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

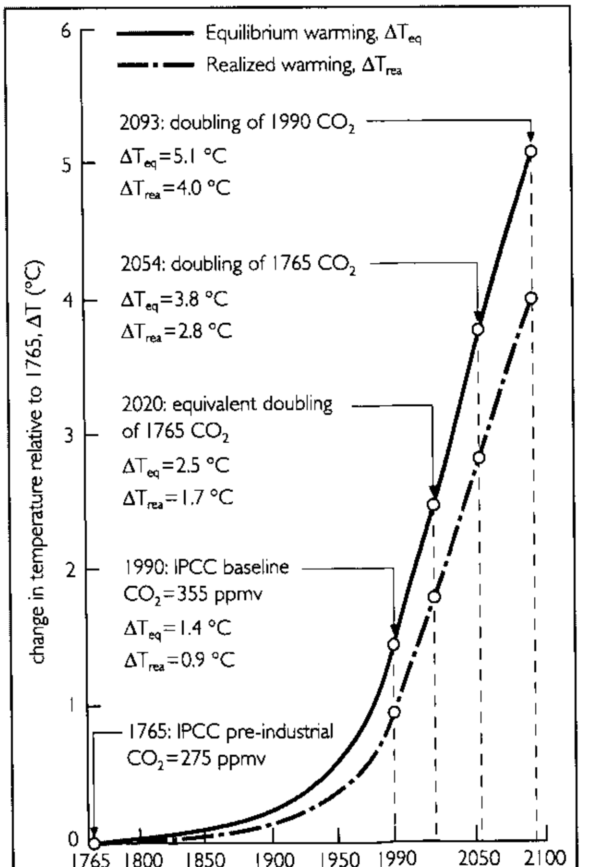
THE RELATIONSHIP OF EQUILIBRIUM AND TRANSIENT WARMING TO INCREASES IN CARBON DIOXIDE AND IN EQUIVALENT CARBON DIOXIDE

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

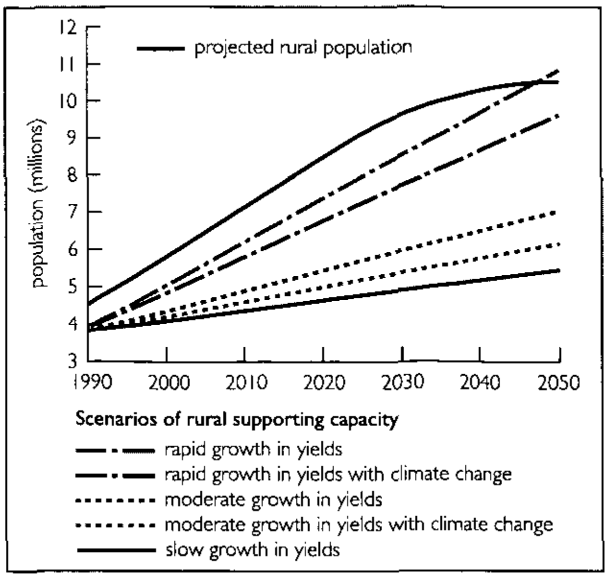
BOX 2
CASE STUDY: EFFECT OF CLIMATE CHANGE ON RURAL POPULATION SUPPORTING CAPACITY IN SENEGAL

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

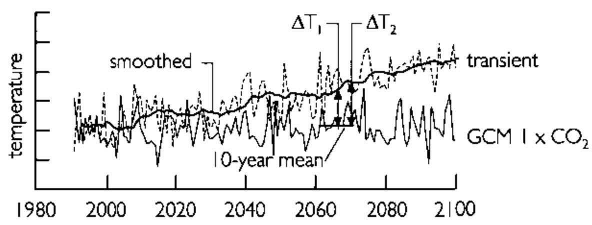
To illustrate how GCM outputs are commonly used to develop climatic scenarios, let us assume that the climatic variable of interest is June surface air temperature at a site, S. A long time series of mean June temperatures is available from a meteorological station at the site (Figure A). GCM estimates 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.

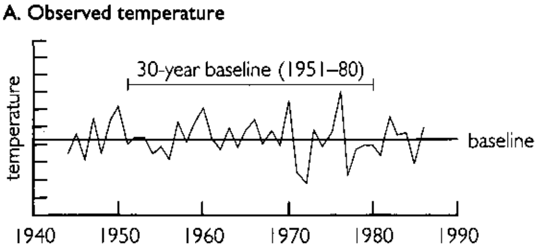
The GCM estimates for the control and equilibrium 2 x CO_2 simulations are shown in Figure B as annual values. Climate modellers usually provide model results only for a period during which the global mean anual temperature approximates equilibrium (often a 10-year period). A similar period is also selected 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).

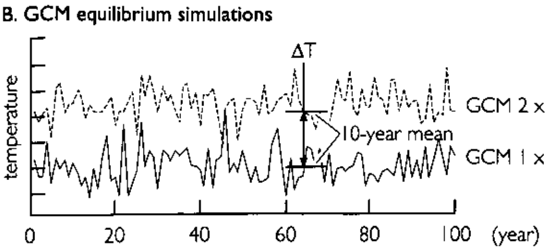
D. GCM transient simulations



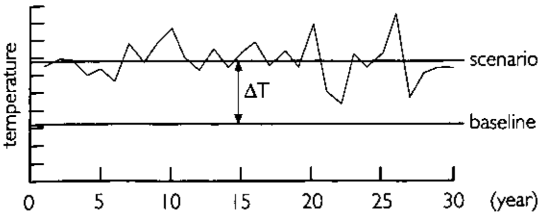
A. Observed temperature



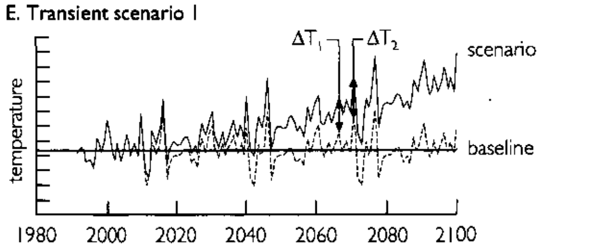
B. GCM equilibrium simulations



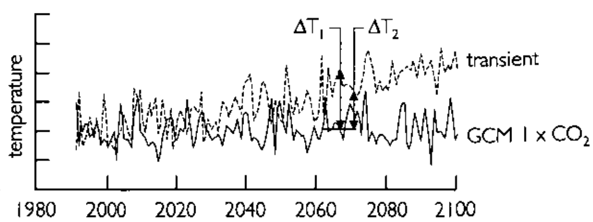
C. 2 x CO_2 scenario



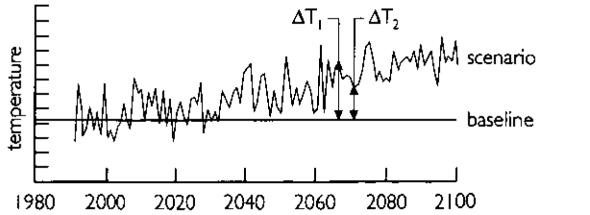
E. Transient scenario 1



F. GMC transient simulations



G. Transient scenario 2



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-