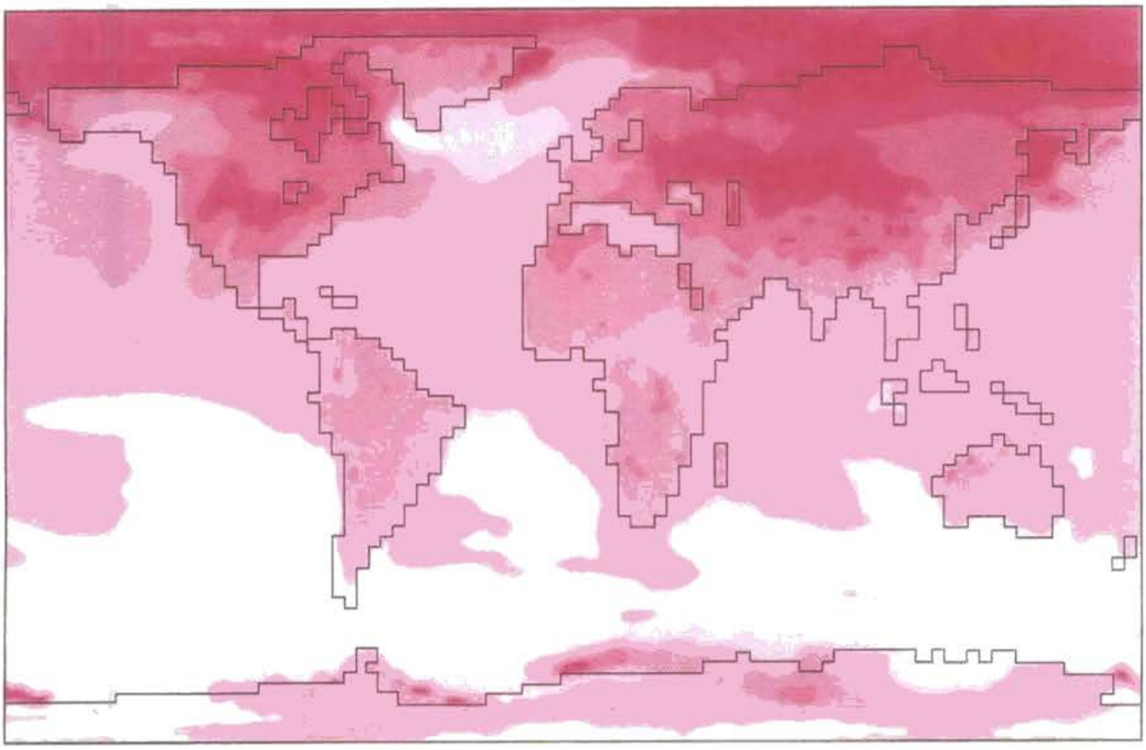
CLIMATE CHANGE

Preliminary Guidelines for Assessing Impacts of Climate Change



INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

WMO World Meteorological Organization/United Nations Environment Programme UNEP

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Preliminary Guidelines for Assessing Impacts of Climate Change

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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. This report is the outcome of the work of the expert group. It is a preliminary report which the IPCC intends to develop and improve. It 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.

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CONTENTS

CONTENTS

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 wavelengths solar radiation from the sun through to the earth's surface, but absorbing the re-radiated radiation (at lower temperatures and higher wavelengths) from the earth. With the exception of CFCs, which are man-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 average temperatures some 33 °C higher than would have been 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:

(a) changes in climate arising from increasing greenhouse gas concentrations in the atmosphere;
(b) the environmental and socio-economic consequences of climate change; and
(c) 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 (1992b). This report is the full version of the guidelines document, including background information on climate impact assessment, reference to further literature, and a number of examples of case studies and methods. While it has undergone peer review, it has not been formally approved by the IPCC.

1.3 General Objectives of Climate Impact Assessment

Climate impact assessment has two mutually-dependent objectives: first, to construct a firm scientific basis for evaluating the interactions of climate, environment and society, and second, to provide the best possible information not only to policy-makers but also to decision-makers and managers in all levels of government and in industry to enable them to predict future environmental impacts and socio-economic consequences and to formulate and implement appropriate responses.

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 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.

1.4 Scope of the Report

This report aims to provide preliminary guidelines on methods of climate impact assessment. It 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 evaluating the social and economic impacts of climatic change is at present limited. This report is therefore a preliminary one. It is desirable that future versions address these topics in more detail. The report does not aim to prescribe a single preferred method, but provides an analytical outline 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.

GENERAL APPROACHES TO CLIMATE IMPACT ASSESSMENT 2

2.1 Purpose of Assessment

There are several different reasons for conducting climate impact assessments. First, there is a need to evaluate how climate affects human activities 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 climatic change. Fourth, it can identify impacts of limitation or adaptation options. Finally, it can alert public awareness to issues of common concern (for example, to educate people about the need for improving the efficiency of resources use) and establish a basis for political decisions.

One of the urgent priorities is to determine how best to include the effects of climate change in the formal processes of environmental impact assessment (EIA). Hitherto, decisions relating to the development of large-scale projects such as the construction of a power station, river diversion or refuge disposal have assumed that climate will not change, a premise that cannot now be relied upon. Although outside the scope of this report, a need clearly exists for some elements reported below to be incorporated within the EIA process (for instance, the development of state-of-the-art regional climatic scenarios). Similarly, many existing EIA procedures (particularly in areas of evaluating costs and benefits, risk and uncertainty) have considerable potential for adoption in the general area of climate impact assessment.

The ultimate objective is to provide the general public and policy-makers with estimates of the extent to which climate change may affect the environment and human activities and result in changes in social and economic welfare. The role of assessments is to assist in the development of alternative strategies for managing human activities under changeable climatic conditions.

2.2 Study Elements

Three general study elements for climate impact assessment are identified by Kates (1985): climate events, exposure units and impacts and consequences.

Climate events can be divided according to scale into three types: between-year weather extremes (such as floods, frost and snowfall), persistent periods or decade-long episodes (such as prolonged drought) and century or multi-century- long climatic trends (such as GHG-induced warming). The distinctions between these classes and the spatial scales they represent are sometimes blurred, but the important thing for the impact analyst is to select an appropriate scale of event, and then to describe its expected variation or change.

Exposure units represent the activity, group, or region exposed to a given climate event (Kates, 1985). These can be chosen on the basis: (a) of the climate event (e.g., within a particular climatic zone affected by the event), (b) of a specific geographical unit (e.g., physiographic characteristics of a river catchment), (c) of the specific type of activity or group affected by the climate (e.g., according to the sector of the economy or section of the population),or (d) of some other criteria (e.g., delimited by administrative unit such as a nation, or by the constraints on available information).

For a given climatic event acting on a given exposure unit there are many types and levels of impacts and consequences that can be studied. These are considered in detail in the following sections.

2.3 Approaches

Climate impact assessments may be conducted according to one of at least 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 layman'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, the approach can be informative. However, the implicit identification of climate as the main determinant of 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, but it is also applied to sectoral

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

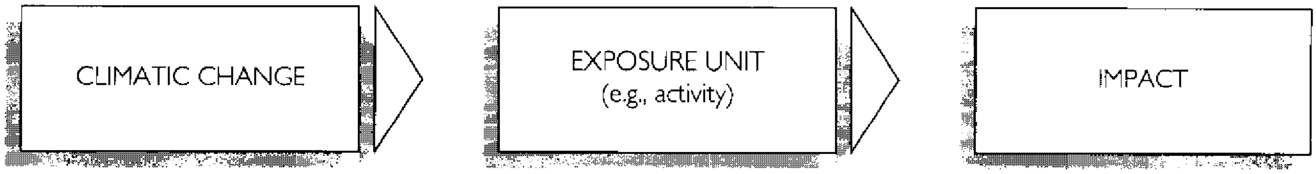
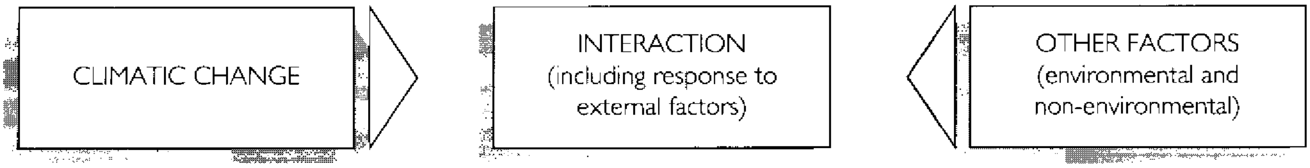


Figure 2. Schema of the interaction approach (after Parry and Carter, 1988)



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).

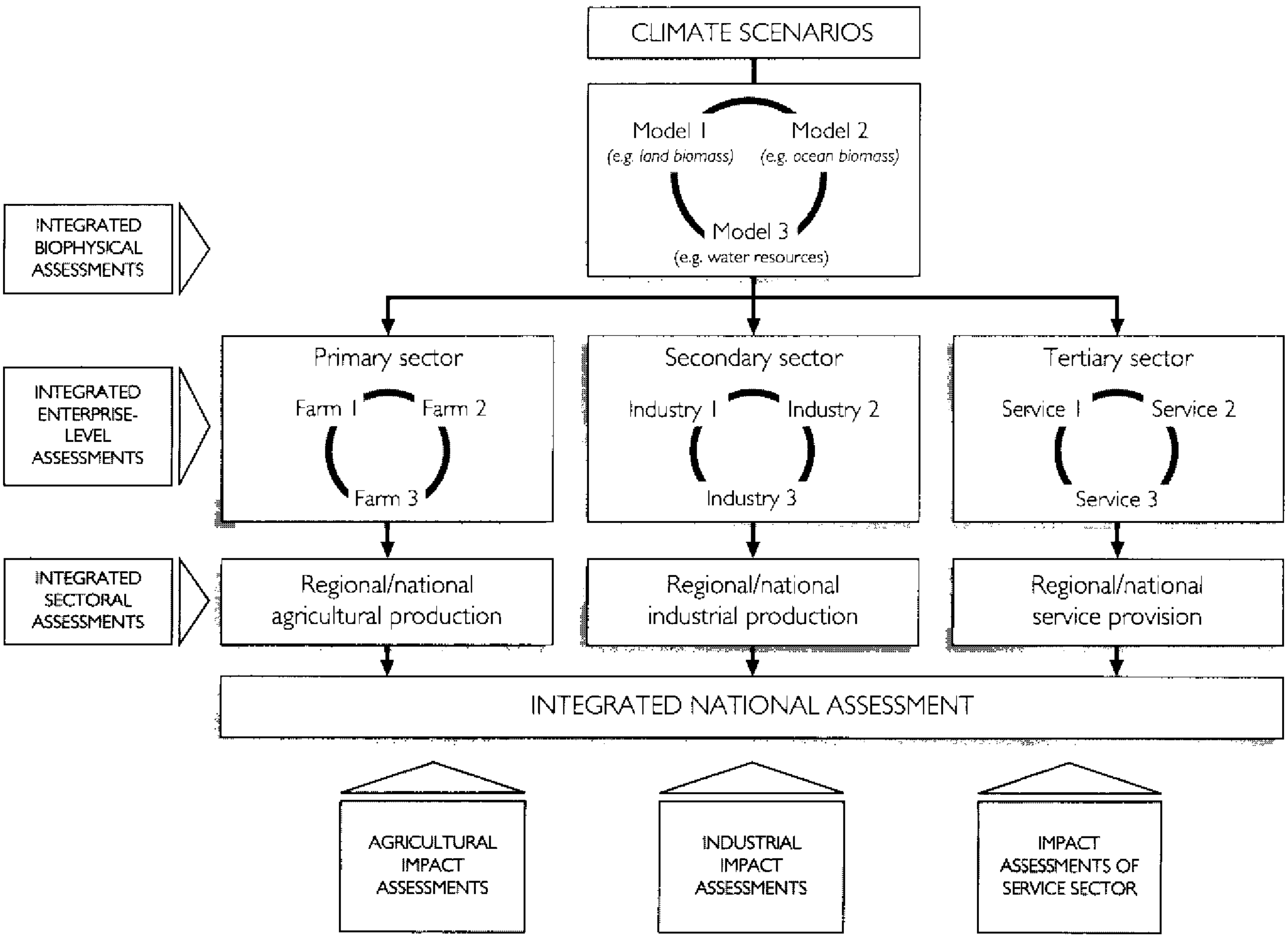
2.3.2 Interaction approach

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,

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



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 climatic event is selected according to the climate-sensitivity of the exposure unit.

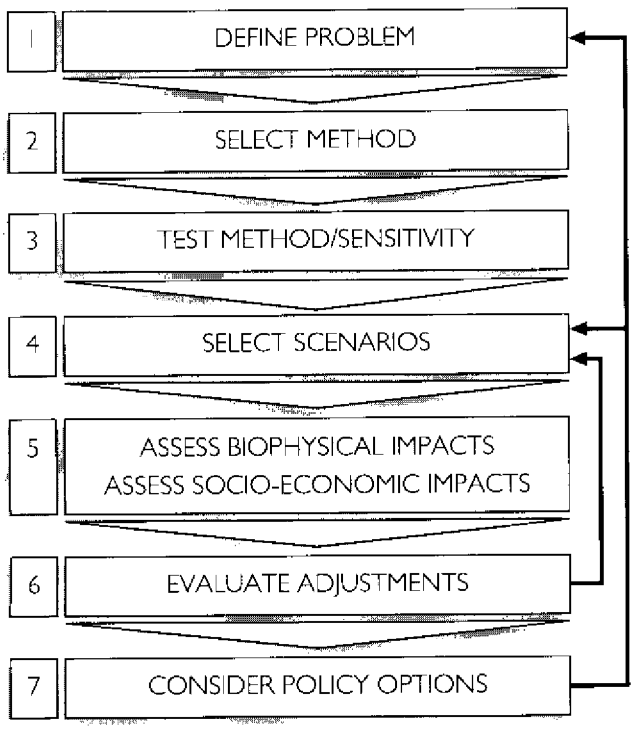
2.3.3 Integrated approach

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 adjustments that may mitigate or exploit the effects of a climatic event (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 was advocated by Chen and Parry (1987), and has been implemented in a number of Integrated Regional Impact Assessments (IRIA) in Canada (Burton and Cohen, 1992) and 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).

METHODS OF ASSESSMENT 3

A general framework for conducting a climate impact assessment is shown in Figure 4. In 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 (single arrows in Figure 4), but the framework also allows for the redefinition and repetition of some steps (double 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



3.1 Definition of the Problem

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 sector(s) of interest, the spatial and temporal scope of the study, the data needs, and the wider context of the work.

3.1.1 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.

3.1.2 Sector to be studied

The sector 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. 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.

3.1.3 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), which may be selected because of their inherent sensitivity to external forcing such as climate change, and 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, 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.

3.1.4 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. Most climate projections rely on general circulation models, and are subject to great 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, weeks into the future. In general, few credible projections of socio-economic factors such as population, economic development and technological change can be made for periods beyond 15—20 years into the future.

3.1.5 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

3.1.6 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

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

3.2 Selection of the Method

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. Four general methods can be identified: experimentation, impact projections, empirical analogue studies and expert judgement.

3.2.1 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). 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 a 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).

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).

3.2.2 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 mobilised policy-makers to demand quantitative 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.

Some of the specific procedures for projecting future impacts are described in Section 3.4. Here, the major classes of predictive models and approaches are described. It is convenient, in categorising impact models, to follow the hierarchical structure of interactions that was introduced in Section 2.3.1. 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.

3.2.2.1 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 simulation models. The use of these in evaluating future impacts is probably best documented for the agricultural sector (e.g., see WMO, 1985) and the hydrological aspects of water resources (e.g., WMO, 1988) 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 criticised for being based on statistical relationships between factors rather than on an understanding of the important causal mechanisms. However, where models are founded on a good knowledge of the determining processes and where there are good grounds for extrapolation, they can still be useful predictive tools in climate impact assessment. Empirical-statistical models are often simple to apply, and less demanding of input data than simulation models (see below).

Simulation models make use of established physical laws and theories to express the dynamics of 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 simulation 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 yield simulation models because the models fail to account for all of the limitations on crops in the field at farm level.

3.2.2.2 *Economic models*

Economic models of several types can be employed to evaluate the implications of first-order impacts for local and regional economies. Although their application in climate impact assessment has been advocated for many years, a disappointingly small number of models have actually been used. Most examples again stem from agriculture, but as with biophysical models, their potential application is general. Three main classes of model are outlined here: microsimulation models, market models and economy-wide models.

Microsimulation models attempt to mimic economic activities at the micro level, considering only a manageable number of interactions between a limited number of key economic agents. Examples of these 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.

Market models attempt to explain how changes that affect all producers or consumers within the defined market may affect market prices and aggregate production, including how such changed processes may influence the behaviour of individuals beyond their original response to a changed climate. The commodity or commodities considered as part of the market must be defined as well as the geographical scope of the market.

Economy-wide models link changes in one sector to changes in the broader economy. The simplest is the input-output approach, which has been adopted in several recent climate impact studies. Input-output 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). For the economy being described, a given level of output from one activity depends on the input requirements for all activities. In the context of climate impact assessment, input-output models can be used to study the effects on the wider economy of changes in production due to climatic events (for example, see Rosenberg and Crosson, 1991).

Within the range of application of an input-output model, it is generally assumed that the relationships of each unit of input to each unit of output are constant. This is a weakness of the approach, since re-organisation 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. 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.

A more ambitious market or economy-wide approach employs macroeconomic models, which attempt to link together different scales and one or more sectors into a regional or global economic analysis. They consider such aspects as regional production, domestic supply and demand for goods and international trade. It is important to distinguish between static and dynamic models. The former are developed on the basis of current patterns of production, trade and policy. This is a drawback for considerations of long-term climatic effects, since this type of model would assume that all other factors remain constant, effectively treating the change as a short-term perturbation. In contrast, a dynamic model attempts to build in more realistic feedback processes in the economic system, simulating, for example, policy adjustments and self-regulating supply, demand and price relationships. Of course, dynamic models, like static models, are only as reliable as the assumptions and understanding upon which they are based.

Some of these models are developed purposefully as large-scale analytical tools, and have been adapted to consider climatic effects. For example, several impact studies have employed regional or global agricultural models (Robinson, 1985; Liverman, 1988; EPA, 1988) and a further study has investigated forest sector impacts (Binkley, 1988). Other models represent hybrids of existing models at different scales, which have been linked together specifically to address questions such as the possible impacts of climatic change (e.g., impacts on the agricultural economy in Canada—Williams *et al.*, 1988; Brklacich and Smit, 1992).

3.2.2.3 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. One important requirement of such models is an ability to simulate system feedbacks, either as regulatory mechanisms internal to the model (e.g., energy consumption leads to GHG emissions that contribute to climate warming, but the warming affects energy demand thus feeding back to consumption), or as external adjustments (e.g., a global protocol limiting GHG-emissions and thus reducing climate warming and its likely impacts).

The main value of this type of model is as a policy tool, to enable decision-makers to evaluate the broad scale implications of climatic change across a range of activities. However, aside from the problems of the complexity, demanding data requirements and testing of such models, a major concern remains about their ability to represent the uncertainties propagating through each level of the modelled system.

No fully integrated systems model has yet been developed, but a partially integrated approach has been pursued in a few recent studies (e.g., Department of the Environment, 1991; Rosenberg and Crosson, 1991; CRU/ERL, 1992). All of these involved the linking of individual models. A potentially powerful method of assessing the direct and indirect effects and benefits and costs of potential climate change employs a general equilibrium modelling approach to environmental and economic interactions. Research to develop such models should be a priority.

3.2.3 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. Three types of analogy can be identified: historical analogies, regional analogies of present climate and regional analogies of future climate.

Historical 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.

Regional analogies of present climate refer to regions having a similar present-day climate to the study region, where the impacts of climate on society are judged also 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.

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., day length, topography, level of development and economic system). Where these conditions cannot be met (e.g., day length 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, see Arnell *et al.* (1990). One method of circumventing these problems is to consider altitudinal differences in the same region. This method is currently being used to investigate tree establishment and growth under the varying climatic conditions at different altitudes in Fenno-Scandinavia (Koski, personal communication, 1991).

3.2.4 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. This method is widely adopted by government departments for producing position papers on issues requiring policy responses. Because 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 formalised 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.

3.3 Testing the Method

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. Three types of analysis may be useful in evaluating the methods: feasibility studies, data acquisition and compilation, and model testing.

3.3.1 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.

3.3.2 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, targetted 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).

Objective survey utilises 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).

Targetted 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.

3.3.3 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—sensitivity analysis and validation—and these should generally precede more formal impact assessment.

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 are 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.
- 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 model application (including its transferability from one climatic region to another, and the range of climatic inputs that can be accommodated).

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 would ideally 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 simulation 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.

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. Simulation models ought, in theory, to be widely applicable (see Section 3.2.2.1), and anyway should be tested in a range of environments. There are fewer grounds, however, for extrapolating the relationships in empirical-statistical models outside the range of conditions 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 3.2.3).

3.4 Selecting 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. It is important to recognize that the environment, society, and economy are not static. Environmental, societal, and economic change will continue, even in the absence of climate change. In order to estimate accurately 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, it is necessary 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. These baseline conditions may then be compared, after impact projections, with environmental and socio-economic conditions under climate change. Thus development of baselines accurately representing current and projected conditions in the absence of climate change is a key and fundamental step in assessment.

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 climatic change is required.

3.4.1 Establishing the present situation

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

3.4.1.1 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., a severe drought or an extremely cool season). 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 adequate local climatological data are available, in terms both of the number of different variables represented and of the geographical coverage of source stations.
- Employing data of sufficient quality for use in evaluating impacts.

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—see IPCC, 1990a). On the other hand, most general circulation models providing regional estimates of climate are initialised using observed climatologies 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 the case. Finally, there is the problem that the more recent periods (particularly during the 1980s), may already include 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 to describe the present climate of the study region, and provide inputs for impact models. In the latter case, several methods are used. Some models produce estimates for periods of a year or less (e.g.,crop growth models). These can generally utilise the original climatological station data for years within the baseline period.

Other models run over long time periods of 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, 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).

3.4.1.2 Environmental baseline

The environmental baseline refers to the present state of other, 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 rise 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.

3.4.1.3 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, fertiliser 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.

3.4.2 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.

3.4.2.1 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 the outer limit on impact projections. GCM estimates seldom extend beyond about 100 years, due to the large uncertainties attached to such long-term projections and to constraints on computational resources. This fixes an outer horizon at about 2100. Many climate projections are for a radiative forcing of the atmosphere equivalent to a doubling of CO_2 relative to pre-industrial levels (see Section 3.4.5.4, below). This could occur as early as 2020 (IPCC, 1990a, 1992a), which could be used as a mid-term projection horizon.

Of course, long time scale projection periods may be wholly unrealistic for considering some impacts (e.g., in many economic assessments). 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.

3.4.2.2 Compatibility of projections

It is important to ensure that future climate, environment and socio-economic projections are mutually consistent over space and time. 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 does not coincide in time with a 2 x CO_2 atmosphere, and there are time lags in the climate response to both of these (see Box 1).

3.4.2.3 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 (a time that is often not easy to define and which usually varies 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

BOX 1

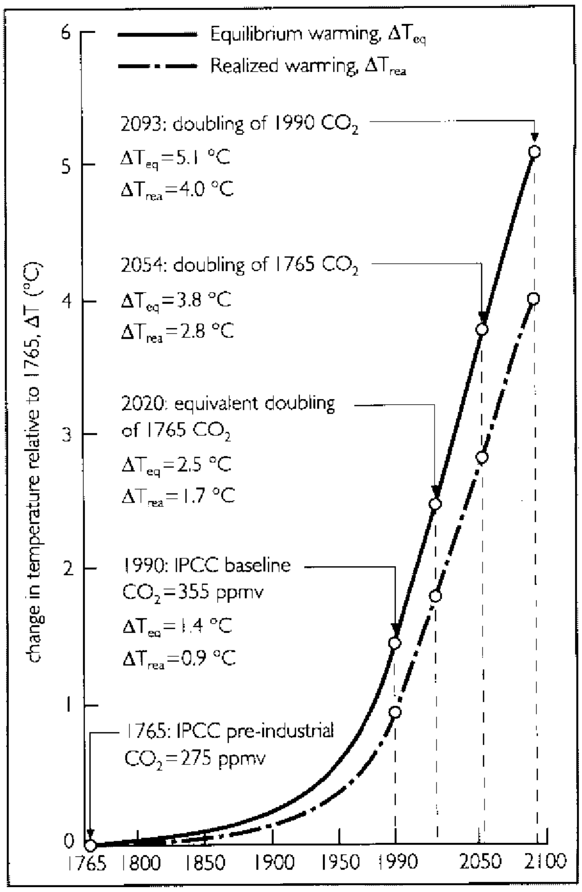
THE RELATIONSHIP OF EQUILIBRIUM AND TRANSIENT WARMING TO INCREASES IN CARBON DIOXIDE AND IN EQUIVALENT CARBON DIOXIDE

The figure below is based on the best estimate of the global mean annual temperature change under a 'Business-as-Usual' emissions scenario produced for the IPCC (IPCC, 1992a). 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 significantly later than the doubling dates for equivalent atmospheric CO_2.

(2) The projected doubling dates occur at different times depending on the selection of a baseline. Climatologists often refer to pre-industrial CO_2 levels (assumed here to represent 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), to provide compatibility with other baseline environmental or socio-economic conditions of importance in impact assessment.

(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.



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.

3.4.3 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, change 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 or simply to extrapolate past trends. Most factors are related to, and projections should be consistent with, trends in socio-economic factors (see Section 3.4.4, below). Greenhouse gas concentrations may also change, but those would usually be linked to climate (which is assumed unchanged here).

3.4.4 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 (e.g., United Nations, 1991), Organization of Economic Cooperation and Development (e.g., OECD, 1990), World Bank (e.g., World Bank, 1990), International Monetary Fund and national governments. 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).

Urbanization has become a serious problem in many developing countries. Urban expansion is often unplanned and can lead to significant vulnerability of the population to climate-related effects such as flooding and landslide. Moreover, urbanization can modify the local climate thus affecting the representativeness of climatological observations, possibly leading to erroneous impact evaluations. Thus, trends in urbanization and data quality should be carefully identified and projected.

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 considering specific technologies that are on the horizon and their probable adoption rates, or by a combination of these. A simple example of socio-economic trend projections is given in Box 2.

3.4.5 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, 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.
- Freely available or easily derivable.
- Suitable as inputs to impact models.

There are four basic types of scenario of future climate: historical instrumentally-based scenarios, palaeoclimatic analogue scenarios, arbitrary adjustments and scenarios from general circulation models.

3.4.5.1 Historical instrumentally-based scenarios

An obvious source of climatological data for scenario development is past instrumental records. These are known to be spatially compatible and mutually consistent because they have actually been observed, and are available for the recent past over a reasonably dense network of land-based stations worldwide. Such scenarios can be developed in different ways:

Historical anomalies focus on weather anomalies 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. They are selected from the instrumental record as individual years or periods of years during which anomalous weather was observed. An extension of this idea is to select 'planning scenarios', 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). Climatic data for all these scenarios are usually taken directly from the chosen periods in the past for use in impact experiments (e.g., Parry and Carter, 1988).

Historical analogues use past periods of global-scale warmth as potential analogues of a GHG-induced warmer world. They are usually developed on the basis of global-scale temperatures during past warm and cold periods, and consist of regional composites of the differences in atmospheric pressure, air temperature and precipitation (for which global historical data are available) between the two periods. The scenarios usually comprise regionally mapped or gridded anomalies of

BOX 2

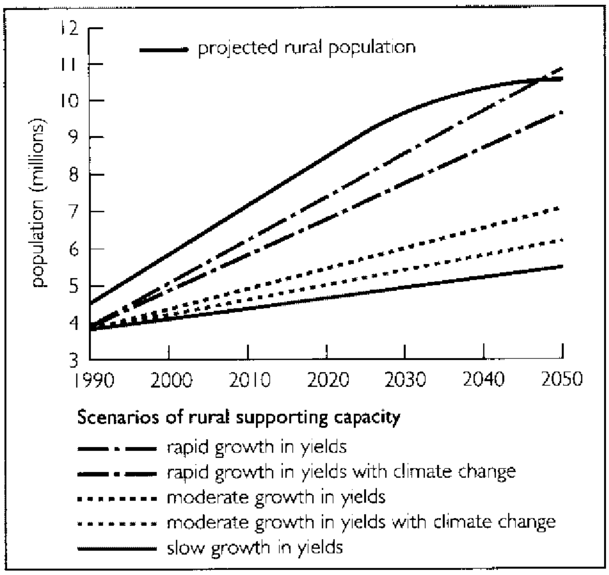
CASE STUDY: EFFECT OF CLIMATE CHANGE ON RURAL POPULATION SUPPORTING CAPACITY IN SENEGAL

Background. Senegal has experienced a long-term decline in per capita food production in recent years, in common with many other sub-Saharan countries. The annual population growth rate is 2.7 percent, and although about 70 percent of the labour force is engaged in agriculture, the agricultural sector has failed to supply this increased demand, due to poor policies, meagre natural resources, drought, high energy prices and declining trade.

Purpose. The study sought to assess the potential impact of climate change on the balance of rural population and national rainfed agricultural potential in Senegal.

Methods. A model of potential agricultural resources was used to evaluate the rainfed production of cereal grains in terms of caloric value, and compared this to the recommended daily consumption requirement. Rainfed cereal grains comprise about 80% of the total calorific consumption. Other sources were ignored in the assessment. Estimates were made assuming different projections of agricultural development with and without climate change.

Scenarios. A climatic scenario of a 4 °C increase in temperature and a 20% decline in precipitation was assumed for the year 2050. Population increases were projected by district, based on past census information and assuming a levelling-off by the year 2050. Scenarios of slow, moderate and rapid growth in yields were employed. Other scenarios of expanded agricultural area, altered crop mix and combined development were used but are not reported here.



Source: Downing (1992)

Impacts. For the case of no climate change, the rapid yield growth scenario would match the projected growth of the rural population (Figure). The effect of this climate change scenario would be to depress yields by about 30%. This could decrease population supporting capacity by one million people. Under the moderate yield growth scenario, three-quarters of the districts would be food deficit regions in 2050. This has serious implications for migration and economic development.

Note: The scenario of climate change is a 30% reduction in yields in the year 2050, corresponding to an extreme scenario of climate change such as the UKMO scenario.

climatic variables. They are interpolated to the study area, and then added to the baseline values in the study area for use in impact experiments (e.g., Lough *et al.*, 1983).

Historical correlations, which represent a variation of the analogue approach, involving the estimation of linear relationships between the historical record of global surface air temperatures and records over the same period of local climatic variables. For a given variation in global temperature, it is then possible to estimate from these relationships expected variations in local climate. The technique utilises the whole of the instrumental record, in contrast to the warm-world analogue approach, which employs composite data only for sub-periods in the record and may overlook any longer-term relationships between climatic variables that this technique would detect. Here, the scenario climate in a study region is defined according to a specified future change in global climate, either simulated or based on expert knowledge (e.g., Vinnikov and Groisman, 1979).

Circulation pattern scenarios are designed for cases where input data for impact models cannot be provided by conventional scenarios (e.g., wind fields for air pollution studies). The approach also utilises linear relationships, this time between past global mean temperatures and regional atmospheric circulation patterns. Individual seasons are then identified in the historical record having circulation types resembling those found to be correlated with global warmth. Detailed data from those seasons are then used directly in impact experiments (e.g., Pitovranov, 1988).

There are a number of difficulties associated with the use of instrumental scenarios:

- They are based on temperature changes during the past century that are much smaller than those expected in the future. Thus, it is doubtful whether they can be applied to conditions outside the range of past variations. Moreover, the rate of future change is projected to be considerably greater than in the past.
- The causes of past variations in global temperature may have been different from those responsible for a future GHG-induced change in temperature.
- The strength of the relationships between past changes in temperature and changes in other climatic variables is usually rather weak.
- The nature of the relationships between variables may be different in the future than those occurring in the past, and it is known that relationships established for the past themselves vary, depending on the time period selected.

3.4.5.2 Palaeoclimatic analogue scenarios

Palaeoclimatic scenarios are based on reconstructions of past climate from fossil evidence. Features of the past temperature and moisture regime in a region (usually at a seasonal time resolution) can often be inferred by assembling the different types of evidence. If absolute dating methods are available, and the spatial coverage of evidence is sufficient, maps can be constructed for particular time periods in the past.

In the context of future climatic warming, palaeoclimatic scenarios for warm periods in the past have been adopted in several climate impact assessment studies as analogues of possible future climate. They have been used extensively in the former USSR, where three periods have been selected to represent progressively warmer conditions in the northern hemisphere (Budyko, 1989; IPCC, 1990a): the Mid-Holocene (5–6000 years Before Present), when northern hemisphere temperatures are estimated to have been about 1 °C warmer than today, the Last (Eemian) Interglacial (125,000 BP) with temperatures about 2 °C warmer than today, and the Pliocene (3-4 million BP) when temperatures were about 3-4 °C warmer than today.

An additional use of these scenarios (and others for past glacial periods) is for the validation of general circulation models (see below). There are various theories about the possible physical mechanisms producing glacial/interglacial epochs, and these can be tested in model simulations, model outputs then being compared with the reconstructed palaeoclimate (e.g., see Kutzbach and Guetter, 1986).

If the evidence upon which they are based is of good quality, palaeoclimatic scenarios can provide a reasonable representation of past climate, which is consistent in space and time. Moreover, they have an advantage over instrumental scenarios in that the level of global warmth is much greater than that experienced in the past century, and more closely analogous to the magnitude of warming expected during the next century.

Palaeoclimatic scenarios usually comprise mapped estimates of seasonal climate. Scenario values for the study region are either read from the map and used directly in impact experiments, or compared with seasonally averaged baseline values and the differences used for adjusting higher resolution baseline values.

There are some serious reservations, however, in using these reconstructions as scenarios of future climate:

- The boundary conditions of the climate system (e.g., sea level, ice volume, land cover) were not the same in the past as they are today. Thus, even if the radiative forcing were the same, the climate response might differ in the future from that in the past.
- It is probable that some periods of past warmth resulted from different forcing factors than greenhouse gas forcing (e.g., orbital variations).
- There are large uncertainties about the quality of the palaeo-climatic reconstructions. None are geographically comprehensive, some may be biased in favour of climatic conditions that preserved the evidence upon which they are based, and the dating of material (especially in the more distant past) may not be precise.
- They represent the average (often only seasonal) conditions prevailing in the past. It is rare for them to yield concrete information on the variability of climate or frequency of extreme events.

3.4.5.3 Arbitrary adjustments

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.

These types of adjustments are of use for testing the robustness of impact models, and for studying sensitivity to climatic variations (see Section 3.3.3). This is also the preferred method of altering climate and/or atmospheric composition when conducting climatic change experiments in the field or laboratory. Furthermore, the approach can be useful for expressing expert estimates of future climate, in the absence of more detailed projections.

Perhaps the most valuable function of arbitrary adjustments, however, is as a diagnostic tool to be used prior to conducting scenario studies. 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), or responses which have a critical impact on the system (e.g., wind speeds 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.

One of the main drawbacks of the approach is that adjustments to combinations of variables may not be physically plausible or consistent. Thus, this approach should normally only be used for sensitivity analysis.

3.4.5.4 Scenarios from general circulation models

General circulation models (GCMs) are the most sophisticated tools currently available for estimating the likely future effects of increasing GHG concentrations on climate. They simulate the major mechanisms affecting the global climate system according to the laws of physics, producing 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).

GCMs are not yet sufficiently realistic to provide reliable predictions of climatic change at the regional level, and even at the global level model estimates are subject to considerable uncertainties. Indeed, GCMs are 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. Clearly, such a step change in atmospheric composition is unrealistic, as increases in GHG concentrations (including CO_2) are occurring continually, and are unlikely to stabilise 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. This also results in difficulties in estimating the simultaneous effects of increasing CO_2 and climate change.

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 available from GCMs for constructing scenarios (see, for example, McKenney and Rosenberg, 1991):

- 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 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, wind speed and vapour pressure 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.

The following procedures should be considered when constructing GCM-based scenarios (and see Box 3 on page 16):

Equilibrium changes. To construct a scenario of the equilibrium climate response, it is necessary to compute the change in climate between the modelled control and 2 x CO_2 conditions for each grid box. There are two methods of achieving this: 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 and most other 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 = 273.15 K).

Scaling to the baseline. Since the GCM outputs are not 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 the baseline data (see Section 3.4.1.1 above) 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. The major weakness of this technique is the assumption that the change in climate between control and 2 x CO_2 model simulations can be applied to the observed baseline climate.

Transient changes. The procedure for constructing transient scenarios is slightly different, as it is difficult to apply the annual transient model outputs as adjustments to the baseline climate, which itself consists of observed annual values. One method is to eliminate the inter-annual variability in the transient-run outputs by smoothing the monthly mean data using a running average. Differences or ratios can then be computed between these values and the average control-run values for each grid box. These are then used to adjust the baseline values on a year-by-year basis, with the baseline repeating if the experiment extends for longer than the baseline period. The underlying assumption of this method is that inter-annual variability under the future climate is unchanged from that of the baseline condition. To avoid this, a long-term average baseline climate could be used, and the annual adjustments applied directly from the transient-run outputs.

Missing variables. In the absence of information on changes in certain climatic variables that are 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 statistical relationships to adjust missing variables according to changes in predicted variables (for example, see Box 4 on page 17).

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 may also be 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 hourly 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 (see also Section 3.4.1.1 and Wilks, 1992).

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 kilometres. 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.*, 1988b; 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

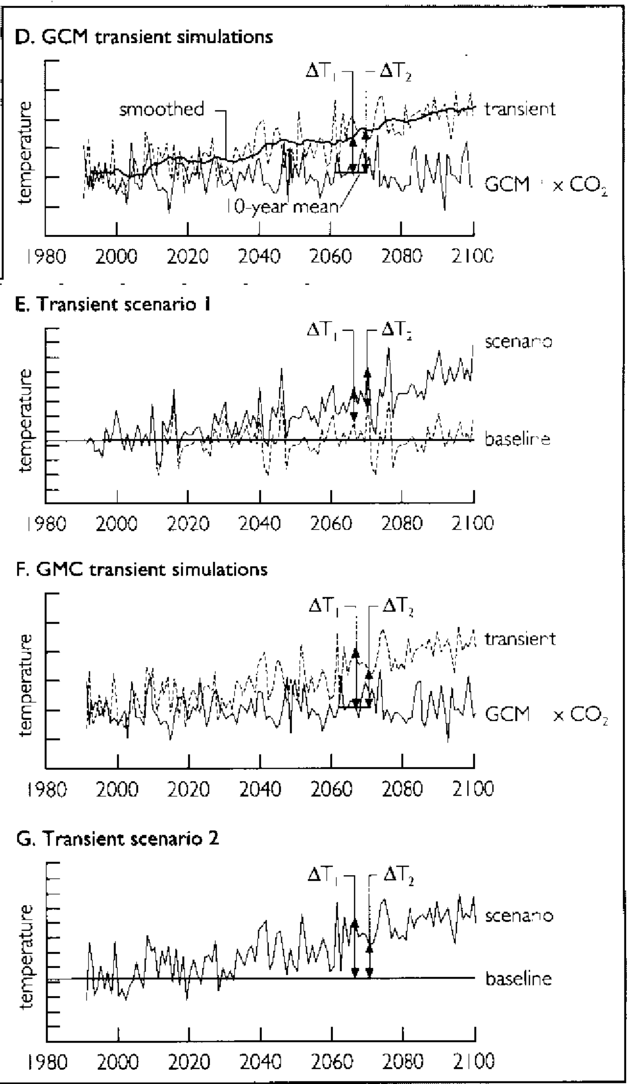
BOX 3
SCENARIOS FROM EQUILIBRIUM AND TRANSIENT GCM OUTPUTS

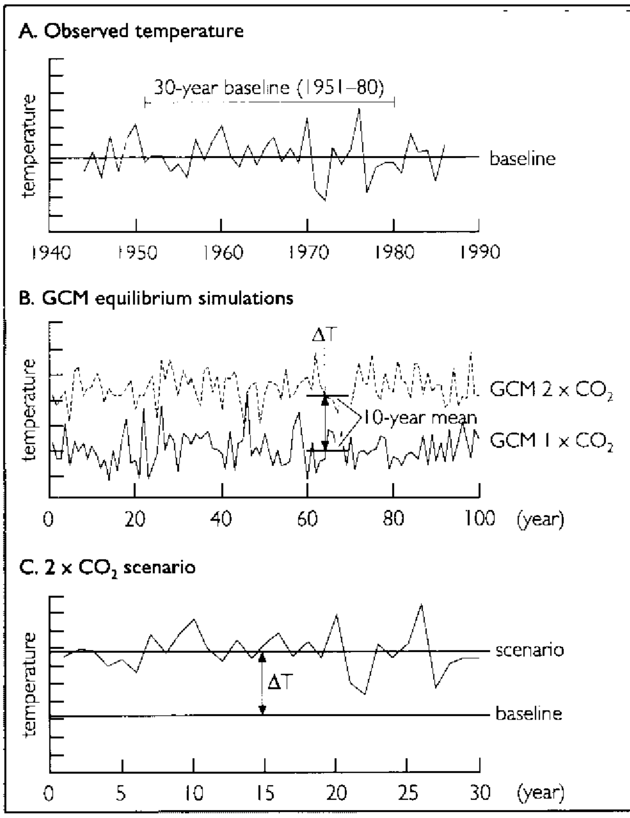
To illustrate how GCM outputs are commonly used to develop climatic scenarios, let us assume that the climatic variable of interest is June surface air temperature at a site, S. A long time series of mean June temperatures is available from a meteorological station at the site (Figure A). GCM estimates of monthly mean temperature for a model grid point adjacent to or interpolated to site S have been obtained for both equilibrium 2 x CO_2 and transient simulations, each accompanied by estimates for a control simulation assuming present-day atmospheric greenhouse gas (GHG) concentrations (Figures B, D and F).

The climatological baseline is selected as the most recent standard 30-year averaging period for which observations are available (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 CO_2 simulations are shown in Figure B as annual values. Climate modellers usually provide model results only for a period during which the global mean anual 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 CO_2 atmosphere to equilibriate. The difference between the mean equilibrium control and mean equilibrium 2 x CO_2 temperature is then computed, and this is applied as an adjustment to each annual baseline value (Figure C).

The procedures for constructing transient scenarios are slightly different, as time dependent values are required for the whole projection period. It is difficult to apply the annual transient model outputs as adjustments to the baseline climate, which itself consisits of annual values, so one of two methods is usually chosen. The first eliminates the inter-annual variability in the transient run outputs by smoothing the monthly mean data (e.g., using a running average) and computing the annual differences between smoothed monthly mean data and the control mean (Figure D). These are then used to adjust the baseline values on a year-by-year basis, with the baseline repeating if the experiment extends for longer than the baseline period (Figure E). The underlying assumption of this method is that inter-annual variability under the future climate is unchanged from that of the baseline condition. Moreover, any short-term trends or cycles in the baseline data will be superimposed on the scenario projection. To avoid this, an alternative is to use the difference between the annual transient and the control mean values (Figure F) and apply these as adjustments to the baseline mean (Figure G).





in (1), but introduces a false precision to the estimates.

(3) 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 weakness here is that the method assumes that sub-grid-scale spatial variability will not change under the future climate.

(4) The baseline and anomaly fields from several scenarios (e.g., GCMs, historical) are interpolated and/or combined into one scenario using dynamical/empirical reasoning (e.g., Pearman, 1988) or averaging (e.g., Department of the Environment, 1991). By definition, however, 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.

In addition, there have also been recent experiments with regional 'fine mesh' climate models, which use inputs from GCMs and are then run at a higher spatial resolution (e.g., Giorgi, 1990).

There have been objections to the concept of using GCMs for developing climate change scenarios for regional impact studies, due to uncertainties that prevent accurate regional-scale simulations. However, scenario projections are often beyond the design criteria of various facilities or resource systems and it seems prudent to begin to test the sensitivities of these systems under various scenarios directly or indirectly based on GCM outputs, to provide an indication of uncertainty in regional terms (Cohen, 1990).

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. It is strongly recommended that recent reviews of GCMs be consulted before selection (e.g., IPCC, 1990a; 1992a; Boer *et al.*, 1991). The National Center of Atmospheric Research, Boulder, Colorado, USA, has been acting as a clearing house for GCM data from different modelling groups.

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). 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).

3.4.6 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 cli-

BOX 4
CASE STUDY: THE IMPACT OF CLIMATE CHANGE ON DRAINAGE BASIN HYDROLOGY IN BELGIUM

Purpose. To assess the effect of climate change on the water cycle and on the water balance of three drainage basins in Belgium.

Methods. Information obtained from general circulation model estimates of climate under doubled CO_2 were used to evaluate a climatic scenario that could be used as an input to a detailed hydrological model. Changes in variables such as precipitation and air temperature were taken directly from GCM outputs, whilst surface energy-balance components were evaluated from empirical equations. The hydrological model was used in each of the three river basins to estimate the effects of climate change on potential and effective evapotranspiration, soil moisture, snow accumulation, groundwater storage, flow components at the outlet and the complete water budget.

Testing of methods/sensitivity. The model was developed and calibrated for medium-sized drainage basins, operating on a daily time step. It was tested over an 84-year period in each of the three basins. It was considered legitimate to apply the model to the scenario climate, since the changes implied in the scenario were well within the range of interannual variability, although extreme events were accentuated in some months.

Scenario. The climatic scenario was based on published information from various sources on modelled changes in the Belgium region under doubled CO_2 conditions. The baseline period 1901–1984 was used. Construction of the climatic scenario, as well as being an input to the hydrological model, also formed part of the investigations in this assessment, as surface energy balance components were not directly available from GCMs and had to be derived. The physiological effects of CO_2 on water exchange through vegetation were not considered in the study.

Impacts. The following general results were obtained: (1) increased potential and effective evapotranspiration throughout the year (implying potentially increased biomass and agricultural production); (2) increased frequency of drought in soils (leading to occasional reductions in plant productivity); (3) a shortening of spells with snow cover; (4) in catchments with high infiltration rates, an increase in groundwater storage and in annual baseflow; (5) in catchments with mainly surface flow, an increase in flood frequencies in winter (implying the need for altered design of hydrologic engineering structures), a decrease of streamflow during the summer (leading to increased pollution risks) and a possible limitation on water supply from local groundwater storage in summer and autumn.

Source. Bultot *et al.* (1988a, b)

mate change. These projections are made using the climate projections and the biophysical models selected for the study (as described in Section 3.2.2.1). 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 3.4.3. 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, *inter alia*, on radiative forcing of the climate, on depletion of stratospheric ozone (e.g., CFCs) and 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 3.4.2.2, above).

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. However, local conditions such as coastal land subsidence should also be taken into account in considering 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). However, some inland locations may be also be affected (for example, through saline incursion of groundwater). The magnitude of future sea level rise is still under discussion, but the estimates reported by the IPCC may serve as a useful basis for constructing scenarios (IPCC, 1990a). Again, these should be consistent with projected changes in climate, and it should be noted that they are projected to vary regionally as well as temporally.

Other factors that are directly affected by climate include river flow, run-off, 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 3.2.2.3).

3.4.7 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 3.4.4). In other cases, projections can be adjusted to accommodate possible effects of climate (e.g., future winter electricity demand may be reduced relative to trend due to climate warming).

Finally, many human responses to climate change are predictable enough to be factored in to future projections. These are often accounted for in model simulations as feedbacks or 'automatic adjustments' to climate change. 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), so it would be altered automatically to suit the conditions. Here, the model is performing internally an adjustment that a farmer might do instinctively.

3.5 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. The impacts provide the basis for the assessment.

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.

3.5.1 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. 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).

3.5.2 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, long-term changes in the average timing of phenological stages in hardy, well-adapted natural plant species might suggest a general warming of the climate. Moreover, 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, and the vulnerable populations located in such regions.

3.5.3 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.

3.5.4 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 5). 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 climatic 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. In addition, such an approach can examine the 'waiting cost' of doing nothing to mitigate future climate change, and the 'unexpected cost' of surprise events.

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. 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 and on social provision. Moreover, the depreciation of capital assets with time, which also varies from country to country, should be explicitly considered in the calculations.

One of the issues in formal cost-benefit analysis is whether, and how, to assign a single metric for all costs and benefits. For example, climatic warming may offer tangible benefits through reducing winter heating bills. However, it may also lead to the disappearance of a rare species adapted to a cooler climate, the cost of which is difficult to assess. These types of consideration have led to the emergence of a new discipline, environmental economics. This seeks to assign quantitative worth to environmental resources that traditionally have been regarded as 'global commons', such as air, water and soil, so that they can be balanced against other more tangible, quantitative measures of worth (e.g., see Barbier and Pearce, 1990).

There are also social costs and benefits that are difficult to assess in economic terms. Alternative quantitative measures do exist for some of these (e.g., for quality of life or social equity), but others have to be considered in purely descriptive terms (for example, aesthetic preferences, psychological effects).

3.5.5 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 climatic 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:

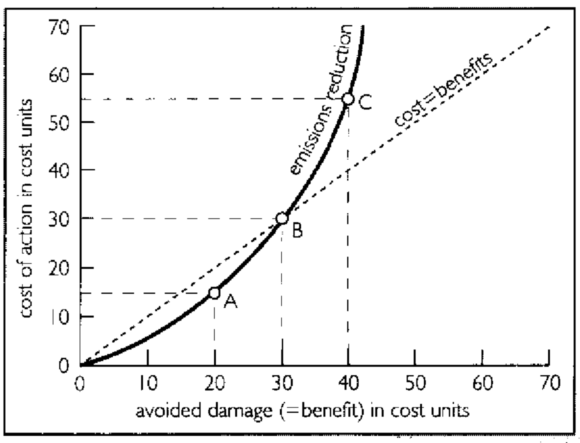
- Depicting patterns of climate (past, present or projected).
- Using simple indices to evaluate the present-day regional potential for different activities based on climate and other

BOX 5
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 reducing greenhouse gas emissions, a cost-benefit analysis might seek to evaluate a question facing a decision maker: 'Do the benefits of reducing emissions by 20 percent outweigh the costs of doing so?' The benefits of this action are the avoided damages (i.e., costs) of climate change due to GHG emissions (evaluated, for instance, using models of the type described in Section 3.2.2). Hence, if it is estimated that the costs of climate change were 100 units and a 30 percent reduction in emissions would limit climate change enough so that 20 percent of the costs (damages) are avoided, then the benefit of reducing emissions would be 20 units. If the cost of this 30 percent emissions reduction was estimated to be 15 units then it would be concluded that the cost-benefit ratio of the action was favourable because the benefits (20 units) were greater than the costs (15 units) (Point A in Figure).

Economic analysis generally concludes that the optimal result is where the marginal cost and marginal benefit of the change are equal. In the example, this occurs at 30 cost units, where the cost of reducing a further kilogram of emissions is just equal to the avoided damage due to that extra kilogram (Point B in Figure). Further emissions reduction beyond this point produces an unfavourable cost-benefit ratio (e.g., an emissions reduction of 45 percent costing 55 units has a benefit in avoided damage of only 40 units—Point C in Figure).

Note, in addition, that it may not be physically possible to remove the full costs of climate change, as no emission policies are capable of fully stabilising GHG-concentrations. Thus, only a proportion of the estimated costs due to climate change can be avoided, serving as a limiting condition in the cost-benefit evaluation. Of course, there may also be benefits of climate change or non-climatic benefits of actions that limit climate change. These become costs in a cost-benefit analysis, because they are benefits that will be diminished or lost if climate change is reduced.



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 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 6. 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 data at a high time resolution, may offer partial solutions.

3.5.6 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: scenario analysis and risk analysis.

3.5.6.1 Scenario analysis

Scenario analysis comprises a set of techniques for anticipating and preparing for the impacts of uncertain future events. It is

BOX 6

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

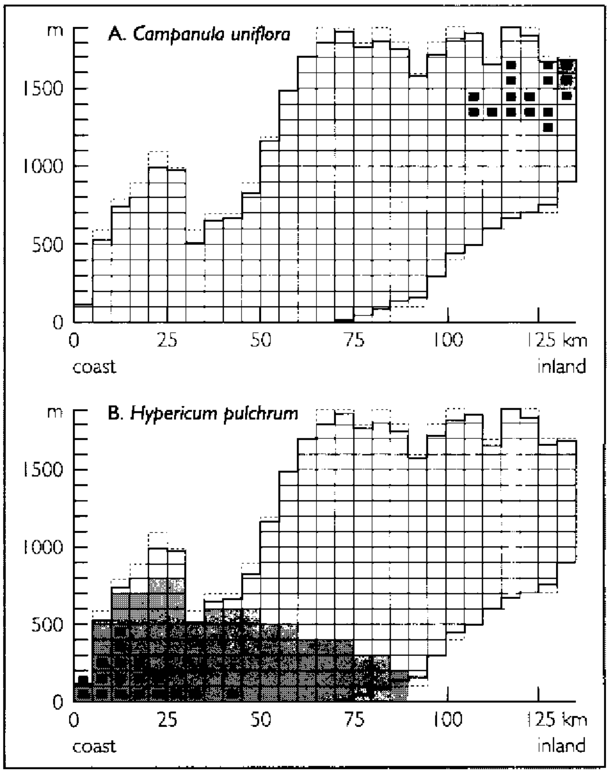
Problem. The objectives of this assessment were to examine the probable patterns of ecological change in Norway under a changed climate regime, with a particular emphasis on identifying plant species and communities sensitive to or at risk from climate change.

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 a 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 vertical transect through central Norway, giving altitude on the vertical axis and distance from the Atlantic coast on the horizontal axis. Figures A and B illustrate the sensitivity of two species: *Campanula uniflora* (a rare



Source: Holten and Carey (1992)

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.

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 (see, for example, Brklacich and Smit, 1992). These are often used as upper, lower and best estimates of an outcome.

3.5.6.2 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 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.

3.6 Evaluation of Adjustments

Impact experiments are usually conducted to evaluate the effects of climate change on an exposure unit in the absence of any adjustments which might prevent, mitigate or exploit them, and are not already automatic or built-in to future projections. It is these adjustments which form the basis of measures to cope with climate change. Two types are described here: feedbacks to climate, and tested adjustments at the enterprise level. A third type, policy responses, is considered in Section 3.7.

3.6.1 Feedbacks to climate

The global climate system is influenced, in part, by interactions with the surface biosphere. To date, projections of future climate have assumed that the biosphere remains unchanged, but this is clearly unrealistic. As climate changes, so the pattern of vegetation and of other important organisms such as oceanic plankton, which feedback to climate, are likely to shift geographically. Impact models can identify these possible shifts, but they have not yet been linked effectively to climate models for simulating feedbacks to climate.

3.6.2 Tested adjustments at the enterprise level

Tested adjustments are experiments that can be conducted with impact models to evaluate alternative options for adjusting to climate change at the level of individual enterprises. To illustrate, a climatic scenario may indicate that the water requirements of a crop are no longer satisfied under a changed rainfall regime. In this case an adjustment that could be tested using a crop growth model might be the substitution of a less demanding, short-season crop variety. Here, the adjustment is chosen by expert judgement, but evaluated using a model (for a similar example, see Box 7 on page 22).

It is important to recognise that any evaluation of potential adjustments necessarily makes assumptions about the way in which groups or individuals will respond when confronted with climate change. There is a whole area of research which examines the actual processes of adaptive response to changes in climate. This includes behavioural studies of actions taken during and after certain climatic events, as well as studies to identify thresholds of tolerance or constraints on adaptation to climate change and its effects (e.g., see Whyte, 1985; Smit, 1991).

When analysing potential adjustments, it is useful to distinguish between two types: anticipatory and reactive. Anticipatory adjustments are put into place in prospect of impacts occurring (e.g., the breeding of drought resistant crop varieties). Reactive adjustments are implemented after impacts have occurred (e.g., the adoption of drought resistant varieties). In many cases, adjustment experiments can assist in evaluating different options so that anticipatory, rather than reactive adjustments can be put in place.

Of course, not all adjustments can be tested. For some, an accurate evaluation may not be possible, and for others the required technology may not yet be available.

3.7 Consideration of Policy Options

Another method of responding to climatic change is through policy decisions. Aside from purely qualitative assessments, two methods of policy evaluation can be identified: policy simulation and policy exercises.

3.7.1 Policy simulation

In some assessments it is possible to simulate the effectiveness of alternative policy adjustments using impact models. Two types of policy response to climatic change are commonly simulated: mitigative and adaptive.

Mitigation policies refer to actions that attempt to prevent or to reduce changes in climate by altering the emission rates of greenhouse gases. These effects can be estimated and the costs evaluated using a range of models. Impact assessments can assist in identifying targets for mitigation policy with respect to minimising the effects of climate change (see Section 3.4.5.3). For instance, a target emissions policy might be set that limited the likely rate of change in climate resulting from increased GHG concentrations to one that natural ecosystems would be able to accommodate and adapt to, through migration or acclimation.

Adaptive policies recognize that climate changes will occur and that it is necessary to accommodate these changes in policy. For instance, the lifting of government subsidies on some food crops might be one policy method of offsetting overproduction due to a more favourable climate. Such a policy would rely on economic factors (i.e., reduced incentive) to bring about farm-level adjustments such as a switch to alternative crops giving a higher return.

3.7.2 Policy exercises

A second 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 gov-

BOX 7
CASE STUDY: POTENTIAL IMPACTS OF CLIMATE CHANGE ON AGRICULTURE IN SASKATCHEWAN, CANADA

Background. The province of Saskatchewan in Canada has about 40% of Canada's farmland and it accounts for about 60% 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 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% 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)

ernment, 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, 1988). The method has been tested in a number of recent climate impact assessments in South-East Asia (Parry *et al.*, 1992).

ORGANIZATION OF RESEARCH 4

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 co-ordination of research, and research collaboration.

4.1 Co-ordination

Experience suggests that the executive responsibility for co-ordinating 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 co-ordinator. 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 co-ordinator, involving the planning of the research, identification of stakeholders, selection of common approaches, initiation of studies and monitoring of the research.

4.1.1 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 and a preliminary schedule. 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 co-operation.

4.1.2 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.

4.1.3 Common approaches

The co-ordinator 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.

4.1.4 Initiation of studies

As a preliminary stage of research, some projects carry out pilot studies to explore the feasibility of the methods (Section 3.3.1). 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 co-ordinators to travel to meetings at each centre. This has the advantage of exposing the co-ordinator 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.

4.1.5 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 co-ordinators, as a means of assessing progress to date, and future goals.

4.2 Collaboration

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

4.2.1 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.

4.2.2 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 jeopardising the integrity of the research by excessive participation, whilst researchers should ensure that their work meets the needs of policy as much as possible.

4.2.3 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.

Other national initiatives can build on existing climate programmes. For example, as part of the Government of Canada's Green Plan, three Integrated Regional Impact Assessments have been launched: a) Mackenzie Basin; b) Prairies; and c) Great Lakes-St. Lawrence Basin. In each case, the regional focus is being used to attract researchers and stakeholders into the planning and execution of these studies.

4.2.4 International activities

Internationally, there are different levels of co-operation 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 Scientific Committee on Problems of the Environment (SCOPE), which is also organised by ICSU, and directs particular attention to the needs of developing countries.
- The Man and the Biosphere Programme of the United Nations Educational, Scientific and Cultural Organization (UNESCO).
- The Organization of Economic Cooperation and Development (OECD)

At an international scale, several organizations, institutes and programmes are active in promoting climate impact studies. They include:

- The Commission of the European Communities (CEC)
- The North Atlantic Treaty Organization (NATO)
- The Joint US/Canada Great Lakes Impacts Programme
- The Nordic Environmental Research Programme
- The International Institute for Applied Systems Analysis (IIASA)

COMMUNICATION OF RESULTS 5

An effective impact assessment is usually characterised by the establishment of good communications between researchers and other interest groups. Three lines of communication are important for researchers: with other researchers, with policy-makers and with the public.

5.1 Communication among Researchers

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

5.1.1 Reporting of results

There is a burgeoning literature on the possible effects of future climate, but as yet there has been little attempt to co-ordinate or standardise 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

5.1.2 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.

5.2 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).

5.3 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.

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