimensions of Global Environmental Change Programme
HEM	Harmonization of Environmental Monitoring
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Greenhouse Effect
IPCC	Intergovernmental Panel on Climate Change
IRIA	Integrated Regional Impact Assessment
ISRIC	International Soil Reference and Information Center
ISSC	International Social Science Council
LDC	Less Developed Country
MAGICC	Model for the Assessment of Greenhouse-Gas Induced Climate Change
MERGE	Model for Evaluating Regional and Global Effects of GHG reduction policies
MINK	Missouri, Iowa, Nebraska, Kansas study on the US Corn Belt
NATO	North Atlantic Treaty Organization
NCAR	National Center of Atmospheric Research, Boulder, Co, USA
NDU	National Defence University
NOAA	National Oceanographic and Atmospheric
AVHRR	Administration, Advanced Very High Resolution Radiometer
N_2O	Nitrous Oxide
OECD	Organization of Economic Cooperation and Development
ppmv	parts per million by volume
SCOPE	Scientific Committee on Problems of the Environment
TSU	Technical Support Unit (IPCC Working Group II)
UKTR	United Kingdom Meteorological Office Transient Model
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VBD	Vector Borne Disease
WMO	World Meteorological Organization
WCP	World Climate Programme
WCIRP	World Climate Impact Assessment and Response Strategies Studies Programme
WRI	World Resources Institute

APPENDIX 4: SOME INTERNATIONAL DATA SOURCES OF INTEREST IN CLIMATE IMPACT ASSESSMENT STUDIES

A4

Table I: Data Sources

Type of data	Source	Spatial/temporal resolution	Content
Projections			
Population	IPCC[1]	7 regions and global/ totals in 2100	Total population (various projections)
Economic development	IPCC[1]	4 regions and global/trends 1990-2100	GNP (average annual rate–various projections)
Gas and aerosol emissions	IPCC[1]	Global/annual rates 1990, 2025 and 2100	IS92a-f scenarios: CO_2, CH_4, N_2O, CFCs, Halocarbons, SO_x
Radiative forcing	Wigley/Raper[2]	Global/annual up to 2100	IS92a-f scenarios and various assumptions
Climate change	NCAR[3]	Gridded (various resolutions)/ daily, monthly and seasonal (time series or time slice up to 2100)	Equilibrium GCM (various models); Transient GCM (various models); Temperature, precipitation and other variables
"	CRU[4]	Gridded (various resolutions) and globally averaged/monthly, seasonal and annual (time series or time slice up to 2100)	Equilibrium GCM (various models, inc. composite); Transient GCM (various models); 1-dimensional model (MAGICC); Temperature, precipitation and other variables
Sea level rise	CRU[5]	Global/annual up to 2100	MAGICC (for any given emissions scenario)
Agriculture, forestry and fisheries	FAO[6]	Regional, global/ totals in 2010	Area, production, trade, consumption and other data
Current baseline			
Population	UN[7]	National/annual	Total population/urban population (various projections)
Economic growth	World Bank[8]	National/annual	GNP, GDP
Climate	CDIAC[9]	Global stations/ monthly (historical time series)	Temperature, precipitation, cloudiness atmospheric pressure
"	UNEP/GRID[10]	Global 0.5° lat:lon grid/ 1931–1960 period monthly means	Temperature, precipitation,
"	CRU[11]	Global 5° lat:lon grid/ 1961–1990 period monthly means Europe 0.5° lat:lon grid/ 1961–1990 period monthly means	Temperature, precipitation Temperature(max, min), precipitation, sunshine, windspeed, vapour pressure, rain days, frost days
"	ECMWF/WCRP[12]	Global 2.5°, 1.125°, 0.5° lat:lon grid/ daily, monthly for individual years	Temperature, precipitation, atmospheric pressure
Land use/cover	UNEP/GRID[13]	Global 0.5° lat:lon grid/recent	Major ecosystem complexes based on maps and observations
"	UNEP/GRID[14]	Global 1° lat:lon grid/ 1960–1979	Predominant vegetation types, cultivation intensity and seasonal albedo based on maps
"	UNEP/GRID[15]	Global 1° lat:lon grid	Wetlands (derived)
Agriculture, forestry and fisheries	FAO[5]	National, regional, global/ 1970, 1980, 1990	Area, production, trade, food supply and other data
General environment	UNEP[16]	National	Water, air, health and other environmental measures
Soil	UNEP/GRID[17]	Global 2 minute grid	FAO/UNESCO Soil Map of the World
"	UNEP/GRID[18]	Global 1° grid	Zobler soil type (based on UNESCO/FAO maps), soil texture, surface slope and other properties
Soil degradation	ISRIC[19]	Global	UNEP World Atlas of Desertification
Global vegetation index	UNEP/GRID[20]	75°N-55°S on 8.6 minute grid/ 1982–1991	NOAA AVHRR Monthly Global Vegetation Index based on satellite data
Natural resources	WRI[21]	National/annual	Energy, raw materials, agriculture, forestry and many others
Human health	WHO[22]	National/annual	Distribution of and mortality from major diseases
Other data			
Elevation/Bathymetry	UNEP/GRID[23]	Global 5 minute grid	Integrated database derived from map information
Boundaries	UNEP/GRID[24]	Global (vector format)	World Databank II: Coastlines, islands, lakes, reefs, ice shelves, glaciers, rivers, canals, railways, administrative boundaries

Notes for Table I:

1) Intergovernmental Panel on Climate Change (Leggett *et al.*, 1992)
2) Wigley and Raper (1992)
3) National Center of Atmospheric Research, Boulder, Colorado, USA (information from R. Jenne and D. Joseph)
4) Climatic Research Unit, University of East Anglia, Norwich, UK (Viner and Hulme, 1994)
5) As 4 (Wigley and Raper, 1992; Warrick *et al.*, 1993)
6) Food and Agriculture Organization of the United Nations (FAO, 1992b; 1993)
7) United Nations (1991; 1992)
8) World Bank (1991)
9) Carbon Dioxide Information and Analysis Center, Oak Ridge, Tennessee, USA (Burtis, 1992)
10) United Nations Environment Programme/Global Resource Information Database (GRID–Geneva, 6, rue de la Gabelle, CH-1227 Carouge, Geneva, Switzerland). Climate data–Leemans and Cramer (1990)
11) As 4 (Jones *et al*, 1986a,b; Hulme, 1994; Hulme *et al.*, 1995b, in press)
12) European Centre for Medium Range Weather Forecasting, Reading, UK/World Climate Research Programme (ECMWF, 1993)
13) As 10 (Olson *et al*, 1985)
14) As 10 (Matthews, 1983; 1985)
15) As 10 (Matthews and Fung, 1987)
16) United Nations Environment Programme (UNEP, 1987)
17) As 10 (FAO/UNESCO, various dates)
18) As 10 (Zobler, 1986)
19) International Soil Reference and Information Center (UNEP, 1992)
20) As 10 (Tarpley, 1991)
21) World Resources Institute (WRI, 1992)
22) World Health Organization (WHO, 1990)
23) As 10 (Haxby *et al*, 1983)
24) As 10 (CIA, 1972)

Table II: Information About Data Sources

Name (and media)	Source	Contents
ACCIS (Hardcopy)	UNEP[1]	Information services and computerized database
HEM (Hardcopy, Disk)	UNEP/GEMS[2]	Data banks; inventory of international research organizations and programmes; directory of environmental monitoring
INFOTERRA (Disk, Hardcopy)	UNEP[3]	Directory of information sources
Master Directory (Network)	NASA[4]	Scientific data information service
CEOS-IDN (Network)	MECCA/NASA/ NASDA/ESA[5]	Directory of remotely sensed data

Notes for Table II:

1) ACCIS (1990)
2) Harmonization of Environmental Monitoring (UNEP/Global Environmental Monitoring System), Fritz (1990); Hicks (1993)
3) International Referral System for Sources of Environmental Information (UNEP, 1987)
4) National Aeronautics and Space Administration (Beier, 1991)
5) Commission on Earth Observing System–International Data Network (NASA/National Aeronautics and Space Development Agency/European Space Agency)