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.