STEP 4: SELECTING THE SCENARIOS 6

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

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

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

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

6.1 Establishing the Present Situation

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

6.1.1 Climatological baseline

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

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

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

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

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

6.1.2 Environmental baseline

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

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

6.1.3 Socio-economic baseline

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

6.2 Time Frame of Projections

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

6.2.1 Limits of predictability

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

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

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

6.2.2 Compatibility of projections

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

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

6.2.3 Point in time or continuous assessment

A distinction can be drawn between considering impacts at discrete points in time in the future and examining continuous or time-dependent impacts. The former are characteristic of many climate impact assessments based on doubled-CO_2 scenarios. These scenarios have the advantage of being mutually comparable, and consider impacts occurring at the time specified by the scenario climate (although that time is often not easy to define

BOX 2

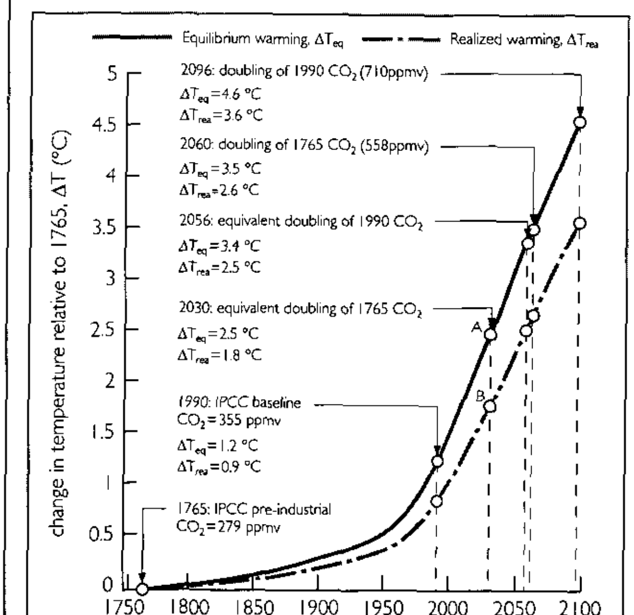
THE RELATIONSHIP OF EQUILIBRIUM AND TRANSIENT WARMING TO INCREASES IN CARBON DIOXIDE AND IN EQUIVALENT CARBON DIOXIDE

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

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

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

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



and can vary from place to place). However, they ignore any effects occurring during the interim period that might influence the final impacts. They also make it very difficult to assess rates of change and thus to evaluate adaptation strategies.

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

6.3 *Projecting Environmental Trends in the Absence of Climate Change*

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

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

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

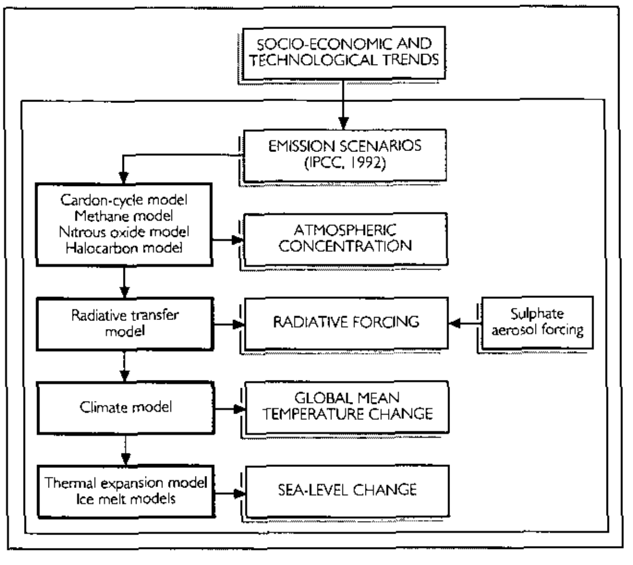
Official projections exist for some of these changes, as they are required for planning purposes. These vary in their time horizon from several years (e.g., economic growth, unemployment), through decades (e.g., urbanization, industrial development, agricultural production) to a century or longer (e.g.,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

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

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

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

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



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

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

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

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

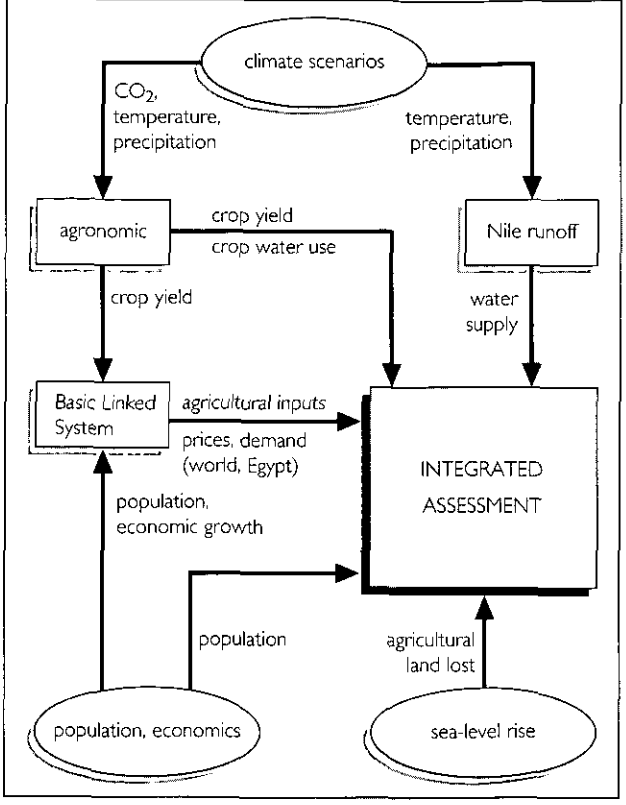
Background: agriculture in Egypt is restricted to the fertile lands of the narrow Nile valley from Aswan to Cairo and the flat Nile Delta north of Cairo. Together this comprises only 3 per cent of the country's land area. Egypt's entire agricultural water supply comes from irrigation, solely from the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

Problem: the study sought to assess the potential impact of a change in climate and sea level on Egypt's agricultural sector, accounting for changes in land area, water resources, crop production and world agricultural trade. The aim was not to predict Egypt's future under a changed climate, but rather to examine the combined effects on agriculture of different natural factors and the adaptability of the economic system.

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

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

Testing of methods: each of the submodels used in the study was validated against local data. Further, an elaborate comparative



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

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

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

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

6.5 Projecting Future Climate

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

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

Several types of climatic scenario have been used in previ-

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

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

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

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

Adaptive responses: adaptations in water resources (major river diversion schemes), irrigation (improved water delivery systems), agriculture (altered crop varieties and crop management) and coastal protection against sea level rise were all tested for the UKMO scenario. They achieve a modest 7–8 per cent increase in agricultural sector performance compared to no adaptation, but together would be extremely expensive to implement. However, investment in improving irrigation efficiency appears to be a robust, 'no regrets' policy that would be beneficial whether or not the climate changes.

Source: Strzepek and Smith (in press)

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

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

1 United Kingdom Meteorological Office model (Wilson and Mitchell, 1987)
2 Goddard Institute for Space Studies model (Hansen *et al.*, 1983)
3 Geophysical Fluid Dynamics Laboratory model (Manabe and Wetherald, 1987)

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

6.5.1 Synthetic scenarios

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

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

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

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

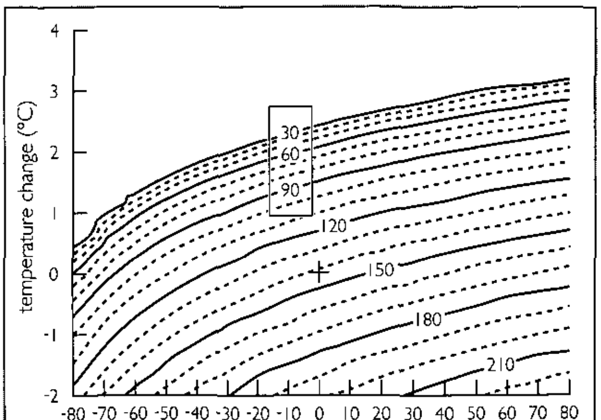
BOX 5
SENSITIVITY STUDIES AND RESPONSE SURFACES

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

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

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

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



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

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

6.5.2 Analogue scenarios

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

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

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

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

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

6.5.3 Scenarios from general circulation models

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

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

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

BOX 6
CASE STUDY: EFFECTS OF CLIMATE CHANGE ON COASTAL ENVIRONMENTS OF THE MARSHALL ISLANDS

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

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

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

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

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

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

Source: Hotthus *et al.* (1992)

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

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

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

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

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

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

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

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

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

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

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

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

6.6 Projecting Environmental Trends with Climate Change

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

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

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

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

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

6.7 Projecting Socio-economic Trends with Climate Change

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

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

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

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