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Climate Scenario Development

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Executive Summary

The Purpose of Climate Scenarios

A climate scenario is a plausible representation of future climate that has been constructed for explicit use in investigating the potential impacts of anthropogenic climate change. Climate scenarios often make use of climate projections (descriptions of the modelled response of the climate system to scenarios of greenhouse gas and aerosol concentrations), by manipulating model outputs and combining them with observed climate data.

This new chapter for the IPCC assesses the methods used to develop climate scenarios. Impact assessments have a very wide range of scenario requirements, ranging from global mean estimates of temperature and sea level, through continental-scale descriptions of changes in mean monthly climate, to point or catchment-level detail about future changes in daily or even sub-daily climate.

The science of climate scenario development acts as an important bridge from the climate science of Working Group I to the science of impact, adaptation and vulnerability assessment, considered by Working Group II. It also has a close dependence on emissions scenarios, which are discussed by Working Group III.

Methods for Constructing Scenarios

Useful information about possible future climates and their impacts has been obtained using various scenario construction methods. These include climate model based approaches, temporal and spatial analogues, incremental scenarios for sensitivity studies, and expert judgement. This chapter identifies advantages and disadvantages of these different methods (see Table 13.1).

All these methods can continue to serve a useful role in the provision of scenarios for impact assessment, but it is likely that the major advances in climate scenario construction will be made through the refinement and extension of climate model based approaches.

Each new advance in climate model simulations of future climate has stimulated new techniques for climate scenario construction. There are now numerous techniques available for scenario construction, the majority of which ultimately depend upon results obtained from general circulation model (GCM) experiments.

Representing the Cascade of Uncertainty

Uncertainties will remain inherent in predicting future climate change, even though some uncertainties are likely to be narrowed with time. Consequently, a range of climate scenarios should usually be considered in conducting impact assessments.

There is a cascade of uncertainties in future climate predictions which includes unknown future emissions of greenhouse gases and aerosols, the conversion of emissions to atmospheric concentrations and to radiative forcing of the climate, modelling the response of the climate system to forcing, and methods for regionalising GCM results.

Scenario construction techniques can be usefully contrasted according to the sources of uncertainty that they address and those that they ignore. These techniques, however, do not always provide consistent results. For example, simple methods based on direct GCM changes often represent model-to-model differences in simulated climate change, but do not address the uncertainty associated with how these changes are expressed at fine spatial scales. With regionalisation approaches, the reverse is often true.

A number of methods have emerged to assist with the quantification and communication of uncertainty in climate scenarios. These include pattern-scaling techniques to interpolate/extrapolate between results of model experiments, climate scenario generators, risk assessment frameworks and the use of expert judgement. The development of new or refined scenario construction techniques that can account for multiple uncertainties merits further investigation.

Representing High Spatial and Temporal Resolution Information

The incorporation of climate changes at high spatial (e.g., tens of kilometres) and temporal (e.g., daily) resolution in climate scenarios currently remains largely within the research domain of climate scenario development. Scenarios containing such high resolution information have not yet been widely used in comprehensive policy relevant impact assessments.

Preliminary evidence suggests that coarse spatial resolution AOGCM (Atmosphere-Ocean General Circulation Model) information for impact studies needs to be used cautiously in regions characterised by pronounced sub-GCM grid scale variability in forcings. The use of suitable regionalisation techniques may be important to enhance the AOGCM results over such regions.

Incorporating higher resolution information in climate scenarios can substantially alter the assessment of impacts. The incorporation of such information in scenarios is likely to become increasingly common and further evaluation of the relevant methods and their added value in impact assessment is warranted.

Representing Extreme Events

Extreme climate/weather events are very important for most climate change impacts. Changes in the occurrence and intensity of extremes should be included in climate scenarios whenever possible.

Some extreme events are easily or implicitly incorporated in climate scenarios using conventional techniques. It is more difficult to produce scenarios of complex events, such as tropical cyclones and ice storms, which may require specialised techniques. This constitutes an important methodological gap in scenario development. The large uncertainty regarding future changes in some extreme events exacerbates the difficulty in incorporating such changes in climate scenarios.

Applying Climate Scenarios in Impact Assessments

There is no single “best” scenario construction method appropriate for all applications. In each case, the appropriate method is determined by the context and the application of the scenario.

The choice of method constrains the sources of uncertainty that can be addressed. Relatively simple techniques, such as those that rely on scaled or unscaled GCM changes, may well be the most appropriate for applications in integrated assessment modelling or for informing policy; more sophisticated techniques, such as regional climate modelling or conditioned stochastic weather generation, are often necessary for applications involving detailed regional modelling of climate change impacts.

Improving Information Required for Scenario Development

Improvements in global climate modelling will bring a variety of benefits to most climate scenario development methods. A more diverse set of model experiments, such as AOGCMs run under a broader range of forcings and at higher resolutions, and regional climate models run either in ensemble mode or for longer time periods, will allow a wider range of uncertainty to be represented in climate scenarios. In addition, incorporation of some of the physical, biological and socio-economic feedbacks not currently simulated in global models will improve the consistency of different scenario elements.

13.1 Introduction

13.1.1 Definition and Nature of Scenarios

For the purposes of this report, a climate scenario refers to a plausible future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change. Such climate scenarios should represent future conditions that account for both human-induced climate change and natural climate variability. We distinguish a climate scenario from a climate projection (discussed in Chapters 9 and 10), which refers to a description of the response of the climate system to a scenario of greenhouse gas and aerosol emissions, as simulated by a climate model. Climate projections alone rarely provide sufficient information to estimate future impacts of climate change; model outputs commonly have to be manipulated and combined with observed climate data to be usable, for example, as inputs to impact models.

To further illustrate this point, Box 13.1 presents a simple example of climate scenario construction based on climate projections. The example also illustrates some other common considerations in performing an impact assessment that touch on issues discussed later in this chapter.

We also distinguish between a climate scenario and a climate change scenario. The latter term is sometimes used in the scientific literature to denote a plausible future climate. However, this term should strictly refer to a representation of the difference between some plausible future climate and the current or control climate (usually as represented in a climate model) (see Box 13.1, Figure 13.1a). A climate change scenario can be viewed as an interim step toward constructing a climate scenario. Usually a climate scenario requires combining the climate change scenario with a description of the current climate as represented by climate observations (Figure 13.1b). In a climate impacts context, it is the contrasting effects of these two climates – one current (the observed "baseline" climate), one

Box 13.1: Example of scenario construction.

Example of basic scenario construction for an impact study: the case of climate change and world food supply (Rosenzweig and Parry, 1994).

Aim of the study

The objective of this study was to estimate how global food supply might be affected by greenhouse gas induced climate change up to the year 2060. The method adopted involved estimating the change in yield of major crop staples under various scenarios using crop models at 112 representative sites distributed across the major agricultural regions of the world. Yield change estimates were assumed to be applicable to large regions to produce estimates of changes in total production which were then input to a global trade model. Using assumptions about future population, economic growth, trading conditions and technological progress, the trade model estimated plausible prices of food commodities on the international market given supply as defined by the production estimates. This information was then used to define the number of people at risk from hunger in developing countries.

Scenario information

Each of the stages of analysis required scenario information to be provided, including:

- scenarios of carbon dioxide (CO_2) concentration, affecting crop growth and water use, as an input to the crop models;
- climate observations and scenarios of future climate, for the crop model simulations;
- adaptation scenarios (e.g., new crop varieties, adjusted farm management) as inputs to the crop models;
- scenarios of regional population and global trading policy as an input to the trade model.

To the extent possible, the scenarios were mutually consistent, such that scenarios of population (United Nations medium range estimate) and Gross Domestic Product (GDP) (moderate growth) were broadly in line with the transient scenario of greenhouse gas emissions (based on the Goddard Institute for Space Studies (GISS) scenario A, see Hansen *et al*., 1988), and hence CO_2 concentrations. Similarly, the climate scenarios were based on $2\times CO_2$ equilibrium GCM projections from three models, where the radiative forcing of climate was interpreted as the combined concentrations of CO_2 (555 ppm) and other greenhouse gases (contributing about 15% of the change in forcing) equivalent to a doubling of CO_2, assumed to occur in about 2060.

Construction of the climate scenario

Since projections of current (and hence future) regional climate from the GCM simulations were not accurate enough to be used directly as an input to the crop model, modelled changes in climate were applied as adjustments to the observed climate at a location. Climate change by 2060 was computed as the difference (air temperature) or ratio (precipitation and solar radiation) of monthly mean climate between the GCM (unforced) control and $2\times CO_2$ simulations at GCM grid boxes coinciding with the crop modelling sites (Figure 13.1b). These estimates were used to adjust observed time-series of daily climate for the baseline period (usually 1961 to 1990) at each site (Figure 13.1b,c). Crop model simulations were conducted for the baseline climate and for each of the three climate scenarios, with and without CO_2 enrichment (to estimate the relative contributions of CO_2 and climate to crop yield changes), and assuming different levels of adaptation capacity.

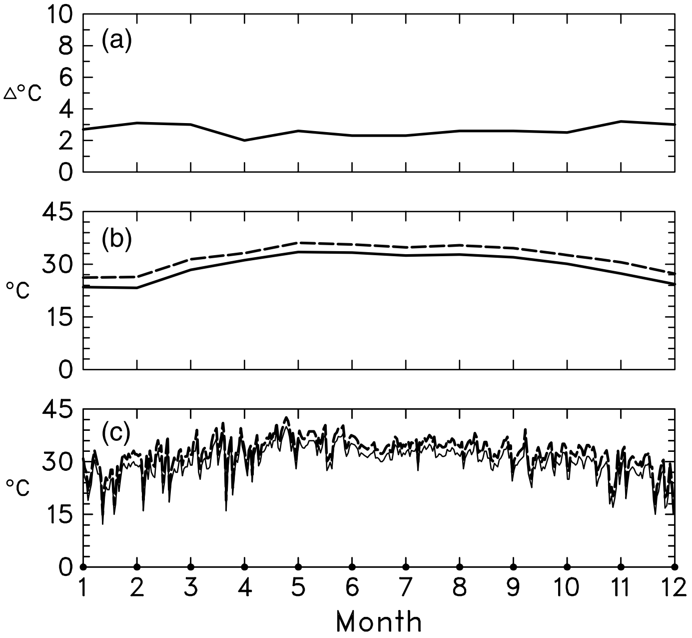

Figure 13.1: Example of the stages in the formation of a simple climate scenario for temperature using Poza Rica (20.3° N, 97.3° W) as a typical site used in the Mexican part of the Rosenzweig and Parry (1994) study.
(a) Mean monthly differences (Δ) (2×CO_2 minus control) of average temperature (°C) as calculated from the control and 2×CO_2 runs of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Manabe and Wetherald, 1987) for the model grid box that includes the geographic location of Poza Rica. The climate model spatial resolution is 4.4° latitude by 7.5° longitude.
(b) The average 17-year (1973 to 1989) observed mean monthly maximum temperature for Poza Rica (solid line) and the 2×CO_2 mean monthly maximum temperature produced by adding the differences portrayed in (a) to this baseline (dashed line). The crop models, however, require daily climate data for input.
(c) A sample of one year's (1975) observed daily maximum temperature data (solid line) and the 2×CO_2 daily values created by adding the monthly differences in a) to the daily data (dashed line). Thus, the dashed line is the actual daily maximum temperature time-series describing future climate that was used as one of the weather inputs to the crop models for this study and for this location (see Liverman *et al*., 1994 for further details).

future (the climate scenario) – on the exposure unit[1] that determines the impact of the climate change (Figure 13.1c).

A treatment of climate scenario development, in this specific sense, has been largely absent in the earlier IPCC Assessment Reports. The subject has been presented in independent IPCC Technical Guidelines documents (IPCC, 1992, 1994), which were briefly summarised in the Second Assessment Report of Working Group II (Carter *et al*., 1996b). These documents, while serving a useful purpose in providing guidelines for scenario use, did not fully address the science of climate scenario development. This may be, in part, because the field has been slow to develop and because only recently has a critical mass of important research issues coalesced and matured such that a full chapter is now warranted.

The chapter also serves as a bridge between this Report of Working Group I and the IPCC Third Assessment Report of Working Group II (IPCC, 2001) (hereafter TAR WG II) of climate change impacts, adaptation and vulnerability. As such it also embodies the maturation in the IPCC assessment process – that is, a recognition of the interconnections among the different segments of the assessment process and a desire to further integrate these segments. Chapter 3 performs a similar role in the TAR WG II (Carter and La Rovere, 2001) also discussing climate scenarios, but treating, in addition, all other scenarios (socio-economic, land use, environmental, etc.) needed for undertaking policy-relevant impact assessment. Chapter 3 serves in part as the other half of the bridge between the two Working Group Reports.

Scenarios are neither predictions nor forecasts of future conditions. Rather they describe alternative plausible futures that conform to sets of circumstances or constraints within which they occur (Hammond, 1996). The true purpose of scenarios is to illuminate uncertainty, as they help in determining the possible ramifications of an issue (in this case, climate change) along one or more plausible (but indeterminate) paths (Fisher, 1996).

Not all possibly imaginable futures can be considered viable scenarios of future climate. For example, most climate scenarios include the characteristic of increased lower tropospheric temperature (except in some isolated regions and physical circumstances), since most climatologists have very high confidence in that characteristic (Schneider *et al*., 1990; Mahlman, 1997). Given our present state of knowledge, a scenario that portrayed global tropospheric cooling for the 21st century would not be viable. We shall see in this chapter that what constitutes a viable scenario of future climate has evolved along with our understanding of the climate system and how this understanding might develop in the future.

It is worth noting that the development of climate scenarios predates the issue of global warming. In the mid-1970s, for example, when a concern emerged regarding global cooling due to the possible effect of aircraft on the stratosphere, simple incremental scenarios of climate change were formulated to evaluate what the possible effects might be worldwide (CIAP, 1975).

The purpose of this chapter is to assess the current state of climate scenario development. It discusses research issues that are addressed by researchers who develop climate scenarios and that must be considered by impacts researchers when they select scenarios for use in impact assessments. This chapter is not concerned, however, with presenting a comprehensive set of climate scenarios for the IPCC Third Assessment Report.

13.1.2 Climate Scenario Needs of the Impacts Community

The specific climate scenario needs of the impacts community vary, depending on the geographic region considered, the type of impact, and the purpose of the study. For example, distinctions

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[1] An exposure unit is an activity, group, region or resource exposed to significant climatic variations (IPCC, 1994).

can be made between scenario needs for research in climate scenario development and in the methods of conducting impact assessment (e.g., Woo, 1992; Mearns *et al.*, 1997) and scenario needs for direct application in policy relevant impact and integrated assessments (e.g., Carter *et al.*, 1996a; Smith *et al.*, 1996; Hulme and Jenkins, 1998).

The types of climate variables needed for quantitative impacts studies vary widely (e.g., White, 1985). However, six "cardinal" variables can be identified as the most commonly requested: maximum and minimum temperature, precipitation, incident solar radiation, relative humidity, and wind speed. Nevertheless, this list is far from exhaustive. Other climate or climate-related variables of importance may include CO_2 concentration, sea-ice extent, mean sea level pressure, sea level, and storm surge frequencies. A central issue regarding any climate variable of importance for impact assessment is determining at what spatial and temporal scales the variable in question can sensibly be provided, in comparison to the scales most desired by the impacts community. From an impacts perspective, it is usually desirable to have a fair amount of regional detail of future climate and to have a sense of how climate variability (from short to long time-scales) may change. But the need for this sort of detail is very much a function of the scale and purpose of the particular impact assessment. Moreover, the availability of the output from climate models and the advisability of using climate model results at particular scales, from the point of view of the climate modellers, ultimately determines what scales can and should be used.

Scenarios should also provide adequate quantitative measures of uncertainty. The sources of uncertainty are many, including the trajectory of greenhouse gas emissions in the future, their conversion into atmospheric concentrations, the range of responses of various climate models to a given radiative forcing and the method of constructing high resolution information from global climate model outputs (Pittock, 1995; see Figure 13.2). For many purposes, simply defining a single climate future is insufficient and unsatisfactory. Multiple climate scenarios that address at least one, or preferably several sources of uncertainty allow these uncertainties to be quantified and explicitly accounted for in impact assessments. Moreover, a further important requirement for impact assessments is to ensure consistency is achieved among various scenario components, such as between climate change, sea level rise and the concentration of actual (as opposed to equivalent) CO_2 implied by a particular emissions scenario.

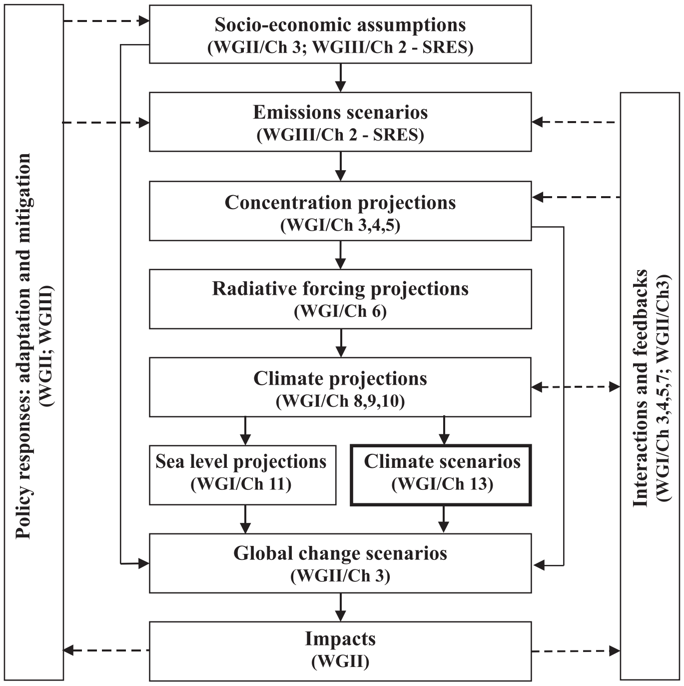

Figure 13.2: The cascade of uncertainties in projections to be considered in developing climate and related scenarios for climate change impact, adaptation and mitigation assessment.

As mentioned above, climate scenarios that are developed for impacts applications usually require that some estimate of climate change be combined with baseline observational climate data, and the demand for more complete and sophisticated observational data sets of climate has grown in recent years. The important considerations for the baseline include the time period adopted as well as the spatial and temporal resolution of the baseline data.

Much of this chapter is devoted to assessing how and how successfully these needs and requirements are currently met.

13.2 Types of Scenarios of Future Climate

Four types of climate scenario that have been applied in impact assessments are introduced in this section. The most common scenario type is based on outputs from climate models and receives most attention in this chapter. The other three types have usually been applied with reference to or in conjunction with model-based scenarios, namely: incremental scenarios for sensitivity studies, analogue scenarios, and a general category of "other scenarios". The origins of these scenarios and their mutual linkages are depicted in Figure 13.3.

The suitability of each type of scenario for use in policy-relevant impact assessment can be assessed according to five criteria adapted from Smith and Hulme (1998):

1. *Consistency* at regional level with global projections. Scenario changes in regional climate may lie outside the range of global mean changes but should be consistent with theory and model-based results.
2. *Physical plausibility and realism*. Changes in climate should be physically plausible, such that changes in different climatic variables are mutually consistent and credible.
3. *Appropriateness* of information for impact assessments. Scenarios should present climate changes at an appropriate temporal and spatial scale, for a sufficient number of variables, and over an adequate time horizon to allow for impact assessments.
4. *Representativeness* of the potential range of future regional climate change.
5. *Accessibility*. The information required for developing climate scenarios should be readily available and easily accessible for use in impact assessments.

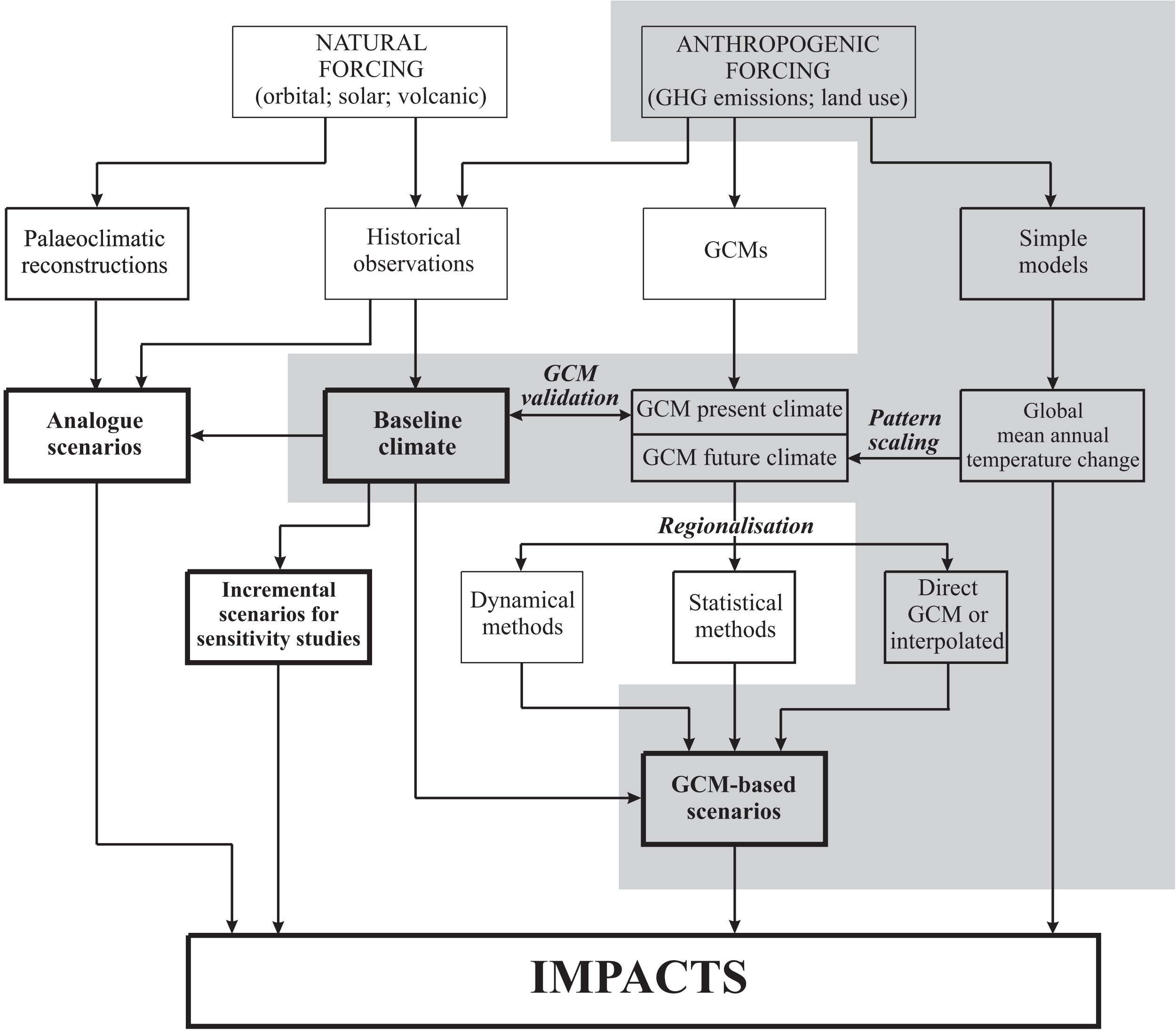

Figure 13.3: Some alternative data sources and procedures for constructing climate scenarios for use in impact assessment. Highlighted boxes indicate the baseline climate and common types of scenario (see text for details). Grey shading encloses the typical components of climate scenario generators.

A summary of the major advantages and disadvantages of different scenario development methods, based on these criteria, is presented in Table 13.1. The relative significance of the advantages and disadvantages is highly application dependent.

13.2.1 Incremental Scenarios for Sensitivity Studies

Incremental scenarios describe techniques where particular climatic (or related) elements are changed incrementally by plausible though arbitrary amounts (e.g., +1, +2, +3, +4°C change in temperature). Also referred to as synthetic scenarios (IPCC, 1994), they are commonly applied to study the sensitivity of an exposure unit to a wide range of variations in climate, often according to a qualitative interpretation of projections of future regional climate from climate model simulations ("guided sensitivity analysis", see IPCC-TGCIA, 1999). Incremental scenarios facilitate the construction of response surfaces – graphical devices for plotting changes in climate against some measure of impact (for example see Figure 13.9b) which can assist in identifying critical thresholds or discontinuities of response to a changing climate. Other types of scenarios (e.g., based on model outputs) can be superimposed on a response surface and the significance of their impacts readily evaluated (e.g., Fowler, 1999). Most studies have adopted incremental scenarios of constant changes throughout the year (e.g., Terjung *et al.*, 1984; Rosenzweig *et al.*, 1996), but some have introduced seasonal and spatial variations in the changes (e.g., Whetton *et al.*, 1993; Rosenthal *et al.*, 1995) and others have examined arbitrary changes in interannual, within-month and diurnal variability as well as changes in the mean (e.g., Williams *et al.*, 1988; Mearns *et al.*, 1992; Semenov and Porter, 1995; Mearns *et al.*, 1996).

Incremental scenarios provide information on an ordered range of climate changes and can readily be applied in a consistent and replicable way in different studies and regions, allowing for direct intercomparison of results. However, such scenarios do

Table 13.1: *The role of various types of climate scenarios and an evaluation of their advantages and disadvantages according to the five criteria described in the text. Note that in some applications a combination of methods may be used (e.g., regional modelling and a weather generator).*

Scenario type or tool	**Description/Use**	**Advantages**[a]	**Disadvantages**[a]
Incremental	• Testing system sensitivity • Identifying key climate thresholds	• Easy to design and apply (5) • Allows impact response surfaces to be created (3)	• Potential for creating unrealistic scenarios (1, 2) • Not directly related to greenhouse gas forcing (1)
Analogue: Palaeoclimatic	• Characterising warmer periods in past	• A physically plausible changed climate that really did occur in the past of a magnitude similar to that predicted for ~2100 (2)	• Variables may be poorly resolved in space and time (3, 5) • Not related to greenhouse gas forcing (1)
Instrumental	• Exploring vulnerabilities and some adaptive capacities	• Physically realistic changes (2) • Can contain a rich mixture of well-resolved, internally consistent, variables (3) • Data readily available (5)	• Not necessarily related to greenhouse gas forcing (1) • Magnitude of the climate change usually quite small (1) • No appropriate analogues may be available (5)
Spatial	• Extrapolating climate/ecosystem relationships • Pedagogic	• May contain a rich mixture of well-resolved variables (3)	• Not related to greenhouse gas forcing (1, 4) • Often physically implausible (2) • No appropriate analogues may be available (5)
Climate model based: Direct AOGCM outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically-based models (1, 2) • Long integrations (1) • Data readily available (5) • Many variables (potentially) available (3)	• Spatial information is poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4, 5) • Large control run biases may be a concern for use in certain regions (2)
High resolution/stretched grid (AGCM)	• Providing high resolution information at global/continental scales	• Provides highly resolved information (3) • Information is derived from physically-based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4, 5) • Problems in maintaining viable parametrizations across scales (1,2) • High resolution is dependent on SSTs and sea ice margins from driving model (AOGCM) (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Regional models	• Providing high spatial/temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information is derived from physically-based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2, 4)	• Computationally expensive, and thus few multiple scenarios (4, 5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Statistical downscaling	• Providing point/high spatial resolution information	• Can generate information on high resolution grids, or non-uniform regions (3) • Potential,for some techniques, to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1, 2) • Demands access to daily observational surface and/or upper air data that spans range of variability (5) • Not many variables produced for some techniques (3, 5) • Dependent on (usually biased) inputs from driving AOGCM (2)
Climate scenario generators	• Integrated assessments • Exploring uncertainties • Pedagogic	• May allow for sequential quantification of uncertainty (4) • Provides 'integrated' scenarios (1) • Multiple scenarios easy to derive (4)	• Usually rely on linear pattern scaling methods (1) • Poor representation of temporal variability (3) • Low spatial resolution (3)
Weather generators	• Generating baseline climate time-series • Altering higher order moments of climate • Statistical downscaling	• Generates long sequences of daily or sub-daily climate (2, 3) • Variables are usually internally consistent (2) • Can incorporate altered frequency/intensity of ENSO events (3)	• Poor representation of low frequency climate variability (2, 4) • Limited representation of extremes (2, 3, 4) • Requires access to long observational weather series (5) • In the absence of conditioning, assumes constant statistical characteristics (1, 2)
Expert judgment	• Exploring probability and risk • Integrating current thinking on changes in climate	• May allow for a 'consensus' (4) • Has the potential to integrate a very broad range of relevant information (1, 3, 4) • Uncertainties can be readily represented (4)	• Subjectivity may introduce bias (2) • A representative survey of experts may be difficult to implement (5)

[a] Numbers in parentheses under Advantages and Disadavantages indicate that they are relevant to the criteria described. The five criteria are: (1) *Consistency* at regional level with global projections; (2) *Physical plausibility and realism*, such that changes in different climatic variables are mutually consistent and credible, and spatial and temporal patterns of change are realistic; (3) *Appropriateness* of information for impact assessments (i.e., resolution, time horizon, variables); (4) *Representativeness* of the potential range of future regional climate change; and (5) *Accessibility* for use in impact assessments.

not necessarily present a realistic set of changes that are physically plausible. They are usually adopted for exploring system sensitivity prior to the application of more credible, model-based scenarios (Rosenzweig and Iglesias, 1994; Smith and Hulme, 1998).

13.2.2 Analogue Scenarios

Analogue scenarios are constructed by identifying recorded climate regimes which may resemble the future climate in a given region. Both spatial and temporal analogues have been used in constructing climate scenarios.

13.2.2.1 Spatial analogues

Spatial analogues are regions which today have a climate analogous to that anticipated in the study region in the future. For example, to project future grass growth, Bergthórsson *et al.* (1988) used northern Britain as a spatial analogue for the potential future climate over Iceland. Similarly, Kalkstein and Greene (1997) used Atlanta as a spatial analogue of New York in a heat/mortality study for the future. Spatial analogues have also been exploited along altitudinal gradients to project vegetation composition, snow conditions for skiing, and avalanche risk (e.g., Beniston and Price, 1992; Holten and Carey, 1992; Gyalistras *et al.*, 1997). However, the approach is severely restricted by the frequent lack of correspondence between other important features (both climatic and non-climatic) of a study region and its spatial analogue (Arnell *et al.*, 1990). Thus, spatial analogues are seldom applied as scenarios, *per se*. Rather, they are valuable for validating the extrapolation of impact models by providing information on the response of systems to climatic conditions falling outside the range currently experienced at a study location.

13.2.2.2 Temporal analogues

Temporal analogues make use of climatic information from the past as an analogue for possible future climate (Webb and Wigley, 1985; Pittock, 1993). They are of two types: palaeoclimatic analogues and instrumentally based analogues.

Palaeoclimatic analogues are based on reconstructions of past climate from fossil evidence, such as plant or animal remains and sedimentary deposits. Two periods have received particular attention (Budyko, 1989; Shabalova and Können, 1995): the mid-Holocene (about 5 to 6 ky BP[2]) and the Last (Eemian) Interglacial (about 120 to 130 ky BP). During these periods, mean global temperatures were as warm as or warmer than today (see Chapter 2, Section 2.4.4), perhaps resembling temperatures anticipated during the 21st century. Palaeoclimatic analogues have been adopted extensively in the former Soviet Union (e.g., Frenzel *et al.*, 1992; Velichko *et al.*, 1995a,b; Anisimov and Nelson, 1996), as well as elsewhere (e.g., Kellogg and Schware, 1981; Pittock and Salinger, 1982). The major disadvantage of using palaeoclimatic analogues for climate scenarios is that the causes of past changes in climate (e.g., variations in the Earth's orbit about the Sun; continental configuration) are different from those posited for the enhanced greenhouse effect, and the resulting regional and seasonal patterns of climate change may be quite different (Crowley, 1990; Mitchell, 1990). There are also large uncertainties about the quality of many palaeoclimatic reconstructions (Covey, 1995). However, these scenarios remain useful for providing insights about the vulnerability of systems to abrupt climate change (e.g., Severinghaus *et al*., 1998) and to past El Niño-Southern Oscillation (ENSO) extremes (e.g., Fagan, 1999; Rodbell *et al*., 1999). They also can provide valuable information for testing the ability of climate models to reproduce past climate fluctuations (see Chapter 8).

Periods of observed global scale warmth during the historical period have also been used as analogues of a greenhouse gas induced warmer world (Wigley *et al*., 1980). Such scenarios are usually constructed by estimating the difference between the regional climate during the warm period and that of the long-term average or a similarly selected cold period (e.g., Lough *et al.*, 1983). An alternative approach is to select the past period on the basis not only of the observed climatic conditions but also of the recorded impacts (e.g., Warrick, 1984; Williams *et al.*, 1988; Rosenberg *et al.*, 1993; Lapin *et al.*, 1995). A further method employs observed atmospheric circulation patterns as analogues (e.g., Wilby *et al*., 1994). The advantage of the analogue approach is that the changes in climate were actually observed and so, by definition, are internally consistent and physically plausible. Moreover, the approach can yield useful insights into past sensitivity and adaptation to climatic variations (Magalhães and Glantz, 1992). The major objection to these analogues is that climate anomalies during the past century have been fairly minor compared to anticipated future changes, and in many cases the anomalies were probably associated with naturally occurring changes in atmospheric circulation rather than changes in greenhouse gas concentrations (e.g., Glantz, 1988; Pittock, 1989).

13.2.3 Scenarios Based on Outputs from Climate Models

Climate models at different spatial scales and levels of complexity provide the major source of information for constructing scenarios. GCMs and a hierarchy of simple models produce information at the global scale. These are discussed further below and assessed in detail in Chapters 8 and 9. At the regional scale there are several methods for obtaining sub-GCM grid scale information. These are detailed in Chapter 10 and summarised in Section 13.4.

13.2.3.1 Scenarios from General Circulation Models

The most common method of developing climate scenarios for quantitative impact assessments is to use results from GCM experiments. GCMs are the most advanced tools currently available for simulating the response of the global climate system to changing atmospheric composition.

All of the earliest GCM-based scenarios developed for impact assessment in the 1980s were based on equilibrium-response experiments (e.g., Emanuel *et al*., 1985; Rosenzweig, 1985; Gleick, 1986; Parry *et al*., 1988). However, most of these scenarios contained no explicit information about the time of

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[2] ky BP = thousand years before present.

realisation of changes, although time-dependency was introduced in some studies using pattern-scaling techniques (e.g., Santer *et al*., 1990; see Section 13.5).

The evolving (transient) pattern of climate response to gradual changes in atmospheric composition was introduced into climate scenarios using outputs from coupled AOGCMs from the early 1990s onwards. Recent AOGCM simulations (see Chapter 9, Table 9.1) begin by modelling historical forcing by greenhouse gases and aerosols from the late 19th or early 20th century onwards. Climate scenarios based on these simulations are being increasingly adopted in impact studies (e.g., Neilson *et al*., 1997; Downing *et al*., 2000) along with scenarios based on ensemble simulations (e.g., papers in Parry and Livermore, 1999) and scenarios accounting for multi-decadal natural climatic variability from long AOGCM control simulations (e.g., Hulme *et al*., 1999a).

There are several limitations that restrict the usefulness of AOGCM outputs for impact assessment: (i) the large resources required to undertake GCM simulations and store their outputs, which have restricted the range of experiments that can be conducted (e.g., the range of radiative forcings assumed); (ii) their coarse spatial resolution compared to the scale of many impact assessments (see Section 13.4); (iii) the difficulty of distinguishing an anthropogenic signal from the noise of natural internal model variability (see Section 13.5); and (iv) the difference in climate sensitivity between models.

13.2.3.2 Scenarios from simple climate models

Simple climate models are simplified global models that attempt to reproduce the large-scale behaviour of AOGCMs (see Chapter 9). While they are seldom able to represent the non-linearities of some processes that are captured by more complex models, they have the advantage that multiple simulations can be conducted very rapidly, enabling an exploration of the climatic effects of alternative scenarios of radiative forcing, climate sensitivity and other parametrized uncertainties (IPCC, 1997). Outputs from these models have been used in conjunction with GCM information to develop scenarios using pattern-scaling techniques (see Section 13.5). They have also been used to construct regional greenhouse gas stabilisation scenarios (e.g., Gyalistras and Fischlin, 1995). Simple climate models are used in climate scenario generators (see Section 13.5.2) and in some integrated assessment models (see Section 13.6).

13.2.4 Other Types of Scenarios

Three additional types of climate scenarios have also been adopted in impact studies. The first type involves extrapolating ongoing trends in climate that have been observed in some regions and that appear to be consistent with model-based projections of climate change (e.g., Jones *et al*., 1999). There are obvious dangers in relying on extrapolated trends, and especially in assuming that recent trends are due to anthropogenic forcing rather than natural variability (see Chapters 2 and 12). However, if current trends in climate are pointing strongly in one direction, it may be difficult to defend the credibility of scenarios that posit a trend in the opposite direction, especially over a short projection period.

A second type of scenario, which has some resemblance to the first, uses empirical relationships between regional climate and global mean temperature from the instrumental record to extrapolate future regional climate on the basis of projected global or hemispheric mean temperature change (e.g. Vinnikov and Groisman, 1979; Anisimov and Poljakov, 1999). Again, this method relies on the assumption that past relationships between local and broad-scale climate are also applicable to future conditions.

A third type of scenario is based on expert judgement, whereby estimates of future climate change are solicited from climate scientists, and the results are sampled to obtain probability density functions of future change (NDU, 1978; Morgan and Keith, 1995; Titus and Narayanan, 1996; Kuikka and Varis, 1997; Tol and de Vos, 1998). The main criticism of expert judgement is its inherent subjectivity, including problems of the representativeness of the scientists sampled and likely biases in questionnaire design and analysis of the responses (Stewart and Glantz, 1985). Nevertheless, since uncertainties in estimates of future climate are inevitable, any moves towards expressing future climate in probabilistic terms will necessarily embrace some elements of subjective judgement (see Section 13.5).

13.3 Defining the Baseline

A baseline period is needed to define the observed climate with which climate change information is usually combined to create a climate scenario. When using climate model results for scenario construction, the baseline also serves as the reference period from which the modelled future change in climate is calculated.

13.3.1 The Choice of Baseline Period

The choice of baseline period has often been governed by availability of the required climate data. Examples of adopted baseline periods include 1931 to 1960 (Leemans and Solomon, 1993), 1951 to 1980 (Smith and Pitts, 1997), or 1961 to 1990 (Kittel *et al*., 1995; Hulme *et al*., 1999b).

There may be climatological reasons to favour earlier baseline periods over later ones (IPCC, 1994). For example, later periods such as 1961 to 1990 are likely to have larger anthropogenic trends embedded in the climate data, especially the effects of sulphate aerosols over regions such as Europe and eastern USA (Karl *et al*., 1996). In this regard, the “ideal” baseline period would be in the 19th century when anthropogenic effects on global climate were negligible. Most impact assessments, however, seek to determine the effect of climate change with respect to “the present”, and therefore recent baseline periods such as 1961 to 1990 are usually favoured. A further attraction of using 1961 to 1990 is that observational climate data coverage and availability are generally better for this period compared to earlier ones.

Whatever baseline period is adopted, it is important to acknowledge that there are differences between climatological averages based on century-long data (e.g., Legates and Wilmott, 1990) and those based on sub-periods. Moreover, different 30-year periods have been shown to exhibit differences in regional annual mean baseline temperature and precipitation of up to

±0.5ºC and ±15% respectively (Hulme and New, 1997; Visser *et al*., 2000; see also Chapter 2).

13.3.2 The Adequacy of Baseline Climatological Data

The adequacy of observed baseline climate data sets can only be evaluated in the context of particular climate scenario construction methods, since different methods have differing demands for baseline climate data.

There are an increasing number of gridded global (e.g., Leemans and Cramer, 1991; New *et al*., 1999) and national (e.g., Kittel *et al*., 1995, 1997; Frei and Schär, 1998) climate data sets describing mean surface climate, although few describe inter-annual climate variability (see Kittel *et al*., 1997; Xie and Arkin, 1997; New *et al*., 2000). Differences between alternative gridded regional or global baseline climate data sets may be large, and these may induce non-trivial differences in climate change impacts that use climate scenarios incorporating different baseline climate data (e.g., Arnell, 1999). These differences may be as much a function of different interpolation methods and station densities as they are of errors in observations or the result of sampling different time periods (Hulme and New, 1997; New, 1999). A common problem that some methods endeavour to correct is systematic biases in station locations (e.g., towards low elevation sites). The adequacy of different techniques (e.g., Daly *et al*., 1994; Hutchinson, 1995; New *et al*., 1999) to interpolate station records under conditions of varying station density and/or different topography has not been systematically evaluated.

A growing number of climate scenarios require gridded daily baseline climatological data sets at continental or global scales yet, to date, the only observed data products that meet this criterion are experimental (e.g., Piper and Stewart, 1996; Widmann and Bretherton, 2000). For this and other reasons, attempts have been made to combine monthly observed climatologies with stochastic weather generators to allow "synthetic" daily observed baseline data to be generated for national (e.g., Carter *et al*., 1996a; Semenov and Brooks, 1999), continental (e.g., Voet *et al*., 1996; Kittel *et al*., 1997), or even global (e.g., Friend, 1998) scales. Weather generators are statistical models of observed sequences of weather variables, whose outputs resemble weather data at individual or multi-site locations (Wilks and Wilby, 1999). Access to long observed daily weather series for many parts of the world (e.g., oceans, polar regions and some developing countries) is a problem for climate scenario developers who wish to calibrate and use weather generators.

A number of statistical downscaling techniques (see Section 13.4 and Chapter 10, Section 10.6, for definition) used in scenario development employ Numerical Weather Prediction (NWP) reanalysis data products as a source of upper air climate data (Kalnay *et al*., 1996). These reanalysis data sets extend over periods up to 40 years and provide spatial and temporal resolution sometimes lacking in observed climate data sets. Relatively little detailed work has compared such reanalysis data with independent observed data sets (see Santer *et al*., 1999, and Widmann and Bretherton, 2000, for two exceptions), but it is known that certain reanalysis variables – such as precipitation and some other hydrological variables – are unreliable.

13.3.3 Combining Baseline and Modelled Data

Climate scenarios based on model estimates of future climate can be constructed either by adopting the direct model outputs or by combining model estimates of the changed climate with observational climate data. Impact studies rarely use GCM outputs directly because GCM biases are too great and because the spatial resolution is generally too coarse to satisfy the data requirements for estimating impacts. Mearns *et al*. (1997) and Mavromatis and Jones (1999) provide two of the few examples of using climate model output directly as input into an impact assessment.

Model-based estimates of climate change should be calculated with respect to the chosen baseline. For example, it would be inappropriate to combine modelled changes in climate calculated with respect to model year 1990 with an observed baseline climate representing 1951 to 1980. Such an approach would "disregard" about 0.15°C of mean global warming occurring between the mid-1970s and 1990. It would be equally misleading to apply modelled changes in climate calculated with respect to an unforced (control) climate representing "pre-industrial" conditions (e.g., "forced" t_3 minus "unforced" t_1 in Figure 13.4) to an observed baseline climate representing some period in the 20th century. Such an approach would introduce an unwarranted amount of global climate change into the scenario. This latter definition of modelled climate change was originally used in transient climate change experiments to overcome problems associated with climate "drift" in the coupled AOGCM simulations (Cubasch *et al*., 1992), but was not designed to be used in conjunction with observed climate data. It is more appropriate to define the modelled change in climate with respect to the same baseline period that the observed climate data set is representing (e.g., "forced" t_3 minus "forced" t_1 in Figure 13.4, added to a 1961 to 1990 baseline climate).

Whatever baseline period is selected, there are a number of ways in which changes in climate can be calculated from model results and applied to baseline data. For example, changes in

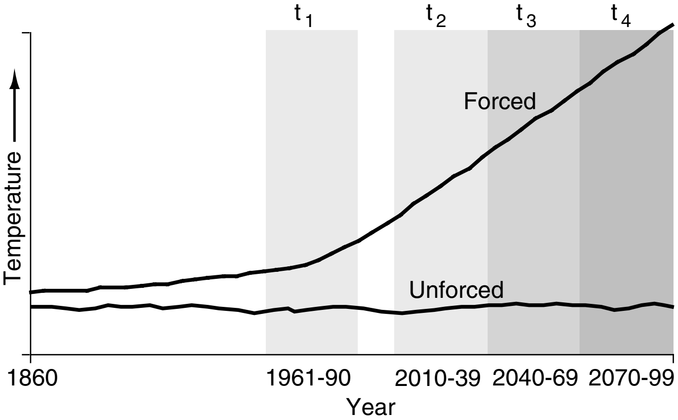

Figure 13.4: A schematic representation of different simulations and periods in a coupled AOGCM climate change experiment that may be used in the definition of modelled climate change. t_1 to t_4 define alternative 30-year periods from either forced or unforced experiments.

climate can be calculated either as the difference or as the ratio between the simulated future climate and the simulated baseline climate. These differences or ratios are then applied to the observed baseline climate – whether mean values, monthly or a daily time-series. Differences are commonly applied to temperature (as in Box 13.1), while ratios are usually used with those surface variables, such as precipitation, vapour pressure and radiation, that are either positive or zero. Climate scenarios have been constructed using both absolute and relative changes for precipitation. The effects of the two different approaches on the resulting climate change impacts depend on the types of impacts being studied and the region of application. Some studies report noticeable differences in impacts (e.g., Alcamo *et al*., 1998), especially since applying ratio changes alters the standard deviation of the original series (Mearns *et al*., 1996); in others, differences in impacts were negligible (e.g., Torn and Fried, 1992).

13.4 Scenarios with Enhanced Spatial and Temporal Resolution

The spatial and temporal scales of information from GCMs, from which climate scenarios have generally been produced, have not been ideal from an impacts point of view. The desire for information on climate change regarding changes in variability as well as changes in mean conditions and for information at high spatial resolutions has been consistent over a number of years (Smith and Tirpak, 1989).

The scale at which information can appropriately be taken from relatively coarse-scale GCMs has also been debated. For example, many climate scenarios constructed from GCM outputs have taken information from individual GCM grid boxes, whereas most climate modellers do not consider the outputs from their simulation experiments to be valid on a single grid box scale and usually examine the regional results from GCMs over a cluster of grid boxes (see Chapter 10, Section 10.3). Thus, the scale of information taken from coarse resolution GCMs for scenario development often exceeds the reasonable resolution of accuracy of the models themselves.

In this section we assess methods of incorporating high resolution information into climate scenarios. The issue of spatial and temporal scale embodies an important type of uncertainty in climate scenario development (see Section 13.5.1.5).

Since spatial and temporal scales in atmospheric phenomena are often related, approaches for increasing spatial resolution can also be expected to improve information at high-frequency temporal scales (e.g., Mearns *et al*., 1997; Semenov and Barrow, 1997; Wang *et al*., 1999; see also Chapter 10).

13.4.1 Spatial Scale of Scenarios

The climate change impacts community has long bemoaned the inadequate spatial scale of climate scenarios produced from coarse resolution GCM output (Gates, 1985; Lamb, 1987; Robinson and Finkelstein, 1989; Smith and Tirpak, 1989; Cohen, 1990). This dissatisfaction emanates from the perceived mismatch of scale between coarse resolution GCMs (hundreds of kilometres) and the scale of interest for regional impacts (an order or two orders of magnitude finer scale) (Hostetler, 1994; IPCC, 1994). For example, many mechanistic models used to simulate the ecological effects of climate change operate at spatial resolutions varying from a single plant to a few hectares. Their results may be highly sensitive to fine-scale climate variations that may be embedded in coarse-scale climate variations, especially in regions of complex topography, along coastlines, and in regions with highly heterogeneous land-surface covers.

Conventionally, regional "detail" in climate scenarios has been incorporated by applying changes in climate from the coarse-scale GCM grid points to observation points that are distributed at varying resolutions, but often at resolutions higher than that of the GCMs (e.g., see Box 13.1; Whetton *et al*., 1996; Arnell, 1999). Recently, high resolution gridded baseline climatologies have been developed with which coarse resolution GCM results have been combined (e.g., Saarikko and Carter, 1996; Kittel *et al*., 1997). Such relatively simple techniques, however, cannot overcome the limitations imposed by the fundamental spatial coarseness of the simulated climate change information itself.

Three major techniques (referred to as regionalisation techniques) have been developed to produce higher resolution climate scenarios: (1) regional climate modelling (Giorgi and Mearns, 1991; McGregor, 1997; Giorgi and Mearns, 1999); (2) statistical downscaling (Wilby and Wigley, 1997; Murphy, 1999); and (3) high resolution and variable resolution Atmospheric General Circulation Model (AGCM) time-slice techniques (Cubasch *et al*., 1995; Fox-Rabinovitz *et al*., 1997). The two former methods are dependent on the large-scale circulation variables from GCMs, and their value as a viable means of increasing the spatial resolution of climate change information thus partially depends on the quality of the GCM simulations. The variable resolution and high resolution time-slice methods use the AGCMs directly, run at high or variable resolutions. The high resolution time-slice technique is also dependent on the sea surface temperature simulated by a coarser resolution AOGCM. There have been few completed experiments using these AGCM techniques, which essentially are still under development (see Chapter 10, Section 10.4). Moreover, they have rarely been applied to explicit scenario formation for impacts purposes (see Jendritzky and Tinz, 2000, for an exception) and are not discussed further in this chapter. See Chapter 10 for further details on all techniques.

13.4.1.1 Regional modelling

The basic strategy in regional modelling is to rely on the GCM to reproduce the large-scale circulation of the atmosphere and for the regional model to simulate sub-GCM scale regional distributions or patterns of climate, such as precipitation, temperature, and winds, over the region of interest (Giorgi and Mearns, 1991; McGregor, 1997; Giorgi and Mearns, 1999). The GCM provides the initial and lateral boundary conditions for driving the regional climate model (RCM). In general, the spatial resolution of the regional model is on the order of tens of kiilometres, whereas the GCM scale is an order of magnitude coarser. Further details on the techniques of regional climate modelling are covered in Chapter 10, Section 10.5.

13.4.1.2 Statistical downscaling

In statistical downscaling, a cross-scale statistical relationship is developed between large-scale variables of observed climate such as spatially averaged 500 hPa heights, or measure of vorticity, and local variables such as site-specific temperature and precipitation (von Storch, 1995; Wilby and Wigley, 1997; Murphy, 1999). These relationships are assumed to remain constant in the climate change context. Also, it is assumed that the predictors selected (i.e., the large-scale variables) adequately represent the climate change signal for the predictand (e.g., local-scale precipitation). The statistical relationship is used in conjunction with the change in the large-scale variables to determine the future local climate. Further details of these techniques are provided in Chapter 10, Section 10.6.

13.4.1.3 Applications of the methods to impacts

While the two major techniques described above have been available for about ten years, and proponents claim use in impact assessments as one of their important applications, it is only quite recently that scenarios developed using these techniques have actually been applied in a variety of impact assessments, such as temperature extremes (Hennessy *et al.*, 1998; Mearns, 1999); water resources (Hassall and Associates, 1998; Hay *et al.*, 1999; Wang *et al.*, 1999; Wilby *et al.*, 1999; Stone *et al.*, 2001); agriculture (Mearns *et al.*, 1998, 1999, 2000a, 2001; Brown *et al.*, 2000) and forest fires (Wotton *et al.*, 1998). Prior to the past couple of years, these techniques were mainly used in pilot studies focused on increasing the temporal (and spatial) scale of scenarios (e.g., Mearns *et al.*, 1997; Semenov and Barrow, 1997).

One of the most important aspects of this work is determining whether the high resolution scenario actually leads to significantly different calculations of impacts compared to that of the coarser resolution GCM from which the high resolution scenario was partially derived. This aspect is related to the issue of uncertainty in climate scenarios (see Section 13.5). We provide examples of such studies below.

Application of high resolution scenarios produced from a regional model (Giorgi *et al.*, 1998) over the Central Plains of the USA produced changes in simulated crop yields that were significantly different from those changes calculated from a coarser resolution GCM scenario (Mearns *et al.*, 1998; 1999, 2001). For simulated corn in Iowa, for example, the large-scale (GCM) scenario resulted in a statistically significant decrease in yield, but the high resolution scenario produced an insignificant increase (Figure 13.5). Substantial differences in regional economic impacts based on GCM and RCM scenarios were also found in a recent integrated assessment of agriculture in the south-eastern USA (Mearns *et al.*, 2000a,b). Hay *et al.* (1999), using a regression-based statistical downscaling technique, developed downscaled scenarios based on the Hadley Centre Coupled AOGCM (HadCM2) transient runs and applied them to a hydrologic model in three river basins in the USA. They found that the standard scenario from the GCM produced changes in surface runoff that were quite different from those produced from the downscaled scenario (Figure 13.6).

13.4.2 Temporal Variability

The climate change information most commonly taken from climate modelling experiments comprises mean monthly, seasonal, or annual changes in variables of importance to impact assessments. However, changes in climate will involve changes in variability as well as mean conditions. As mentioned in Section 13.3 on baseline climate, the interannual variability in climate scenarios constructed from mean changes in climate is most commonly inherited from the baseline climate, not from the climate change experiment. Yet, it is known that changes in variability could be very important to most areas of impact assessment (Mearns, 1995; Semenov and Porter, 1995). The most obvious way in which variability changes affect resource systems is through the effect of variability change on the frequency of extreme events. As Katz and Brown (1992) demonstrated, changes in standard deviation have a proportionately greater effect than changes in means on changes in the frequency of extremes. However, from a climate scenario point of view, it is the relative size of the change in the mean versus standard deviation of a variable that determines the final relative contribution of these statistical moments to a change in extremes. The construction of scenarios incorporating extremes is discussed in Section 13.4.2.2.

The conventional method of constructing mean change scenarios for precipitation using the ratio method (discussed in Section 13.3) results in a change in variability of daily precipitation intensity; that is, the variance of the intensity is changed by a factor of the square of the ratio (Mearns *et al.*, 1996). However, the frequency of precipitation is not changed. Using the difference method (as is common for temperature variables) the variance of the time-series is not changed. Hence, from the perspective of variability, application of the difference approach to precipitation produces a more straightforward scenario. However, it can also result in negative values of precipitation. Essentially neither approach is realistic in its effect on the daily characteristics of the time-series. As mean (monthly) precipitation changes, both the daily intensity and frequency are usually affected.

13.4.2.1 Incorporation of changes in variability: daily to interannual time-scales

Changes in variability have not been regularly incorporated in climate scenarios because: (1) less faith has been placed in climate model simulations of changes in variability than of changes in mean climate; (2) techniques for changing variability are more complex than those for incorporating mean changes; and (3) there may have been a perception that changes in means are more important for impacts than changes in variability (Mearns, 1995). Techniques for incorporating changes in variability emerged in the early 1990s (Mearns *et al.*, 1992; Wilks, 1992; Woo, 1992; Barrow and Semenov, 1995; Mearns, 1995).

Some relatively simple techniques have been used to incorporate changes in interannual variability alone into scenarios. Such techniques are adequate in cases where the impact models use monthly climate data for input. One approach is to calculate present day and future year-by-year anomalies relative to the modelled baseline period, and to apply these anomalies (at an annual, seasonal or monthly resolution) to the long-term mean

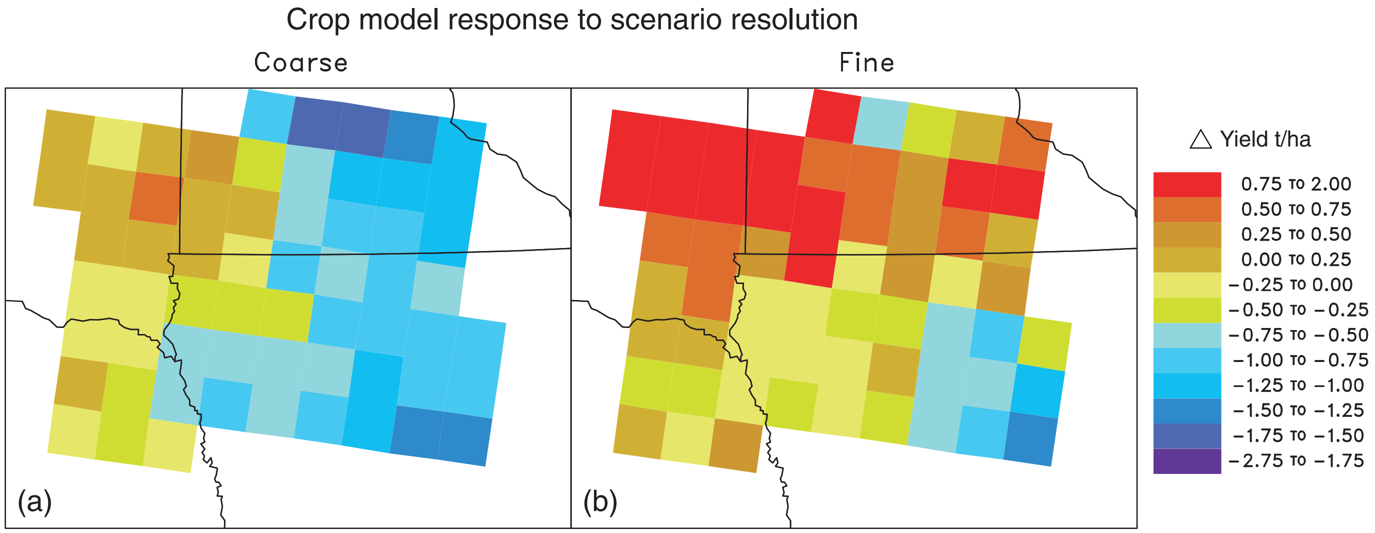

Figure 13.5: Spatial pattern of differences (future climate minus baseline) in simulated corn yields based on two different climate change scenarios for the region covering north-west Iowa and surrounding states (a) coarse spatial resolution GCM scenario (CSIRO); (b) high spatial resolution region climate model scenario (RegCM) (modified from Mearns *et al*., 1999).

observed baseline climate. This produces climate time-series having an interannual variability equivalent to that modelled for the present day and future, both superimposed on the observed baseline climate. The approach was followed in evaluating impacts of variability change on crop yields in Finland (Carter *et al*., 2000a), and in the formation of climate scenarios for the United States National Assessment, though in the latter case the observed variability was retained for the historical period.

Another approach is to calculate the change in modelled interannual variability between the baseline and future periods, and then to apply it as an inflator or deflator to the observed baseline interannual variability. In this way, modelled changes in interannual variability are carried forward into the climate scenario, but the observed baseline climate still provides the initial definition of variability. This approach was initially developed in Mearns *et al*. (1992) and has recently been experimented with by Arnell (1999). However, this approach can produce unrealistic features, such as negative precipitation or inaccurate autocorrelation structure of temperature, when applied to climate data on a daily time-scale (Mearns *et al*., 1996).

The major, most complete technique for producing scenarios with changes in interannual and daily variability involves manipulation of the parameters of stochastic weather generators (defined in Section 13.3.2). These are commonly based either on a Markov chain approach (e.g., Richardson, 1981) or a spell length approach (e.g., Racksko *et al*., 1991), and simulate changes in variability on daily to interannual time-scales (Wilks, 1992). More detailed information on weather generators is provided in Chapter 10, Section 10.6.2.

To bring about changes in variability, the parameters of the weather generator are manipulated in ways that alter the daily variance of the variable of concern (usually temperature or precipitation) (Katz, 1996). For precipitation, this usually involves changes in both the frequency and intensity of daily precipitation. By manipulating the parameters on a daily time-scale, changes in variability are also induced on the interannual time-scale (Wilks, 1992). Some weather generators operating at sub-daily time-scales have also been applied to climate scenario generation (e.g., Kilsby *et al*., 1998).

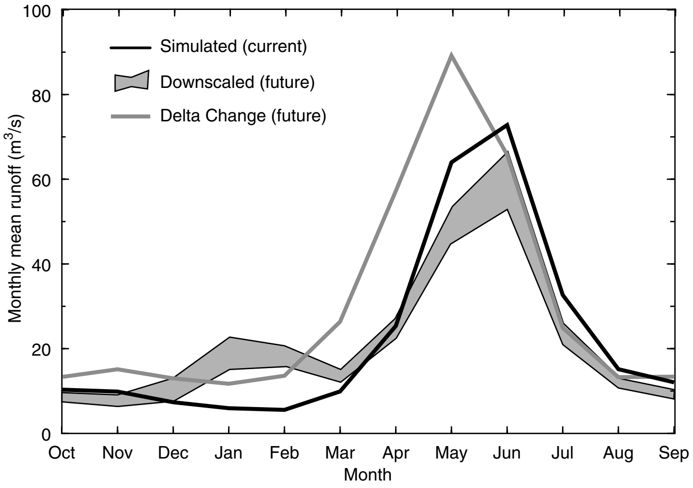

Figure 13.6: Differences in simulated runoff (m^3/s) based on a statistically downscaled climate scenario and a coarse resolution GCM scenario (labelled Delta Change) for the Animas River Basin in Colorado (modified from Hay *et al*., 1999). The downscaled range (grey area) is based on twenty ensembles.

A number of crop model simulations have been performed to determine the sensitivity of crop yields to incremental changes in daily and interannual variability (Barrow and Semenov, 1995; Mearns, 1995; Mearns *et al*., 1996; Riha *et al*., 1996; Wang and Erda, 1996; Vinocur et al., 2000). In most of these studies, changes in variability resulted in significant changes in crop yield. For example, Wang and Erda (1996) combined systematic incremental changes in daily variance of temperature and precipitation with mean climate scenarios in their study of climate change and corn yields in China. They found that increases in the variance of temperature and precipitation combined, further decreased crop yields compared to the effect of the mean change scenarios alone taken from several GCMs.

Studies using the variance changes in addition to mean changes from climate models to form climate scenarios also emerged in the past decade (Kaiser *et al*., 1993; Bates *et al*. 1994). For example, Bates *et al*. (1994, 1996) adapted Wilks' (1992) method and applied it to changes in daily variability from doubled CO_2 runs of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) climate model (CSIRO9). They then applied the changed time-series to a hydrological model. Combined changes in mean and variability are also evident in a broad suite of statistical downscaling methods (e.g., Katz and Parlange, 1996; Wilby *et al*., 1998). See also Chapter 10, Section 10.6.3, for further discussion of statistical downscaling and changes in variability.

In recent years, more robust and physically meaningful changes in climatic variability on daily to interannual time scales have been found in runs of GCMs and RCMs for some regions (e.g., Gregory and Mitchell, 1995; Mearns *et al*., 1995a,b; Whetton *et al*., 1998a; Mearns, 1999; Boer *et al*., 2000). For example, on both daily and interannual time-scales many models simulate temperature variability decreases in winter and increases in summer in northern mid-latitude land areas (see Chapter 9, Section 9.3). This result is likely to encourage the further application of model-derived variability changes in climate scenario construction.

The most useful studies, from the point of view of elucidating uncertainty in climate scenarios and impacts, are those that compare applying scenarios with only mean changes to those with mean and variability change. Semenov and Barrow (1997) and Mearns *et al*. (1997) used mean and variance changes from climate models, formed scenarios of climate change using weather generators and applied them to crop models. In both studies important differences in the impacts of climatic change on crop yields were calculated when including the effect of variance change, compared to only considering mean changes. They identified three key aspects of changed climate relevant to the role played by change in daily to interannual variability of climate: the marginality of the current climate for crop growth, the relative size of the mean and variance changes, and the timing of these changes.

It is difficult to generalise the importance of changes in variability to climate change impacts since significance of changes in variability is region, variable, and resource system specific. For example, based on results of equilibrium control and $2\times CO_2$ experiments of DARLAM (a regional model developed in Australia) nested within the CSIRO climate model over New South Wales, Whetton *et al*. (1998a) emphasised that most of the change in temperature extremes they calculated resulted from changes in the mean, not through change in the daily variance. In contrast, Mearns (1999) found large changes (e.g., decreases in winter) in daily variance of temperature in control and $2\times CO_2$ experiments with a regional climate model (RegCM2) over the Great Plains of the U.S. (Giorgi *et al*., 1998). These changes were sufficient to make a significant difference in the frequency of daily temperature extremes. Note, however, that these results are not contradictory since they concern two very different regions. More generalised statements may be made regarding the importance of change in the variability of precipitation from climate change experiments for determining changes in the frequency of droughts and floods (e.g., Gregory *et al*., 1997; Kothavala, 1999). As noted in Chapters 9 and 10, high intensity rainfall events are expected to increase in general, and precipitation variability would be expected to increase where mean precipitation increases.

Other types of variance changes, on an interannual time-scale, based on changes in major atmospheric circulation oscillations, such as ENSO and North Atlantic Oscillation (NAO), are difficult to incorporate into impact assessments. The importance of the variability of climate associated with ENSO phases for resources systems such as agriculture and water resources have been well demonstrated (e.g., Cane *et al*., 1994; Chiew *et al.*, 1998; Hansen *et al*., 1998).

Where ENSO signals are strong, weather generators can be successfully conditioned on ENSO phases; and therein lies the potential for creating scenarios with changes in the frequency of ENSO events. By conditioning on the phases, either discretely (Wang and Connor, 1996) or continuously (Woolhiser *et al*., 1993), a model can be formed for incorporating changes in the frequency and persistence of such events, which would then induce changes in the daily (and interannual) variability of the local climate sites. Weather generators can also be successfully conditioned using NAO signals (e.g., Wilby, 1998). However, it must be noted that there remains much uncertainty in how events such as ENSO might change with climate change (Knutson, *et al*., 1997; Timmerman *et al*., 1999; Walsh *et al*., 1999; see also Chapter 9, Section 9.3.5, for further discussion on possible changes in ENSO events). While there is great potential for the use of conditioned stochastic models in creating scenarios of changed variability, to date, no such scenario has actually been applied to an impact model.

13.4.2.2 Other techniques for incorporating extremes into climate scenarios

While the changes in both the mean and higher order statistical moments (e.g., variance) of time-series of climate variables affect the frequency of relatively simple extremes (e.g., extreme high daily or monthly temperatures, damaging winds), changes in the frequency of more complex extremes are based on changes in the occurrence of complex atmospheric phenomena (e.g., hurricanes, tornadoes, ice storms). Given the sensitivity of many exposure units to the frequency of extreme climatic events (see Chapter 3 of TAR WG II, Table 3.10 (Carter and La Rovere, 2001)), it would be desirable to incorporate into climate scenarios the frequency and intensity of some composite atmospheric phenomena associated with impacts-relevant extremes.

More complex extremes are difficult to incorporate into scenarios for the following reasons: (1) high uncertainty on how they may change (e.g., tropical cyclones); (2) the extremes may not be represented directly in climate models (e.g., ice storms); and (3) straightforward techniques of how to incorporate changes at a particular location have not been developed (e.g., tropical cyclone intensity at Cairns, Australia).

The ability of climate models to adequately represent extremes partially depends on their spatial resolution (Skelly and Henderson-Sellers, 1996; Osborn, 1997; Mearns, 1999). This is particularly true for complex atmospheric phenomena such as hurricanes (see Chapter 10, Box 10.2). There is some very limited information on possible changes in the frequency and intensity of tropical cyclones (Bengtsson *et al*., 1996; Henderson-Sellers *et al*., 1998; Krishnamurti *et al*., 1998; Knutson and Tuleya, 1999; Walsh and Ryan, 2000); and of mid-latitude cyclones (Schubert *et al*., 1998), but these studies are far from definitive (see Chapter 9, Section 9.3.6, and Chapter 10 for discussion on changes of extremes with changes in climate).

In the case of extremes that are not represented at all in climate models, secondary variables may sometimes be used to derive them. For example, freezing rain, which results in ice storms, is not represented in climate models, but frequencies of daily minimum temperatures on wet days might serve as useful surrogate variables (Konrad, 1998).

An example of an attempt to incorporate such complex changes into climate scenarios is the study of McInnes *et al*. (2000), who developed an empirical/dynamical model that gives return period versus height for tropical cyclone-related storm surges for Cairns on the north Australian coast. To determine changes in the characteristics of cyclone intensity, they prepared a climatology of tropical cyclones based on data drawn from a much larger area than Cairns locally. They incorporated the effect of climate change by modifying the parameters of the Gumbel distribution of cyclone intensity based on increases in tropical cyclone intensity derived from climate model results over a broad region characteristic of the location in question. Estimates of sea level rise also contributed to the modelled changes in surge height. Other new techniques for incorporating such complex changes into quantitative climate scenarios are yet to be developed.

13.5 Representing Uncertainty in Climate Scenarios

13.5.1 Key Uncertainties in Climate Scenarios

Uncertainties about future climate arise from a number of different sources (see Figure 13.2) and are discussed extensively throughout this volume. Depending on the climate scenario construction method, some of these uncertainties will be explicitly represented in the resulting scenario(s), while others will be ignored (Jones, 2000a). For example, scenarios that rely on the results from GCM experiments alone may be able to represent some of the uncertainties that relate to the modelling of the climate response to a given radiative forcing, but might not embrace uncertainties caused by the modelling of atmospheric composition for a given emissions scenario, or those related to future land-use change. Section 13.5.2 therefore assesses different approaches for representing uncertainties in climate scenarios. First, however, five key sources of uncertainty, as they relate to climate scenario construction, are very briefly described. Readers are referred to the relevant IPCC chapters for a comprehensive discussion.

13.5.1.1 Specifying alternative emissions futures

In previous IPCC Assessments, a small number of future greenhouse gas and aerosol precursor emissions scenarios have been presented (e.g., Leggett *et al*., 1992). In the current Assessment, a larger number of emissions scenarios have been constructed in the Special Report on Emissions Scenarios (SRES) (Nakićenović *et al*., 2000), and the uncertain nature of these emissions paths have been well documented (Morita and Robinson, 2001). Climate scenarios constructed from equilibrium GCM experiments alone (e.g., Howe and Henderson-Sellers, 1997; Smith and Pitts, 1997) do not consider this uncertainty, but some assumption about the driving emissions scenario is required if climate scenarios are to describe the climate at one or more specified times in the future. This source of uncertainty is quite often represented in climate scenarios (e.g., Section 13.5.2.1).

13.5.1.2 Uncertainties in converting emissions to concentrations

It is uncertain how a given emissions path converts into atmospheric concentrations of the various radiatively active gases or aerosols. This is because of uncertainties in processes relating to the carbon cycle, to atmospheric trace gas chemistry and to aerosol physics (see Chapters 3, 4 and 5). For these uncertainties to be reflected in climate scenarios that rely solely on GCM outputs, AOGCMs that explicitly simulate the various gas cycles and aerosol physics are needed. At present, however, they are seldom, if ever, represented in climate scenarios.

13.5.1.3 Uncertainties in converting concentrations to radiative forcing

Even when presented with a given greenhouse gas concentration scenario, there are considerable uncertainties in the radiative forcing changes, especially aerosol forcing, associated with changes in atmospheric concentrations. These uncertainties are discussed in Chapters 5 and 6, but again usually remain unrepresented in climate scenarios.

13.5.1.4 Uncertainties in modelling the climate response to a given forcing

An additional set of modelling uncertainties is introduced into climate scenarios through differences in the global and regional climate responses simulated by different AOGCMs for the same forcing. Different models have different climate sensitivities (see Chapter 9, Section 9.3.4.1), and this remains a key source of uncertainty for climate scenario construction. Also important is the fact that different GCMs yield different regional climate change patterns, even for similar magnitudes of global warming (see Chapter 10). Furthermore, each AOGCM simulation includes not only the response (i.e., the "signal") to a specified forcing, but also an unpredictable component (i.e., the "noise") that is due to internal climate variability. This latter may itself be an imperfect replica of true climate variability (see Chapter 8). A fourth source of uncertainty concerns important processes that are missing from most model simulations. For instance AOGCM-based climate scenarios do not usually allow for the effect on climate of future land use and land cover change (which is itself, in part, climatically induced). Although the first two sources of model uncertainty − different climate sensitivities and regional climate change patterns – are usually represented in climate scenarios, it is less common for the third and fourth sources of uncertainty – the variable signal-to-noise ratio and incomplete description of key processes and feedbacks – to be effectively treated.

13.5.1.5 Uncertainties in converting model response into inputs for impact studies

Most climate scenario construction methods combine model-based estimates of climate change with observed climate data (Section 13.3). Further uncertainties are therefore introduced into a climate scenario because observed data sets seldom capture the full range of natural decadal-scale climate variability, because of errors in gridded regional or global baseline climate data sets, and because different methods are used to combine model and observed climate data. These uncertainties relating to the use of observed climate data are usually ignored in climate scenarios. Furthermore, regionalisation techniques that make use of information from AOGCM and RCM experiments to enhance spatial and temporal scales introduce additional uncertainties into regional climate scenarios (their various advantages and diasdvantages are assessed in Chapter 10 and in Section 13.4). These uncertainties could be quantified by employing a range of regionalisation techniques, but this is rarely done.

13.5.2 Approaches for Representing Uncertainties

There are different approaches for representing each of the above five generic sources of uncertainty when constructing climate scenarios. The cascade of uncertainties, and the options for representing them at each of the five stages, can result in a wide range of climate outcomes in the finally constructed scenarios (Henderson-Sellers, 1996; Wigley, 1999; Visser *et al*., 2000). Choices are most commonly made at the stage of modelling the climate response to a given forcing, where it is common for a set of climate scenarios to include results from different GCMs. In practice, this sequential and conditional approach to representing uncertainty in climate scenarios has at least one severe limitation: at each stage of the cascade, only a limited number of the conditional outcomes have been explicitly modelled. For example, GCM experiments have used one, or only a small number, of the concentration scenarios that are plausible (for example, most transient AOGCM experiments that have been used for climate scenarios adopted by impacts assessments have been forced with a scenario of a 1% per annum growth in greenhouse gas concentration). Similarly, regionalisation techniques have been used with only a small number of the GCM experiments that have been conducted. These limitations restrict the choices that can be made in climate scenario construction and mean that climate scenarios do not fully represent the uncertainties inherent in climate prediction.

In order to overcome some of these limitations, a range of techniques has been developed to allow more flexible treatment of the entire cascade of uncertainty. These techniques manipulate or combine different modelling results in a variety of ways. If we are truly to assess the risk of climate change being dangerous, then impact and adaptation studies need scenarios that span a very substantial part of the possible range of future climates (Pittock, 1993; Parry *et al*., 1996; Risbey, 1998; Jones, 1999; Hulme and Carter, 2000). The remainder of this section assesses four aspects of climate scenario development that originate from this concern about adequately representing uncertainty:

1. scaling climate response patterns across a range of forcing scenarios;
2. defining appropriate climate change signals;
3. risk assessment approaches;
4. annotation of climate scenarios to reflect more qualitative aspects of uncertainty.

13.5.2.1 Scaling climate model response patterns

Pattern-scaling methods allow a wider range of possible future forcings (e.g., the full range of IS92 (Leggett *et al*., 1992) or SRES emissions scenarios) and climate sensitivities (e.g., the 1.5ºC to 4.5ºC IPCC range) to be represented in climate scenarios than if only the direct results from GCM experiments were used. The approach involves normalising GCM response patterns according to the global mean temperature change (although in some cases zonal mean temperature changes have been used). These normalised patterns are then rescaled using a scalar derived from simple climate models and representing the particular scenario under consideration.

This pattern-scaling method was first suggested by Santer *et al*. (1990) and was employed in the IPCC First Assessment Report to generate climate scenarios for the year 2030 (Mitchell *et al*., 1990) using patterns from 2×CO_2 GCM experiments. It has subsequently been widely adopted in climate scenario generators (CSGs), for example in ESCAPE (Rotmans *et al*., 1994), IMAGE-2 (Alcamo *et al*., 1994), SCENGEN (Hulme *et al*., 1995a,b), SILMUSCEN (Carter *et al*., 1995, 1996a), COSMIC (Schlesinger *et al*., 1997) and CLIMPACTS (Kenny *et al*., 2000). A climate scenario generator is an integrated suite of simple models that takes emissions or forcing scenarios as inputs and generates geographically distributed climate scenarios combining response patterns of different greenhouse gases from GCMs with observational climate data. CSGs allow multiple sources of uncertainty to be easily represented in the calculated scenarios, usually by using pattern-scaling methods.

Two fundamental assumptions of pattern-scaling are, first, that the defined GCM response patterns adequately depict the climate "signal" under anthropogenic forcing (see Section 13.5.2.2) and, second, that these response patterns are representative across a wide range of possible anthropogenic forcings. These assumptions have been explored by Mitchell *et al*. (1999) who examined the effect of scaling decadal, ensemble mean temperature and precipitation patterns in the suite of HadCM2 experiments. Although their response patterns were defined using only 10-year means, using four-member ensemble means improved the performance of the technique when applied to reconstructing climate response patterns in AOGCM experiments forced with alternative scenarios (see Figure 13.7). This confirmed earlier work by Oglesby and Saltzman (1992), among others, who demonstrated that temperature response patterns derived from equilibrium GCMs were fairly uniform over a wide range of concentrations, scaling linearly with global mean temperature. The main exception occurred in the

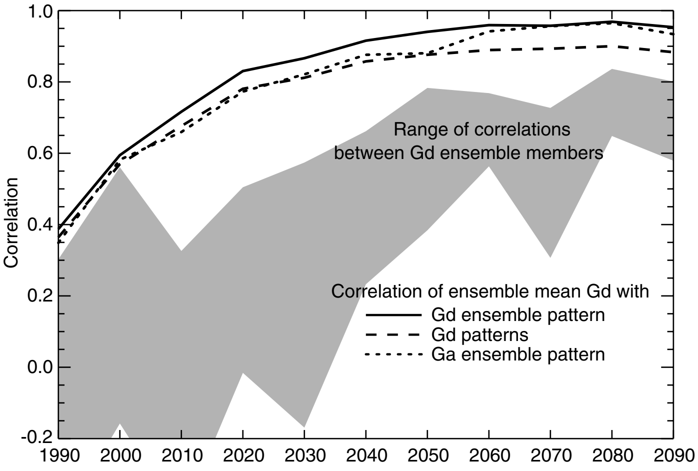

Figure 13.7: Pattern correlations between the decadal ensemble mean temperature (Northern Hemisphere only) from the HadCM2 experiment forced with a 0.5%/yr increase in greenhouse gas concentrations (Gd) and: the scaled ensemble mean pattern (solid line); the four scaled individual ensemble member patterns – average coefficient (dashed line); and the scaled ensemble mean pattern derived from the HadCM2 experiment forced with a 1%/yr increase in greenhouse gas concentrations (Ga) (dotted line). The correlations increase with time as the pattern of greenhouse gas response (the "signal") increasingly dominates the random effects of internal climate variability (the "noise"). The shaded area shows the spread of correlations between the pairs of the individual members of the Gd ensemble; these correlations are lower than those between the realised and scaled patterns above, indicating that the scaled pattern is not due to internal climate variability. (Source: Mitchell *et al.*, 1999.)

regions of enhanced response near sea ice and snow margins. Mitchell *et al.* (1999) concluded that the uncertainties introduced by scaling ensemble decadal mean temperature patterns across different forcing scenarios are smaller than those due to the model's internal variability, although this conclusion may not hold for variables with high spatial variability such as precipitation.

Two situations where the pattern-scaling techniques may need more cautious application are in the cases of stabilisation forcing scenarios and heterogenous aerosol forcing. Whetton *et al.* (1998b) have shown that for parts of the Southern Hemisphere a highly non-linear regional rainfall response was demonstrated in an AOGCM forced with a stabilisation scenario, a response that could not easily be handled using a linear pattern-scaling technique. In the case of heterogeneous forcing, similar global mean warmings can be associated with quite different regional patterns, depending on the magnitude and pattern of the aerosol forcing. Pattern-scaling using single global scalars is unlikely to work in such cases. There is some evidence, however, to suggest that separate greenhouse gas and aerosol response patterns can be assumed to be additive (Ramaswamy and Chen, 1997) and pattern-scaling methods have subsequently been adapted by Schlesinger *et al.* (1997, 2000) for the case of heterogeneously forced scenarios. This is an area, however, where poor signal-to-noise ratios hamper the application of the technique and caution is advised.

The above discussion demonstrates that pattern-scaling techniques provide a low cost alternative to expensive AOGCM and RCM experiments for creating a range of climate scenarios that embrace uncertainties relating to different emissions, concentration and forcing scenarios and to different climate model responses. The technique almost certainly performs best in the case of surface air temperature and in cases where the response pattern has been constructed so as to maximise the signal-to-noise ratio. When climate scenarios are needed that include the effects of sulphate aerosol forcing, regionally differentiated response patterns and scalars must be defined and signal-to-noise ratios should be quantified. It must be remembered, however, that while these techniques are a convenient way of handling several types of uncertainty simultaneously, they introduce an uncertainty of their own into climate scenarios that is difficult to quantify. Little work has been done on exploring whether patterns of change in inter-annual or inter-daily climate variability are amenable to scaling methods.

13.5.2.2 Defining climate change signals

The question of signal-to-noise ratios in climate model simulations was alluded to above, and has also been discussed in Chapters 9 and 12. The treatment of "signal" and "noise" in constructing climate scenarios is of great importance in interpreting the results of impact assessments that make use of these scenarios. If climate scenarios contain an unspecified combination of signal plus noise, then it is important to recognise that the impact response to such scenarios will only partly be a response to anthropogenic climate change; an unspecified part of the impact response will be related to natural internal climate variability. However, if the objective is to specify the impacts of the anthropogenic climate signal alone, then there are two possible strategies for climate scenario construction:

- attempt to maximise the signal and minimise the noise;
- do not try to disentangle signal from noise, but supply impact assessments with climate scenarios containing both elements and also companion descriptions of future climate that contain only noise, thus allowing impact assessors to generate their own impact signal-to-noise ratios (Hulme *et al.*, 1999a).

The relative strength of the signal-to-noise ratio can be demonstrated in a number of ways. Where response patterns are reasonably stable over time, this ratio can be maximised in a climate change scenario by using long (30-year or more) averaging periods. Alternatively, regression or principal component techniques may be used to extract the signal from the model response (Hennessy *et al.*, 1998). A third technique is to use results from multi-member ensemble simulations, as first performed by Cubasch *et al.* (1994). Sampling theory shows that in such simulations the noise is reduced by a factor of $\sqrt{(n)}$, where n is the ensemble size. Using results from the HadCM2 four-member ensemble experiments, Giorgi and Francisco (2000), for example, suggest that uncertainty in future regional climate change associated with internal climate variability at sub-continental scales (10^7 km^2), is generally smaller than the

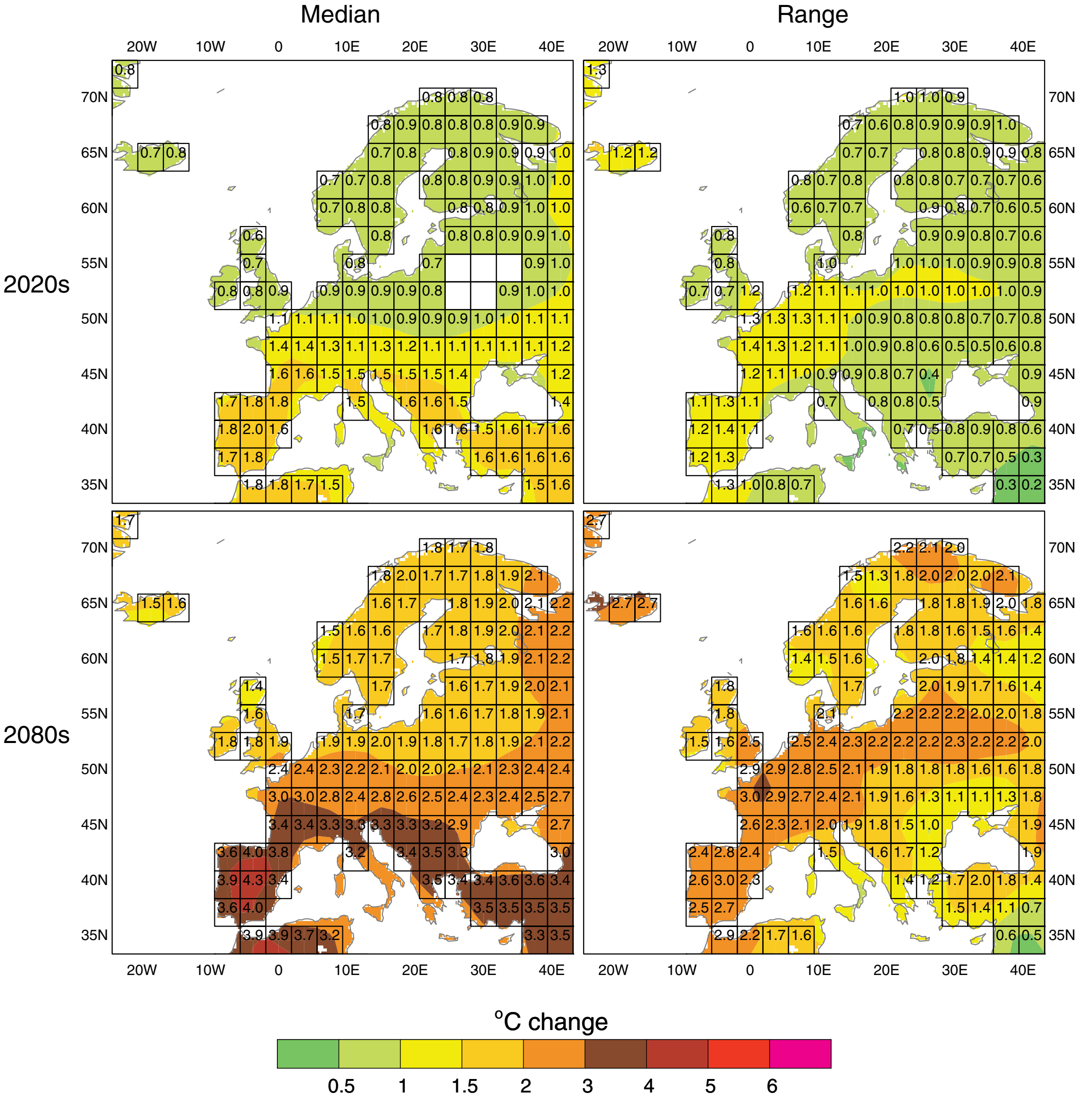

Figure 13.8: A summer (JJA) temperature change scenario for Europe for the 2020s and 2080s. Left panel is the median scaled response of five GCM experiments available on the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/) and the right panel is the inter-model range (largest scaled response minus the smallest scaled response). (Source: Hulme and Carter, 2000.)

uncertainty associated with inter-model or forcing differences. This conclusion is scale- and variable-dependent, however (see Chapter 9, Figure 9.4; see also Räisänen, 1999), and the inverse may apply at the smaller scales (10^4 to 10^5 km^2) at which many impact assessments are conducted. Further work is needed on resolving this issue for climate scenario construction purposes.

A different way of maximising the climate change signal is to compare the responses of single realisations from experiments completed using different models. If the error for different models is random with zero mean, then sampling theory shows that this model average will yield a better estimate of the signal than any single model realisation. This approach was first suggested in the context of climate scenarios by Santer *et al.* (1990) and is illustrated further in Chapter 9, Section 9.2.2. Treating different GCM simulations in this way, i.e., as members of a multi-model ensemble, is one way of defining a more robust climate change signal, either for use in pattern-scaling techniques or directly in constructing a climate scenario. The approach has been discussed by Räisänen (1997) and used recently by Wigley (1999), Hulme and Carter (2000; see Figure 13.8) and Carter *et al.* (2000b) in providing regional characterisations of the SRES emissions scenarios.

The second strategy requires that the noise component be defined explicitly. This can be done by relying either on observed climate data or on model-simulated natural climate variability (Hulme *et al.*, 1999a; Carter *et al.*, 2000b). Neither approach is ideal. Observed climate data may often be of short duration and therefore yield a biased estimate of the noise. Multi-decadal internal climate variability can be extracted from multi-century unforced climate simulations such as those performed by a number of modelling groups (e.g., Stouffer *et al.*, 1994; Tett *et al.*, 1997; von Storch *et al.*, 1997). In using AOGCM output in this way, it is important not only to demonstrate that these unforced simulations do not drift significantly (Osborn, 1996), but also to evaluate the extent to which model estimates of low-frequency variability are comparable to those estimated from measured climates (Osborn *et al*., 2000) or reconstructed palaeoclimates (Jones *et al*., 1998). Furthermore, anthropogenic forcing may alter the character of multi-decadal climate variability and therefore the noise defined from model control simulations may not apply in the future.

13.5.2.3 Risk assessment approaches

Uncertainty analysis is required to perform quantitative risk or decision analysis (see Toth and Mwandosya (2001) for discussion of decision analysis). By itself, scenario analysis is not equivalent to uncertainty analysis because not all possible scenarios are necessarily treated and, especially, because probabilities are not attached to each scenario (see Morgan and Henrion (1990) for a general treatment of uncertainty analysis; see Katz (2000) for a more recent overview focusing on climate change). Recognising this limitation, a few recent studies (Jones, 2000b; New and Hulme, 2000) have attempted to modify climate scenario analysis, grouping a range of scenarios together and attaching a probability to the resultant classes. Such an approach can be viewed as a first step in bridging the gap between scenario and uncertainty analysis. Single climate scenarios, by definition, are limited to plausibility with no degree of likelihood attached. Since risk analysis requires that probabilities be attached to each climate scenario, subjective probabilities can be applied to the input parameters that determine the climate outcomes (e.g., emissions scenarios, the climate sensitivity, regional climate response patterns), thus allowing distributions of outcomes to be formally quantified.

In formal risk analysis, the extremes of the probability distribution should encompass the full range of possible outcomes, although in climate change studies this remains hard to achieve. The ranges for global warming and sea level rise from the IPCC WGI Second Assessment Report (IPCC, 1996) (hereafter SAR), for example, deliberately did not encompass the full range of possible outcomes and made no reference to probability distributions. As a consequence, the bulk of impact assessments have treated these IPCC ranges as having a uniform probability, i.e., acting as if no information is available about what changes are more likely than others. As pointed out by Titus and Narayanan (1996), Jones (1998, 2000a), and Parkinson and Young (1998), however, where several sources of uncertainty are combined, the resulting probability distribution is not uniform but is a function of the component probability distributions and the relationship between the component elements. For example, descriptions of regional changes in temperature and rainfall over Australia constructed from regional response patterns have been used in a number of hydrological studies where the extreme outcomes have been considered as likely as outcomes in the centre of the range (e.g., Chiew *et al*., 1995; Schreider *et al*., 1996; Whetton, 1998). However, when the two component ranges – global warming and normalised local temperature and rainfall change – are randomly sampled and then multiplied together, they offer a distinctly non-uniform distribution (see Figure 13.9a). Further refinements of these approaches for quantifying the risk of climate change are needed (New and Hulme, 2000).

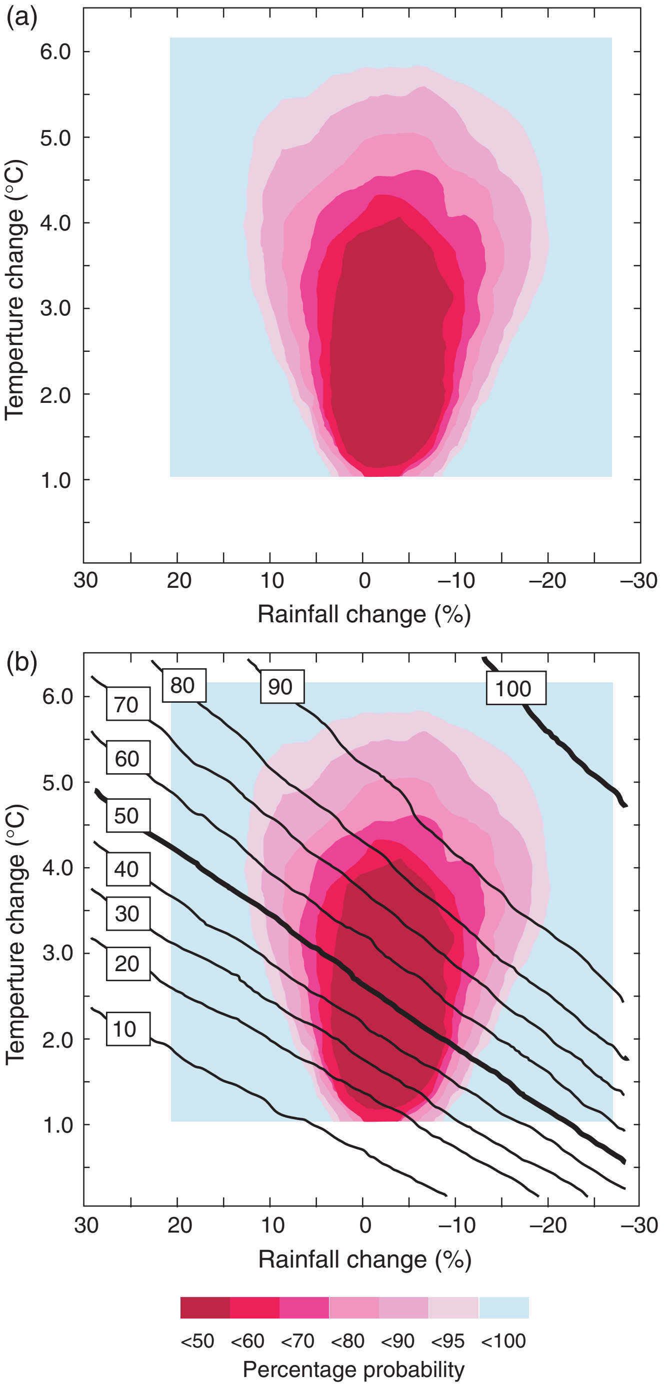

Figure 13.9: (a) Projected ranges of regional annual temperature and rainfall change for inland southern Australia in 2100 extrapolated from CSIRO (1996) with temperature sampled randomly across the projected ranges of both global and normalised regional warming and then multiplied together. Projected regional ranges for normalised seasonal rainfall change were randomly sampled, multiplied by the randomly sampled global warming as above, and then averaged. The resulting probability density surface reveals the likelihood of different climate change outcomes for this region; (b) Response surface of irrigation demand for the same region superimposed on projected climate changes as (a), showing the likelihood of exceeding an annual allocation of irrigation water supply. Risk can be calculated by summing the probabilities of all climates below a given level of annual exceedance of annual water supply; e.g., 50%, or exceedance of the annual water limit in at least one of every two years. (Source: Jones, 2000b.)

This approach to portraying uncertainty has potentially useful applications when combined with climate impact sensitivity response surfaces (see Section 13.2.1; see also Chapter 3 of TAR WG II (Carter and La Rovere, 2001)). The superimposed response surfaces allow the calculation of probabilities for exceeding particular impact thresholds (Figure 13.9b). Another method of assessing risk using quantified probability distributions is through a series of linked models such as those used for calculating sea level rise (Titus and Narayanan, 1996) and economic damage due to sea level rise (Yohe and Schlesinger, 1998), for quantifying climate uncertainty (Visser *et al*., 2000), and in integrated assessments (Morgan and Dowlatabadi, 1996). Efforts to make explicit probabilistic forecasts of the climate response to a given emissions scenario for the near future have been made using the current observed climate trajectory to constrain the "forecasts" from several GCMs (Allen *et al.,* 2000). More details on this technique are given in Section 12.4.3.3.

13.5.2.4 Annotation of climate scenarios

Even if quantifiable uncertainties are represented, further uncertainties in climate scenarios may still need to be documented or explicitly treated. These include the possible impact on scenarios of errors in the unforced model simulation, the possibility that current models cannot adequately simulate the enhanced greenhouse response of a climatic feature of interest, or inconsistencies between results of model simulations and emerging observed climatic trends. For these reasons climate scenarios are often annotated with a list of caveats, along with some assessment as to their importance for the scenario user.

When choosing which GCM(s) to use as the basis for climate scenario construction, one of the criteria that has often been used is the ability of the GCM to simulate present day climate. Many climate scenarios have used this criterion to assist in their choice of GCM, arguing that GCMs that simulate present climate more faithfully are likely to simulate more plausible future climates (e.g., Whetton and Pittock, 1991; Robock *et al*., 1993; Risbey and Stone, 1996; Gyalistras *et al*., 1997; Smith and Pitts, 1997; Smith and Hulme, 1998; Lal and Harasawa, 2000). A good simulation of present day climate, however, is neither a necessary nor a sufficient condition for accurate simulation of climate change (see Chapter 8). It is possible, for example, that a model with a poor simulation of present day climate could provide a more accurate simulation of climate change than one which has a good simulation of present climate, if it contains a better representation of the dominant feedback processes that will be initiated by radiative forcing. While such uncertainties are difficult to test, useful insights into the ability of models to simulate long-term climate change can also be obtained by comparing model simulations of the climate response to past changes in radiative forcing against reconstructed paleoclimates.

This approach to GCM selection, however, raises a number of questions. Over which geographic domain should the GCM be evaluated – the global domain or only over the region of study? Which climate variables should be evaluated – upper air synoptic features that largely control the surface climate, or only those climate variables, mostly surface, that are used in impact studies? Recent AOGCMs simulate observed 1961 to 1990 mean climate more faithfully than earlier GCMs (Kittel *et al*., 1998; see also Chapter 8), but they still show large errors in simulating inter-annual climate variability in some regions (Giorgi and Francisco, 2000; Lal *et al*., 2000) and in replicating ENSO-like behaviour in the tropics (Knutson *et al*., 1997). These questions demonstrate that there is no easy formula to apply when choosing GCMs for climate scenario construction; there will always be a role for informed but, ultimately, individual judgement. This judgement, however, should be made not just on empirical grounds (for example, which model's present climate correlates best with observations) but also on the basis of understanding the reasons for good or bad model performance, particularly if those reasons are important for the particular scenario application.

Several examples of such annotations can be given. Lal and Giorgi (1997) suggested that GCMs that cannot simulate the observed interannual variability of the Indian monsoon correctly should not be used as the basis for climate scenarios. Giorgi *et al*. (1998) commented that model-simulated spring temperatures over the USA Central Plains were too cold in both the CSIRO GCM and in the CSIRO-driven RegCM2 control simulations and affected the credibility of the ensuing temperature climate scenarios. Finally, scenarios prepared for the Australian region have often been accompanied by the note that ENSO is an important component of Australian climate that may change in the future, but that is not yet adequately simulated in climate models (e.g., Hennessy *et al*., 1998). Expert judgment can also be used to place confidence estimates on scenario ranges (Morgan and Keith, 1995). For example, Jones *et al*. (2000) placed "high confidence" on the temperature scenarios (incorporating quantifiable uncertainty) prepared for the South Pacific, but only "moderate to low confidence" in the corresponding rainfall scenarios.

13.6 Consistency of Scenario Components

This section discusses some of the caveats of climate scenario development and focuses on the need for consistency in representing different physical aspects of the climate system. It does not discuss the many possible inconsistencies with respect to socio-economic issues in scenario development. Chapter 3 of the TAR WG II (Carter and La Rovere, 2001) and Chapter 2 of the TAR WG III (Morita and Robinson, 2001) provide a detailed treatment of these issues. Three common inconsistencies in applying climate scenarios are discussed, concerning the representation of ambient versus equivalent CO_2 concentrations, biosphere-ocean-atmosphere interactions and time lags between sea level rise and temperature change.

The climate system consists of several components that interact with and influence each other at many different temporal and spatial scales (see Chapter 7). This complexity adds further constraints to the development of climate scenarios, though their relevance is strongly dependent on the objectives and scope of the studies that require scenarios. Most climate scenarios are based on readily available climate variables (e.g., from AOGCMs) and, where these are used in impact assessments, studies are often restricted to an analysis of the effects of changes in climate alone. However, other related environmental aspects may also change, and these are often neglected or inadequately represented, thus potentially reducing the comprehensiveness of the impact assessment. Furthermore, some feedback processes that are seldom considered in AOGCM simulations, may modify regional changes in climate (e.g., the effect of climate-induced shifts in vegetation on albedo and surface roughness).

Concurrent changes in atmospheric concentrations of gases such as CO_2, sulphur dioxide (SO_2) and ozone (O_3) can have important effects on biological systems. Studies of the response of biotic systems require climate scenarios that include consistent information on future levels of these species. For example, most published AOGCM simulations have used CO_2-equivalent concentrations to represent the combined effect of the various gases. Typically, only an annual 1% increase in CO_2-equivalent concentrations, which approximates changes in radiative forcing of the IS92a emission scenario (Leggett *et al*., 1992), has been used. However, between 10 and 40% of this increase results from non-CO_2 greenhouse gases (Alcamo *et al*., 1995). The assumption that CO_2 concentrations equal CO_2-equivalent concentrations (e.g., Schimel *et al*., 1997; Walker *et al*., 1999) has led to an exaggeration of direct CO_2 effects. If impacts are to be assessed more consistently, proper CO_2 concentration levels and CO_2-equivalent climate forcing must be used. Many recent impact assessments that recognise these important requirements (e.g., Leemans *et al*., 1998; Prinn *et al*., 1999; Downing *et al*., 2000) make use of tools such as scenario generators (see Section 13.5.2.1) that explicitly treat atmospheric trace gas concentrations. Moreover, some recent AOGCM simulations now discriminate between the individual forcings of different greenhouse gases (see Chapter 9, Table 9.1)

The biosphere is an important control in defining changes in greenhouse gas concentrations. Its surface characteristics, such as albedo and surface roughness, further influence climate patterns. Biospheric processes, such as CO_2-sequestration and release, evapotranspiration and land-cover change, are in turn affected by climate. For example, warming is expected to result in a poleward expansion of forests (IPCC, 1996b). This would increase biospheric carbon storage, which lowers future CO_2 concentrations and change the surface albedo which would directly affect climate. A detailed discussion of the role of the biosphere on climate can be found elsewhere (Chapters 3 and 7), but there is a clear need for an improved treatment of biospheric responses in scenarios that are designed for regional impact assessment. Some integrated assessment models, which include simplifications of many key biospheric responses, are beginning to provide consistent information of this kind (e.g., Alcamo *et al*., 1996, 1998; Harvey *et al*., 1997; Xiao *et al*., 1997; Goudriaan *et al*., 1999).

Another important input to impact assessments is sea level rise. AOGCMs usually calculate the thermal expansion of the oceans directly, but this is only one component of sea level rise (see Chapter 11). Complete calculations of sea level rise, including changes in the mass balance of ice sheets and glaciers, can be made with simpler models (e.g., Raper *et al*., 1996), and the transient dynamics of sea level rise should be explicitly calculated because the responses are delayed (Warrick *et al*., 1996). However, the current decoupling of important dynamic processes in most simple models could generate undesirable inaccuracies in the resulting scenarios.

Climate scenario generators can comprehensively address some of these inconsistencies. Full consistency, however, can only be attained through the use of fully coupled global models (earth system models) that systematically account for all major processes and their interactions, but these are still under development.

References

Alcamo, J., G.J. van denBorn, A.F. Bouwman, B.J. deHaan, K. Klein Goldewijk, O. Klepper, J. Krabec, R. Leemans, J.G.J. Olivier, A.M.C. Toet, H.J.M. deVries, and H.J. van der Word, 1994: Modeling the global society-biosphere-climate system. *Water Air Soil Pollut.*, **76**, 1-78.

Alcamo, J., A. Bouwman, J. Edmonds, A. Grübler, T. Morita and A. Sugandhy, 1995: An evaluation of the IPCC IS92 emission scenarios. In: *Climate Change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. Reports of Working Groups I and III of the Intergovernmental Panel on Climate Change* [Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 247-304.

Alcamo, J., G.J.J. Kreileman, J.C. Bollen, G.J. van den Born, R. Gerlagh, M.S. Krol, A.M.C. Toet and H.J.M. de Vries, 1996: Baseline scenarios of global environmental change. *Global Environ. Change*, **6**, 261-303.

Alcamo, J., R. Leemans, and E. Kreileman (eds.), 1998: *Global Change Scenarios of the 21st Century*. Pergamon & Elseviers Science, London, UK, 296 pp.

Allen, M. R., P. A. Stott, R. Schnur, T. Delworth, and J. F. B. Mitchell, 2000: Uncertainty in forecasts of anthropogenic climate change. Nature, **407**, 617-620.

Anisimov, O.A. and F.E. Nelson, 1996: Permafrost distribution in the northern hemisphere under scenarios of climatic change. *Global Planet. Change*, **14**, 59-72.

Anisimov, O.A. and V.Yu. Poljakov, 1999: On the prediction of the air temperature in the first quarter of the XXI century. *Meteorology and Hydrology*, **2**, 25-31 (in Russian).

Arnell, N.W., 1999: A simple water balance model for the simulation of streamflow over a large geographic domain. *J. Hydrol.*, **217**, 314-335.

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

Barrow, E. M., and M. A. Semenov, 1995: Climate change scenarios with high resolution and temporal resolution and agricultural applications. *Forestry,* **68,** 349-360.

Bates, B.C., S.P. Charles, N.R. Sumner, and P.M. Fleming, 1994: Climate change and its hydrological implications for South Australia*. T. Roy. Soc. South. Aust.* **118(1),** 35-43.

Bates, B.C., A.J. Jakeman, S.P. Charles, N.R. Sumner, and P.M. Fleming, 1996: Impact of climate change on Australia's surface water resources. In: *Greenhouse: Coping with Climate Change* [Bouma, W.J., G.I. Pearman, and M.R. Manning (eds.)]. CSIRO, Melbourne, pp. 248-262.

Bengtsson, L., M. Botzet, and M. Esch, 1996: Will greenhouse gas induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus*, **48A**, 57-73.

Beniston, M. and M. Price, 1992: Climate scenarios for the Alpine regions: a collaborative effort between the Swiss National Climate Program and the International Center for Alpine Environments. *Env. Conserv*., **19**, 360-363.

Bergthórsson, P., H. Björnsson, O. Dórmundsson, B. Gudmundsson, A. Helgadóttir, and J.V. Jónmundsson, 1988: The effects of climatic variations on agriculture in Iceland. In: *The Impact of Climatic*

Variations on Agriculture, Volume 1, Assessments in Cool Temperate and Cold Regions [Parry, M.L., T.R. Carter, and N.T. Konijn (eds.)]. Kluwer, Dordrecht, The Netherlands, pp. 381-509.

Boer, G.J., G.M. Flato, and D. Ramsden, 2000: A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century. *Clim. Dyn.*, **16(6)**, 427-450.

Brown, R.A., N. J. Rosenberg, W.E. Easterling, C. Hays, and L. O. Mearns, 2000: Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the MINK region of the central United States. *Ecol. Agric. Environ.*, **78**, 31-47.

Budyko, M.I., 1989: Empirical estimates of imminent climatic changes. *Soviet Meteorology and Hydrology,* **10**, 1-8.

Cane, M.A., G. Eshel, and R.W. Buckland, 1994: Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature*, **370**, 204-205.

Carter, T., M. Posch, and H. Tuomenvirta, 1995: SILMUSCEN and CLIGEN user's guide. Guidelines for the construction of climatic scenarios and use of a stochastic weather generator in the Finnish Research Programme on Climate Change (SILMU). *Publications of the Academy of Finland,* **1/95**, 62 pp.

Carter, T.R., M. Posch, and H. Tuomenvirta, 1996a: The SILMU scenarios: specifying Finland's future climate for use in impact assessment. *Geophysica*, **32**, 235-260.

Carter, T.R., M. Parry, S. Nishioka, and H. Harasawa, 1996b: Technical Guidelines for assessing climate change impacts and adaptations. In: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowere and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 823-833.

Carter, T.R., R.A. Saarikko, and S.K.H. Joukainen, 2000a: Modelling climate change impacts on wheat and potatoes in Finland. In: *Climate Change, Climate Variability and Agriculture in Europe: An Integrated Assessment* [Downing, T.E., P.E. Harrison, R.E. Butterfield and K.G. Lonsdale (eds.)]. Research Report No. 21, ECU, University of Oxford, Oxford, UK, pp. 289-312.

Carter, T.R., M. Hulme, J.F. Crossley, S. Malyshev, M.G. New, M.E. Schlesinger and H. Tuomenvirta, 2000b: *Climate change in the 21st century: interim characterizations based on the new IPCC SRES Emissions Scenarios*. Finnish Environment Institute Report, No. 433, Helsinki, Finland, 148pp.

Carter, T.R. and E.L. La Rovere, 2001: Developing and Applying Scenarios. In *Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the IPCC Third Assessment Report.*

Chiew, F.H.S., P.H. Whetton, T.A. McMahon, and A.B. Pittock, 1995: Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. *J. Hydrol*., **167**, 121-147.

Chiew, F.H.S., T.C. Piechota, J.A. Dracup, and T.A. McMahon, 1998: El Niño Southern Oscillation and Australian rainfall, streamflow and drought—links and potential for forecasting. *J. Hydrol.*, **204**, 138-149.

Climate Impact Assessment Program (CIAP), 1975: *Impacts of Climatic Change on the Biosphere*. CIAP Monograph 5, Part 2 - Climate Effects. Department of Transportation, CIAP, Washington, D.C.

Cohen, S. J., 1990: Bringing the global warming issue closer to home: the challenge of regional impact studies. *Bull. Am. Met. Soc*., **71**, 520-526.

Covey, C., 1995: Using paleoclimates to predict future climate: how far can analogy go? *Clim. Change*, **29**, 403-407.

Crowley, T.J., 1990: Are there any satisfactory geologic analogs for a future greenhouse warming? *J. Climate*, **3**, 1282-1292.

CSIRO, 1996: OzClim: A climate scenario generator and impacts package for Australia. CSIRO, Canberra, November 1996, 4pp. [Available on line from http: //www.dar.csiro.au/publications/ozclim.htm]

Cubasch, U., K. Hasselmann, H. Hock, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer, and R. Sausen, 1992: Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Clim. Dyn.*, **8**, 55-69.

Cubasch, U., B.D. Santer, A. Hellbach, G. Hegerl, H. Höck, E. Maier-Reimer, U. Mikolajewicz, A. Stössel, and R. Voss, 1994: Monte Carlo climate change forecasts with a global coupled ocean-atmosphere model. *Clim. Dyn.*, **10**, 1-19.

Cubasch, U., J. Waszkewitz, G. Hegerl, and J. Perlwitz, 1995: Regional climate changes as simulated in time-slice experiments. *Clim. Change*, **31,** 273-304.

Daly, C., R.P. Neilson, and D.L. Phillips, 1994: A statistical-topographic model for maping climatological precipitation over mountainous terrain. *J. Appl. Met*., **33**, 140-158.

Downing, T.E., P.A. Harrison, R.E. Butterfield, and K.G. Lonsdale (eds.), 2000: *Climate Change, Climatic Variability and Agriculture in Europe: An Integrated Assessment.* Research Report No. 21, Environmental Change Unit, University of Oxford, Oxford, UK, 445 pp.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson, 1985: Climatic change and the broad-scale distribution of terrestrial ecosystem complexes**.** *Clim. Change*, **7**, 29-43.

Fagan, B. 1999: *Floods, Famines and Emperors; El Nino and the Fate of Civilizations*. Basic Books, NY, 284 pp.

Fisher, R. W., 1996: Future Energy Use. *Future Research Quarterly*, **31**, 43-47.

Fowler, A., 1999: Potential climate change impacts on water resources in the Auckland Region (New Zealand). *Clim. Res.*, **11**, 221-245.

Fox-Rabinovitz, M. S., G. Stenchikov, and L.L.Takacs, 1997: A finite-difference GCM dynamical core with a variable resolution stretched grid. *Mon. Wea. Rev*., **125**, 2943-2961.

Frei, C. and C. Schär, 1998: A precipitation climatology of the Alps from high-resolution rain-gauge observations. *Int. J. Climatol*., **18**, 873-900.

Frenzel, B., B. Pecsi, and A.A. Velichko (eds.), 1992: *Atlas of Palaeoclimates and Palaeoenvironments of the Northern Hemisphere***.** INQUA/Hungarian Academy of Sciences, Budapest.

Friend, A.D., 1998: Parameterisation of a global daily weather generator for terrestrial ecosystem modelling. *Ecol. Modelling*, **109**, 121-140.

Gates, W. L., 1985: The use of general circulation models in the analysis of the ecosystem impacts of climatic change. *Clim. Change*, **7,** 267-284.

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

Giorgi, F. and L.O. Mearns, 1999: Regional climate modeling revisited: an introduction to the special issue*. J. Geophys. Res*., **104(D6)**, 6335-6352.

Giorgi, F. and R. Francisco, 2000: Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with HadCM2 coupled AOGCM. *Clim. Dyn.*, **16**, 169-182.

Giorgi, F., L. Mearns, S. Shields, and L. McDaniel, 1998: Regional nested model simulations of present day and 2xCO_2 climate over the Central Great Plains of the United States. *Clim. Change,* **40,** 457-493.

Glantz, M., 1988: *Societal Responses to Regional Climatic Change: Forecasting by Analogy*. Westview Press, Boulder, Colorado, 77 pp.

Gleick, P.H., 1986: Methods for evaluating the regional hydrologic impacts of global climatic changes. *J. Hydrol*., **88**, 97-116.

Goudriaan, J., H.H. Shugart, H. Bugmann, W. Cramer, A. Bondeau, R.H. Gardner, L.A. Hunt, W.K. Lauwenroth, J.J. Landberg, S. Linder, I.R. Noble, W. J. Parton, L.F. Pitelka, M. Staford Smith, R.W.

Sutherst, C. Valentin and F.I. Woodward, 1999: Use of models in global change studies. In: *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems* [Walker, B., W. Steffen, J. Canadell and J. Ingram (eds.)]. Cambridge University Press, Cambridge, pp. 106-140.

Gregory, J.M. and J.F.B. Mitchell, 1995: Simulation of daily variability of surface temperature and precipitation over Europe in the current and 2xCO2 climates using the UKMO climate model. *Quart. J. R. Met. Soc.*, **121**, 1451-1476.

Gregory, J.M., J.F.B. Mitchell, and A.J. Brady, 1997: Summer drought in northern midlatitudes in a time-dependent CO2 climate experiment. *J. Climate*, **10**, 662-686.

Gyalistras, D. and A. Fischlin, 1995. Downscaling: applications to ecosystems modelling. In: *Proceedings of the 6th International Meeting on Statistical Climatology, Galway, Ireland, June 19-23, 1995* [Muirterchaigh, I. (ed.)]. University College, Galway, pp. 189-192.

Gyalistras, D., C. Schär, H.C. Davies, and H. Wanner, 1997: Future alpine climate. In: *Views from the Alps: Regional Perspectives on Climate Change* [Cebon, P., U. Dahinden, H. Davies, D.M. Imboden, and C.C. Jaeger (eds.)]. The MIT Press, Cambridge, MA, pp. 171-223.

Hammond, A., 1996: *Which World*? Island Press, Washington, D.C., 306 pp.

Hansen, J., Il Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone, 1988: Global climate changes as forecast by the GISS 3-D model. *J. Geophys. Res.*, **93(D8),** 9341-9364.

Hansen, J.W., A.W. Hodges, and J.W. Jones, 1998: ENSO influences on agriculture in the southeastern US. *J. Climate*, **11**, 404-411.

Harvey, D., J. Gregory, M. Hoffert, A. Jain, M. Lal, R. Leemans, S. Raper, T. Wigley and J. de Wolde, 1997: *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report*. Intergovernmental Panel on Climate Change, Geneva, February 1977, IPCC Technical Paper II, 50 pp.

Hassall and Associates, 1998: *Climate Change Scenarios and Managing the Scarce Water Resources of the Macquarie River*. Australian Greenhouse Office, Canberra, 113 pp.

Hay, E.L., R. B. Wilby, and G.H. Leavesy, 1999: A comparison of delta change and downscaled GCM scenarios: implications for climate change scenarios in three mountainous basins in the United States. In: *Proceedings of the AWRA Specialty conference on Potential Consequences of Climatic Variability and Change to Water Resources of the United States, May, 1999, Atlanta, GA* [Adams, D.B. (ed.)]. AWRA, Middleburg, VA, 424 pp.

Henderson-Sellers, A., 1996: Can we integrate climatic modelling and assessment? *Environ. Modeling & Assessment*, **1**, 59-70.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.L. Shieh, P. Webster, and K. McGuffie, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Am. Met. Soc*., **79**, 19-38.

Hennessy, K.J., P.H. Whetton, J.J. Katzfey, J.L. McGregor, R.N. Jones, C.M. Page, and K.C. Nguyen, 1998: *Fine Resolution Climate Change Scenarios for New South Wales*. Annual Report, 1997/98, CSIRO, Australia, 48 pp.

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

Hostetler, S., 1994: Hydrologic and atmospheric models: the problem of discordant scales: an editorial comment. *Clim. Change*, **27**, 345-350.

Howe, W. and A. Henderson-Sellers (eds.), 1997: *Assessing Climate Change*. Results from the Model Evaluation Consortium for Climate Assessment. Gordon Breach Science Publishers, Amsterdam, 418 pp.

Hulme, M. and M. New, 1997: The dependence of large-scale precipitation climatologies on temporal and spatial gauge sampling. *J.Climate*, **10**, 1099-1113.

Hulme, M. and G.J. Jenkins, 1998: *Climate change scenarios for the United Kingdom*. UKCIP Technical Note No.1, Climatic Research Unit, Norwich, UK, 80 pp.

Hulme, M. and T.R. Carter, 2000: The changing climate of Europe. Chapter 3 in: *Assessment of the Potential Effects of Climate Change in Europe* [Parry, M.L. (ed.)]. Report of the ACACIA Concerted Action, November 2000, UEA, Norwick, UK, 350 pp.

Hulme, M., T. Jiang, and T.M.L. Wigley, 1995a: *SCENGEN: A Climate Change SCENario GENerator, Software User Manual, Version 1.0*. Climatic Research Unit, University of East Anglia, Norwich, 38 pp.

Hulme, M., S.C.B. Raper, and T.M.L. Wigley, 1995b: An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy*, **23**, 347-355.

Hulme, M., E.M. Barrow, N. Arnell, P.A. Harrison, T.E. Downing, and T.C. Johns, 1999a: Relative impacts of human-induced climate change and natural climate variability. *Nature*, **397**, 688-691.

Hulme, M., J.F.B. Mitchell, W. Ingram, T.C. Johns, J.A. Lowe, M.G. New and D. Viner, 1999b: Climate change scenarios for global impacts studies. *Global Environ. Change,* **9**, S3-S19.

Hutchinson, M.F., 1995: Interpolating mean rainfall using thin-plate smoothing splines. *Int. J. Geogr. Inf. Systems*, **9**, 385-403.

IPCC, 1992: *Preliminary Guidelines for Assessing Impacts of Climate Change. Prepared by Intergovernmental Panel on Climate Change*, Working Group II for WMO and UNEP [Carter, T.R., M.L. Parry, S. Nishioka, and H. Harasawa (eds.)]. Cambridge University Press, Cambridge, United Kingdom.

IPCC, 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Prepared by Working Group II [Carter, T.R., M.L. Parry, H.Harasawa, and S. Nishioka] and WMO/UNEP. CGER-IO15-'94. University College London, UK and Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 59 pp.

IPCC, 1996a: *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 572 pp.

IPCC, 1996b: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 880 pp.

IPCC, 1997: *An introduction to simple climate models used in the IPCC Second Assessment Report* [Harvey, L.D., J. Gregory, M.Hoffert, A. Jain, M. Lal, R. Leemans, S. Raper, T. Wigley and J. de Wolde]. IPCC Technical Paper 2, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 50 pp.

IPCC, 2001: Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC-TGCIA, 1999: *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessmen*t. Version 1. Prepared by Carter, T.R., M. Hulme, and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment. Cambridge University Press, Cambridge, United Kingdom, 69 pp.

Jendritzky, G. and B. Tinz, 2000: Human bioclimate maps for climate impact research. In: *Proceedings of Int. Conf. Biomet and Int. Conf. Urban Climate.* ICB-ICUC '99, Sidney, 8-12 November 1999 (in press).

Jones, R.N., 1998: Climate change scenarios, impact thresholds and risk. In*: Proceedings of the Workshop on Impacts of Global Change on Australian Temperate Forests* [Gorman, J. and S.M. Howden (eds.)]. February 1998, CSIRO Wildlife and Ecology, Canberra, Australia, pp. 14-28.

Jones, R.N., 1999: Climate change scenarios, impact thresholds and risk. In: *Impacts of Global Change on Australian Temperate Forests* [Howden, S.M. and J. Gorman (eds.)]. Working Paper Series 99/08, Resource Future Program, CSIRO Wildlife and Ecology, Canberra, Australia, pp. 40-52.

Jones, R.N., 2000a: Managing uncertainty in climate change projections-issues for impact assessment. *Clim. Change,* **45(3/4)**, 403-419.

Jones, R.N., 2000b: Analyzing the risk of climate change using an irrigation demand model. *Clim. Res.*, **14**, 89-100.

Jones, P.D., K.R. Briffa, T.P. Barnett, and S.F.B. Tett, 1998: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with GCM control-run temperatures. *The Holocene*, **8**, 455-471.

Jones, R.N., K.J. Hennessy, and D.J. Abbs, 1999: *Climate Change Analysis Relevant to Jabiluka*, Attachment C. Assessment of the Jabiluka Project, Report of the Supervising Scientist to the World Heritage Committee. Environment Australia, Canberra.

Jones, R.N., K.J. Hennessy, C.M. Page, A.B. Pittock, R. Suppiah, K.J.E. Walsh, and P.H. Whetton, 2000: *An analysis of the effects of the Kyoto Protocol on Pacific Island countries. Part 2: regional climate change scenarios and risk assessment methods*. South Pacific Regional Environment Programme, Apia, Western Samoa (in press).

Kaiser, H.M., S.J. Riha, D.S. Wilks, D.G. Rossiter, and R. Sampath, 1993: A farm-level analysis of economic and agronomic impacts of gradual climate warming. *Am. J. Ag. Econ.*, **75**, 387-398.

Kalkstein, L.S. and J.S. Greene, 1997: An evaluation of climate/mortality relationships in large U.S. cities and possible impacts of a climate change. *Environmental Health Perspectives*, **105**, 84-93.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc*., **77**, 437-472.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle, 1996: Indices of climate change for the United States. *Bull. Am. Met. Soc*., **77**, 279-292.

Katz, R.W., 1996: The use of stochastic models to generate climate change scenarios. *Clim. Change*, **32,** 237-255.

Katz, R.W., 2000: Techniques for estimating uncertainty in climate change scenarios and impact studies. *Clim. Res.* (accepted).

Katz, R.W. and B.G. Brown, 1992: Extreme events in a changing climate: variability is more important than averages. *Clim. Change*, **21**, 289-302.

Katz, R.W., and M.B. Parlange, 1996: Mixtures of stochastic processes: Application to statistical downscaling. *Clim. Res.*, **7**, 185-193.

Kellogg, W.W. and R. Schware, 1981: *Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide*. Westview Press, Boulder, Colorado, 178 pp.

Kenny, G.J., R.A. Warrick, B.D. Campbell, G.C. Sims, M. Camilleri, P.D. Jamieson, N.D. Mitchell, H.G. McPherson, and M.J. Salinger, 2000: Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. *Clim. Change*, **46(1/2)**, 91-113.

Kilsby, C.G., P.E. O'Connell, and C.S. Fallows, 1998: Producing rainfall scenarios for hydrological impact modelling. In: *Hydrology in a Changing Environment* [Wheater, H. and C. Kirby (eds.)]. Wiley, Chichester, volume 1, pp. 33-42.

Kittel, T.G.F., N.A. Rosenbloom, T.H. Painter, D.S. Schimel, and VEMAP Modeling Participants, 1995: The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change*. J. Biogeography*, **22**, 857-862.

Kittel, T.G.F., J.A. Royle, C. Daly, N.A. Rosenbloom, W.P. Gibson, H.H. Fisher, D.S. Schimel, L.M. Berliner, and VEMAP2 Participants, 1997: A gridded historical (1895-1993) bioclimate dataset for the conterminous United States. In: *Proceedings of the 10th Conference on Applied Climatology*, 20-24 October 1997, Reno, NV, American Meteorological Society, Boston, pp. 219-222.

Kittel, T.G.F., F. Giorgi, and G.A.Meehl, 1998: Intercomparison of regional biases and doubled CO_2-sensitivity of coupled atmosphere-ocean general circulation model experiments. *Clim. Dyn.*, **14**, 1-15.

Knutson, T.R. and R.E. Tuleya, 1999: Increased hurricane intensities with CO2-induced warming as simulated using the GFDL hurricane prediction system. *Clim. Dyn.*, **15(7)**, 503-519.

Knutson, T.R., S. Manabe, and D. Gu, 1997: Simulated ENSO in a global coupled ocean-atmosphere model: Multidecadal amplitude modulation and CO2 sensitivity. *J. Climate*, **10**, 138-161.

Konrad, C.E., 1998: An empirical approach for delineating fine scaled spatial patterns of freezing rain in the Appalachian region of the USA. *Clim. Res.*, **10**, 217-227.

Kothavala, Z., 1999: Extreme precipitation events and the applicability of global climate models to study floods and droughts. *Math. and Comp. in Simulation*, **43**, 261-268.

Krishnamurti, T.N., R. Correa-Torres, M. Latif, and G. Daughenbaugh, 1998: The impact of current and possibly future sea surface temperature anomalies on the frequency of Atlantic hurricanes. *Tellus*, **50A**, 186-210.

Kuikka, S. and O. Varis, 1997: Uncertainties of climatic change impacts in Finnish watersheds: a Bayesian network analysis of expert knowledge*. Boreal Environment Research*, **2**, 109-128.

Lal, M. and F. Giorgi, 1997: *Regional Climate Modelling and Applications*. Paper presented at the World Climate Research Programme: achievements, benefits and challenges, Geneva, Switzerland, 26-28 August, 1997, WMO, Geneva.

Lal, M. and H. Harasawa, 2000: Comparison of the present-day climate simulation over Asia in selected coupled atmosphere-ocean global climate models. *J.Met.Soc.Japan* (in press).

Lal, M., G.A. Meehl and J.M. Arblaster, 2000: Simulation of Indian summer monsoon rainfall and its intraseasonal variability. *Regional Environmental Change* (in press).

Lamb, P., 1987: On the development of regional climatic scenarios for policy oriented climatic impact assessment. *Bull. Am. Met. Soc*., **68**, 1116-1123.

Lapin, M., E. Nieplová, and P Fa?ko, 1995: Regional scenarios of temperature and precipitation changes for Slovakia (In Slovak with English abstract). *Monographs of the Slovak National Climate Program*, **3**, 17-57.

Leemans, R. and W. Cramer, 1991: *The IIASA Database for Mean Monthly Values of Temperature, Precipitation and Cloudiness on a Global Terrestrial Grid*. IIASA Report RR-91-18, Laxenburg, 63 pp.

Leemans, R. and A.M. Solomon, 1993: Modeling the potential change in yield and distribution of the earth's crops under a warmed climate. *Clim. Res.*, **3**, 79-96.

Leemans, R., E. Kreileman, G. Zuidema, J. Alcamo, M. Berk, G.J. van den Born, M. den Elzen, R. Hootsmans, M. Janssen, M. Schaeffer, A.M.C. Toet and H.J.M. de Vries, 1998: *The IMAGE User Support System: Global Change Scenarios from IMAGE 2.1*. National Institute of Public Health and the Environment, Bilthoven. October 1998. RIVM Publication, CD-rom.

Legates, D.R. and C.J. Willmott, 1990: Mean seasonal and spatial variability in gauge-corrected, global precipitation. *Int. J. Climatol*., **10**, 111-128

Leggett, J., W.J. Pepper and R.J. Swart, 1992. Emissions Scenarios for the IPCC: an Update. In: *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A.

Callander and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 71-95.

Liverman, D., M. Dilley, and K. O'Brien, 1994: Possible impacts of climate change on maize yields in Mexico. In: *Implications of Climate Change for International Agriculture: Crop Modeling Study*. EPA Report 230-B-94-003, United States Environmental Protection Agency, Policy, Planning and Evaluation, Climate Change Division, Washington, DC.

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

Magalhães, A.R. and M.H. Glantz, 1992: *Socioeconomic Impacts of Climate Variations and Policy Responses in Brazil*. United Nations Environment Programme/SEPLAN-CE/Esquel Foundation, Brasilia, Brazil.

Mahlman, J.D., 1997: Uncertainties in projections of human-caused climate warming. *Science*, **278**, 1416-1417 (in Policy Forum).

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

Mavromatis, T. and P.D. Jones, 1999: Evaluation of HadCM2 and direct use of daily GCM data in impact assessment studies. *Clim. Change*, **41**, 583-614.

McGregor, J.J., 1997: Regional climate modeling. *Meteorological Atmospheric Physics*, **63**, 105-117.

McInnes, K.L., K.J.E. Walsh, and A.B. Pittock, 2000*: Impact of sea level rise and storm surges on coastal resorts*. A report for CSIRO Tourism Research: final report. CSIRO Atmospheric Research, Aspendale, Vic., 13 pp.

Mearns, L. O., 1995: Research issues in determining the effects of changing climatic variability on crop yields. In: *Climate Change and Agriculture: Analysis of Potential International Impacts* [Rosenzweig, C. (ed.)]. American Society of Agronomy Special Publication No. 58, Madison, ASA, Chapter 6, pp. 123-146.

Mearns, L. O., 1999: The effect of spatial and temporal resolution of climate change scenarios on changes in frequencies of temperature and precipitation extremes. In: *Elements of Change 1998* [Hassol, S.J. and J. Katzenberger (eds.)]. Aspen Global Change Institute, Aspen, CO, pp. 316-323.

Mearns, L.O., C. Rosenzweig, and R. Goldberg, 1992: Effect of changes in interannual climatic variability on CERES-Wheat yields: sensitivity and $2\times CO_2$ general circulation model studies. *Agric. For. Meteorol.*, **62**, 159-189.

Mearns, L.O., F. Giorgi, C. Shields, and L. McDaniel, 1995a: Analysis of the variability of daily precipitation in a nested modeling experiment: comparison with observations and $2xCO_2$ results. *Global Planet. Change*, **10**, 55-78.

Mearns, L.O., F. Giorgi, C. Shields, and L. McDaniel, 1995b: Analysis of the diurnal range and variability of daily temperature in a nested model experiment: comparison with observations and 2xCO2 results. *Clim. Dyn.*, **11**, 193-209.

Mearns, L. O., C. Rosenzweig, and R. Goldberg, 1996: The effect of changes in daily and interannual climatic variability on CERES-wheat: a sensitivity study. *Clim. Change*, **32,** 257-292.

Mearns, L. O., C. Rosenzweig, and R. Goldberg, 1997: Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. *Clim. Change,* **35,** 367-396.

Mearns, L. O., W. Easterling, and C. Hays 1998: *The Effect of Spatial Scale of Climate Change Scenarios on the Determination of Impacts: An Example of Agricultural Impacts on the Great Plains*. Proceedings of the International Workshop on Regional Modeling of the General Monsoon System in Asia, Beijing, October 20—23, START Regional Center for Temperate East Asia, TEACOM Report No. 4, pp. 70-73.

Mearns, L.O., T. Mavromatis, E. Tsvetsinskaya, C. Hays, and W. Easterling, 1999: Comparative responses of EPIC and CERES crop models to high and low resolution climate change scenario. *J. Geophys. Res.*, **104(D6)**, 6623-6646.

Mearns, L.O., G. Carbone, W. Gao, L. McDaniel, E. Tsvetsinskaya, B. McCarl, and R. Adams, 2000a: The issue of spatial scale in integrated assessments: An example of agriculture in the Southeastern U.S. In: *Preprints of the American Meteorological Society of America Annual Meeting*, 9-14 January, Long Beach, CA. AMS, Boston, MA, pp. 38-41.

Mearns, L.O., G. Carbone, L. McDaniel, W. Gao, B. McCarl, R. Adams, and W. Easterling, 2000b: The importance of spatial scale of climate scenarios for regional climate change impacts analysis: implications for regional climate modeling activities. In: *Preprints of the Tenth PSU/NCAR Mesoscale Model Users' Workshop*, June 21-22 2000, National Center for Atmospheric Research, Mesoscale and Microscale Meteorology Division, Boulder, Colorado, pp. 127-130.

Mearns, L. O., W. Easterling, and C. Hays, 2001: Comparison of agricultural impacts of climate change calculated from high and low resolution climate model scenarios: part I: the uncertainty due to spatial scale. *Clim. Change* (in press).

Mitchell, J.F.B., 1990: Greenhouse warming: is the mid-Holocene a good analogue? *J. Climate*, **3**, 1177-1192.

Mitchell, J.F.B., S. Manabe, V. Meleshko, and T. Tokioka, 1990: Equilibrium climate change - and its implications for the future. In: *Climate Change: The IPCC Scientific Assessment. Report prepared by Working Group I* [Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 131-164.

Mitchell, J.F.B., T.C. Johns, M. Eagles, W.J. Ingram, and R.A. Davis, 1999: Towards the construction of climate change scenarios. *Clim. Change*, **41**, 547-581.

Morgan, M.G. and M. Henrion, 1990: *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, UK.

Morgan, M.G. and D. Keith, 1995: Subjective judgements by climate experts. *Envir. Sci. Tech.*, **29**, 468-476.

Morgan, M.G. and H. Dowlatabadi, 1996: Learning from integrated assessment of climate change. *Clim. Change*, **34**, 337-368.

Morita, T. and J. Robinson, 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. In *Climate Change 2001: Mitigation.* Contribution of Working Group III to the IPCC Third Assessment Report.

Murphy, J.M., 1999: An evaluation of statistical and dynamical techniques for downscaling local climate. *J. Climate*, **12(8)**, 2256-2284.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T. Y. Jung, T. Kram, E. L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Raihi, A. Roehrl, H-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi, 2000: IPCC Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

NDU, 1978: *Climate Change to the Year 2000*. Dept. of Defense, National Defense University, US Government Printing Office, Washington, D.C., 109 pp.

Neilson, R.P., I.C. Prentice, B. Smith, 1997: Simulated changes in vegetation distribution under global warming. In: *The Regional Impacts of Climate Change: An Assessment of Vulnerability. A Special Report of IPCC Working Group II* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 439-456.

New, M., 1999: Uncertainty in representing the observed climate. In: *Proceedings of the ECLAT-2 Helsinki Workshop, 14-16 April, 1999* [Carter, T.R., M. Hulme, and D. Viner (eds.)]. Climatic Research

Unit, Norwich, UK, pp. 59-66.

New, M. and M.Hulme, 2000: Representing uncertainties in climate change scenarios: a Monte Carlo approach. *Integrated Assessment,* **1**, 203-213.

New, M., M. Hulme, M. and P.D. Jones, 1999: Representing twentieth century space-time climate variability. Part 1: development of a 1961-90 mean monthly terrestrial climatology. *J. Climate*, **12**, 829-856.

New, M., M. Hulme, and P.D. Jones, 2000: Representing twentieth century space-time climate variability. Part 2: development of 1901-96 monthly grids of terrestrial surface climate. *J. Climate*, **13(13)**, 2217-2238.

Oglesby, R.J. and B. Saltzman, 1992: Equilibrium climate statistics of a general circulation model as a function of atmospheric carbon dioxide, part I. *J. Climate*, **5**, 66-92.

Osborn, T.J., 1996: Comment on Climate drift in a global ocean general circulation model. *J. Phys. Oceanogr.*, **26**, 166a-1663.

Osborn, T.J., 1997: Areal and point precipitation intensity changes: Implications for the application of climate models. *Geopohys. Res. Lett.*, **24**, 2829-2832.

Osborn, T.J., K.R. Briffa, S.F.B. Tett, P.D. Jones, and R.M. Trigo, 2000: Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. *Clim. Dyn.,* **15(9)**, 685-702.

Parkinson, S.D. and P.C. Young, 1998: Uncertainty and sensitivity in global carbon cycle monitoring. *Clim. Res.*, **9**, 157–174.

Parry, M.L. and M. Livermore (eds.), 1999: A new assessment of the global effects of climate change. *Global Environ.l Change*, **9**, S1-S107, Supplementary Issue.

Parry, M.L., T.R. Carter, and M. Hulme, 1996: What is a dangerous climate change? *Global Environ. Change***,** **6**, 1-6.

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

Piper, S.C. and E.F. Stewart, 1996: A gridded global data set of daily temperature and precipitation for terrestrial biospheric modelling. *Global Biogeochem. Cycles*, **10**, 757-782.

Pittock, A.B., 1989: Book review: Societal Responses to Regional Climatic Change [Glantz, M.] *Bull. Am. Met. Soc*., **70**, 1150-1152.

Pittock, A.B., 1993: Climate scenario development. In: *Modelling Change in Environmental Systems* [Jakeman, A.J., M.B. Beck, and M.J. McAleer (eds.)]. John Wiley, Chichester, New York, pp. 481-503.

Pittock, A.B., 1995: Comments on climate change scenario development. *Math. Comput. Modelling*, **21**, 1-4.

Pittock , A.B. and M.J. Salinger, 1982: Toward regional scenarios for a CO_2-warmed earth. *Clim. Change*, **4**, 23-40.

Prinn, R. H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, D. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, Y. Liu, and G. Holian, 1999: Integrated global system model for climate policy analysis: Feedbacks and sensitivity studies. *Clim. Change***, 41**, 469-546.

Racksko, P., L. Szeidl, and M. Semenov, 1991: A serial approach to local stochastic weather models. *Ecological Modeling,* **57**, 27-41.

Räisänen, J., 1997: Objective comparison of patterns of CO_2 induced climate change in coupled GCM experiments. *Clim. Dyn.*, **13**, 197-212.

Räisänen, J., 1999: Internal variability as a cause of qualitative inter-model disagreement on anthropogenic climate changes *Theor. Appl. Climatol*., **64**, 1-13.

Ramaswamy, V. and T.C. Chen, 1997: Linear additivity of climate response for combined albedo and greenhouse perturbations. *Geophys. Res. Lett*., **24**, 567-570.

Raper, S.C.B., T.M.L. Wigley, and R.A. Warrick, 1996: Global sea level rise: Past and future. In: *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies* [Milliman, J. and B.U. Haq (eds.)]. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 11-45.

Richardson, C.W., 1981: Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resour. Res.*, **17**, 182-190.

Riha, S. J., D. W. Wilks, and P. Simoens, 1996: Impact of temperature and precipitation variability on crop model predictions. *Clim. Change*, **32(3)**, 293-311.

Risbey, J.S., 1998: Sensitivities of water supply planning decisions to streamflow and climate scenario uncertainties. *Water Policy*, **1**, 321-340.

Risbey, J.S. and P.H. Stone, 1996: A case study of the adequacy of GCM simulations for input to regional climate change assessments. *J. Climate*, **9**, 1441-1467.

Robinson, P. J., and P. L. Finkelstein, 1989: *Strategies for Development of Dlimate Scenarios*. Final Report to the U. S. Environmental Protection Agency. Atmosphere Research and Exposure Assessment Laboratory, Office of Research and Development, USEPA, Research Triangle Park, NC, 73 pp.

Robock, A., R.P. Turco, M.A. Harwell, T.P. Ackerman, R. Andressen, H.S. Chang, and M.V.K. Sivakumar, 1993: Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Clim. Change*, **23**, 293-355.

Rodbell, D., G. O. Seltzer, D. M. Anderson, D. B. Enfield, M. B. Abbott, and J. H. Newman, 1999: A high-resolution 15000 year record of El Nino driven alluviation in southwestern Ecuador. *Scienc*e, **283**, 516-520.

Rosenberg, N.J., P.R. Crosson, K.D. Frederick, W.E. Easterling, M.S. McKenney, M.D. Bowes, R.A. Sedjo, J. Darmstadter, L.A. Katz, and K.M. Lemon, 1993: Paper 1. The MINK methodology: background and baseline. *Clim. Change*, **24**, 7-22.

Rosenthal, D.H., H.K. Gruenspecht, and E.A. Moran, 1995: Effects of global warming on energy use for space heating and cooling in the United States. *Energy J.*, **16**, 41-54.

Rosenzweig, C. 1985: Potential CO_2-induced climate effects on North American wheat-producing regions. *Clim. Change*, **4**, 239-254.

Rosenzweig, C. and A. Igesias (eds.), 1994: *Implications of Climate Change for International Agriculture: Crop Modeling Study*. EPA Report 230-B-94-003, United States Environmental Protection Agency, Policy, Planning and Evaluation, Climate Change Division, Washington, DC.

Rosenzweig, C. and M. L. Parry, 1994: Potential impact of climate change on world food supply. *Nature,* **367**, 133-137.

Rosenzweig, C., J. Phillips, R. Goldberg, J. Carroll, and T. Hodges, 1996: Potential impacts of climate change on citrus and potato production in the US. *Agricultural Systems*, **52**, 455-479.

Rotmans, J., M. Hulme, and T.E. Downing, 1994: Climate change implications for Europe: an application of the ESCAPE model. *Global Env. Change*, **4**, 97-124.

Saarikko, R.A., and T.R. Carter, 1996: Estimating regional spring wheat development and suitability in Finland under climatic warming. *Clim. Res.,* **7**, 243-252.

Santer, B.D., T.M.L. Wigley, M.E. Schlesinger, and J.F.B.Mitchell, 1990: *Developing Climate Scenarios from Equilibrium GCM results*. Report No. 47, Max-Planck-Institut-für-Meteorologie, Hamburg, 29 pp.

Santer, B.D., J.J. Hnilo, T.M.L. Wigley, J.S. Boyle, C. Doutriaux, M. Fiorino, D.E. Parker, and K.E. Taylor, 1999: Uncertainties in observationally based estimates of temperature change in the free atmosphere. *J. Geophys. Res*., **104**, 6305-6333.

Schimel, D.S., W. Emanuel, B. Rizzo, T. Smith, F.I. Woodward, H. Fisher, T.G.F. Kittel, R. Mckeown, T. Painter, N. Rosenbloom, D.S. Ojima, W.J. Parton, D.W. Kicklighter, A.D. Mcguire, J.M. Melillo, Y. Pan, A. Haxeltine, C. Prentice, S. Sitch, K. Hibbard, R. Nemani, L. Pierce, S. Running, J. Borchers, J. Chaney, R. Neilson, and B.H. Braswell, 1997: Continental scale variability in ecosystem processes:

models, data, and the role of disturbance. *Ecological Monographs*, **67(2),** 251-271.

Schlesinger, M.E., N. Andronova, A. Ghanem, S. Malyshev, T. Reichler, E. Rozanov, W. Wang, and F. Yang, 1997: *Geographical Scenarios of Greenhouse Gas and Anthropogenic-Sulfate-Aerosol Induced Climate Changes*. CRG manuscript, July 1997, University of Illinois, Department of Atmospheric Sciences, Urbana, IL, 85 pp.

Schlesinger, M.E., S. Malyshev, E.V. Rozanov, F. Yang, N.G. Andronova, B. de Vries, A. Grübler, K. Jiang, T. Masui, T. Morita, J. Penner, W. Pepper, A. Sankovski and Y. Zhang, 2000: Geographical distributions of temperature change for scenarios of greenhouse gas and sulfur dioxide emissions. *Tech. Forecast. Soc. Change,* **65**, 167-193.

Schneider, S. H., P. H. Gleick and L. O. Mearns, 1990: Prospects for Climate Change. In: *Climate and Water: Climate Change, Climatic Variability, and the Planning and Management of U. S. Water Resources*. Wiley Press, New York, Chapter 3, pp. 41-73.

Schreider, S. Yu, A.J. Jakeman, A.B. Pittock, and P.H. Whetton, 1996: Estimation of possible climate change impacts on water availability, extreme flow events and soil moisture in the Goulburn and Ovens Basins, Victoria. *Clim. Change*, **34**, 513–546.

Schubert, M., J. Perlwitz, R. Blender, K. Fraedrich, and F. Lunkeit, 1998: North Atlantic cyclones in CO2-induced warm climate simulations: Frequency, intensity, and tracks. *Clim. Dyn*., **14**, 827-837.

Semenov, M.A. and J.R. Porter, 1995: Climatic variability and the modelling of crop yields*. Agric. For. Meteorol.*, **73**, 265-283.

Semenov, M. A. and E. Barrow, 1997: Use of a stochastic weather generator in the development of climate change scenarios. *Clim. Change,* **35**, 397-414.

Semenov, M.A. and R.J. Brooks, 1999: Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. *Clim. Res.*, **11**, 137-148.

Severinghaus, J.P., T. Sowers, E. Brook, R.B. Alley, and M.L. Bender, 1998: Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. *Nature*, **391**, 141-146.

Shabalova, M.V., and G.P. Können, 1995: Climate change scenarios: comparisons of paleo-reconstructions with recent temperature changes. *Clim. Change*, **29**, 409-428.

Skelly, W.C. and A. Henderson-Sellers, 1996: Grid box or grid point: what type of data do GCMs deliver to climate impacts researchers? *Int. J. Climatol.*, **16**, 1079-1086.

Smith, J.B. and G.J. Pitts, 1997: Regional climate change scenarios for vulnerability and adaptation assessments. *Clim. Change*, **36**, 3-21.

Smith, J.B. and M. Hulme, 1998: Climate change scenarios. In: *Handbook on Methods of Climate Change Impacts Assessment and Adaptation Strategies* [Feenstra, J., I. Burton, J.B. Smith, and R.S.J. Tol (eds.)]. UNEP/IES, Version 2.0, October, Amsterdam, Chapter 3.

Smith, J.B. and D.A. Tirpak (eds.) 1989: *The Potential Effects of Global Climate Change on the United States*. Report to Congress, United States Environmental Protection Agency, EPA-230-05-89-050, Washington, D.C., 409 pp.

Smith, J.B., S. Huq, S. Lenhart, L.J. Mata, I. Neme?ová, and S. Toure (eds.), 1996: *Vulnerability and Adaptation to Climate Change: Interim Results from the U.S. Country Studies Program*. Kluwer, Dordrecht, The Netherlands, 366 pp.

Stewart, T.R. and M.H.Glantz, 1985: Expert judgment and climate forecasting: a methodological critique of Climate Change to the Year 2000. *Clim. Change*, **7**, 159-183.

Stone, M.C., R.H. Hotchkiss, C.M. Hubbard, T.A. Fontaine, L.O. Mearns, and J.G. Arnold, 2001: Impacts of climate change on the water yield of the Missouri River. *J. Am. Water Resour. As.* (accepted).

Stouffer, R.J., S. Manabe, and K.Ya. Vinnikov, 1994: Model assessment of the role of natural variability in recent global warming. *Nature*, **367**, 634-636.

Terjung, W.H., D.M. Liverman, J.T. Hayes, and collaborators, 1984: Climatic change and water requirements for grain corn in the North American Great Plains. *Clim. Change*, **6**, 193-220.

Tett, S.F.B., T.C. Johns, and J.F.B. Mitchell, 1997: Global and regional variability in a coupled AOGCM. *Clim. Dyn.*, **13**, 303-323.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, 1999: Increased El Nino frequency in a climate model forced by future greenhouse warming. *Nature,* **398**, 694-696.

Titus, J.G. and V. Narayanan, 1996: The risk of sea level rise. *Clim. Change*, **33**, 151-212.

Tol, R.S.J. and A.F. de Vos, 1998. A Bayesian statistical analysis of the enhanced greenhouse effect. *Clim. Change*, **38**, 87-112.

Torn, M.S and J.S. Fried, 1992: Predicting the impacts of global warming on wildland fire. *Clim. Change*, **21**, 257-274.

Toth, L. and M. Mwandosya, 2001: Decision-making Frameworks. In *Climate Change 2001: Mitigation.* Contribution of Working Group III to the IPCC Third Assessment Report, Cambridge University Press.

Velichko, A. A., O. K. Borisova, E. M. Zelikson, and V. P Nechaev, 1995a: Permafrost and vegetation response to global warming in North Eurasia. In: *Biotic Feedbacks in the Global Climatic System*. New York, Oxford, Oxford University Press, pp. 134-156.

Velichko, A.A., L.O. Karpachevsky, and T.D. Morozova, 1995b: Water reserves in soils under global climate warming: an approach to forecasting for Eastern Europe as an example. *Pochvovedenie*, **8**, 933-942 (in Russian).

Vinnikov, K. Ya. and P. Ya. Groisman, 1979: An empirical model of present-day climatic changes. *Meteor. Gidrol.*, **3**, 25-28 (in Russian).

Vinocur, M.G., R.A. Seiler, and L.O. Mearns, 2000: Forecasting the impact of climate variability on peanut crop production in Argentina. In: *Proceedings of the International Forum on Climate Prediction, Agriculture and Development*. International Research Institute for Climate Prediction (IRI), Palisades, NY (in press).

Visser, H., R.J.M. Folkert, J. Hoekstra, and J.J. deWolff, 2000: Identifying key sources of uncertainty in climate change projections. *Clim. Change*, **45(3/4)**, 421-457.

Voet, P. van der, K. Kramer, and C.A. van Diepen, 1996: *Parametrization of the Richardson Weather Generator within the European Union*. DLO Winand Staring Centre Report 92, Wageningen, The Netherlands, 73 pp.

von Storch, H., 1995: Inconsistencies at the interface of climate impact studies and global climate research. *Meteor. Z.*, **4 NF**, 72-80.

von Storch, J.S., V. Kharin, U. Cubasch, G.C. Hergel, D. Schriever, H. von Storch, and E. Zorita, 1997: A description of a 1260-year control integration with the coupled ECHAM1/LSG general circulation model. *J. Climate*, **10**, 1525-1543.

Walker, B., W. Steffen, J. Canadell and J. Ingram (eds.), 1999: *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems*. Cambridge University Press, Cambridge, 439 pp.

Walsh, K.J.E. and B.F. Ryan, 2000: Tropical cyclone intensity increase near Australia as a result of climate change. *J. Climate*, **13**, 3029-3036.

Walsh, K., R. Allan, R. Jones, B. Pittock, R. Suppiah, and P. Whetton, 1999: *Climate Change in Queensland under Enhanced Greenhouse Conditions*. First Annual Report, CSIRO Atmospheric Branch, Aspendale, Victoria, Australia, 84 pp.

Wang, Y. P., and D. J. Connor, 1996: Simulation of optimal development for spring wheat at two locations in southern Australia under present and changed climate conditions. *Agric. For. Meteorol*., **79**, 9-28.

Wang, J. and L. Erda, 1996: The Impacts of potential climate change and climate variability on simulated maize production in China. *Water Air Soil Pollut.,* **92**, 75-85.

Wang, Q. J., R. J. Nathan, R. J. Moran, and B. James, 1999: *Impact of climate Changes on the Security of the Water Supply of the Campaspe System*. Proceedings of 25th Hydrology and Water Resources

Symposium, Vol. 1, 6-8 July 1999, Brisbane, Institution of Engineers, Australia, Water 99 Joint Congress, pp. 135-140.

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

Warrick, R.A., C. Leprovost, M.F. Meier, J. Oerlemans, P.L. Woodworth, R.B. Alley, R.A. Bindschadler, C.R. Bentley, R.J. Braithwaite, J.R. de Wolde, B.C. Douglas, M. Dyurgerov, N.C. Flemming, C. Genthon, V. Gornitz, J. Gregory, W. Haeberli, P. Huybrechts, T. Jóhannesson, U. Mikolajewicz, S.C.B. Raper, D.L. Sahagian, R.S.W. van de Wal and T.M.L. Wigley, 1996: Changes in sea level. In: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assesesment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., L.G.M. Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 359-405.

Webb, T., III, and T.M.L. Wigley, 1985: What past climates can indicate about a warmer world. In: *Projecting the Climatic Effects of Increasing Carbon Dioxide* [MacCracken, M.C. and F.M. Luther (eds.)]. United States Department of Energy, Office of Energy Research, DOE/ER-0237, Washington, D.C., pp. 237-257.

Whetton, P. H., 1998: Climate change impacts on the spatial extent of snow-cover in the Australian Alps. In: *Snow: A Natural History, An Uncertain Future* [K. Green (ed.)]. Australian Alps Liaison Committee, Canberra, pp. 195-206.

Whetton, P.H. and A.B. Pittock, 1991*: Australian Region Intercomparison of the Results of some Greenhouse General Circulation Modelling Experiments*. Tech. Paper No. 21, CSIRO Div. of Atmospheric Research, Melbourne, Australia, 73 pp.

Whetton, P.H., A.M. Fowler, M.R. Haylock, and A.B. Pittock, 1993: Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. *Climatic Change*, **25(3-4)**, 289-317.

Whetton, P.H., M.R. Haylock, and R. Galloway, 1996: Climate change and snow-cover duration in the Australian Alps. *Clim. Change*, **32(4)**, 447-479.

Whetton, P.H., J.J. Katzfey, K.C. Nguyen, J.L. McGregor, C.M. Page, T.I. Elliott, and K.J. Hennessy, 1998a: *Fine Resolution Climate Change Scenarios for New South Wales*. *Part 2: Climatic Variability.* Annual Report, 1996/7, CSIRO, Australia, 51 pp.

Whetton, P. H., Z. Long, and I.N. Smith, 1998b: Comparison of simulated climate change under transient and stabilised increased CO2 conditions. In: *Coupled Climate Modelling: Abstracts of Presentations at the Tenth Annual BMRC Modelling Workshop, BMRC, Melbourne* [P. J. Meighen (ed.)]. BMRC Research Report, 69, Melbourne, Bureau of Meteorology Research Centre, pp. 93-96.

White, M.R., 1985: *Characterization of Information Requirements for Studies of* CO_2 *Effects: Water Resources, Agriculture, Fisheries, Forests, and Human Health*. US Dept. of Energy, Office of Energy Research, DOE/ER-0236, Washington, DC.

Widmann, M. and C.S. Bretherton, 2000: Validation of mesoscale precipitation in the NCEP reanalysis using a new grid-cell data set for the northwestern United States. *J.Climate*, **13(11)**, 936-950.

Wigley, T.M.L., 1999: *The Science of Climate Change: Global and US Perspectives*. Pew Center on Global Climate Change, Arlington, VA, 48 pp.

Wigley, T.M.L., P.D. Jones, and P.M. Kelly, 1980: Scenarios for a warm, high-CO_2 world. *Nature*, **288**, 17-21.

Wilby, R.L., 1998: Statistical downscaling of daily precipitation using daily airflow and seasonal teleconnection indices. *Clim. Res.*, **10**, 163-178.

Wilby, R.L. and T.M.L. Wigley, 1997: Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography*, **21**, 530-548.

Wilby, R.L., B. Greenfield, and C. Glenny, 1994: A coupled synoptic-hydrological model for climate change impact assessment. *Journal of Hydrology*, **153**, 265-290.

Wilby, R.L., T.M.L. Wigley, D. Conway, P.D. Jones, B.C. Hewitson, J. Main, and D.S. Wilks, 1998: Statistical downscaling of General Circulation Model output: a comparison of methods. *Water Resources Research*, **34**, 2995-3008.

Wilby, R.L., L.E. Hay, and G.H. Leavesley, 1999: A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River Basin, Colorado. *J. Hydrol.* **225**, 67-91.

Wilks, D. S., 1992: Adapting stochastic weather generation algorithms for climate change studies. *Clim.Change,* **22**, 67-84.

Wilks, D. S. and R.L. Wilby, 1999: The weather generation game: A review of stochastic weather models. *Progress in Physical Geography*, **23**, 329-358.

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

Woo, M.K., 1992: Application of stochastic simulation to climatic change studies. *Clim.Change,* **20**, 313-330.

Woolhiser, D.A., T.O. Keefer, and K.T. Redmond, 1993: Southern Oscillation effects on daily precipitation in the southwestern United States. *Water Resour. Res.,* **29**, 1287-1295.

Wotton, B.M., B. J. Stocks, M.D. Flannigan, R. LaPrise, and J-P Blanchet, 1998: Estimating future 2xCO_2 fire climates in the boreal forest of Canada using a regional climate model. In: *Proceedings of Third International Conference on Forest Fire Research and the 14th Conference in Fire and Forest Meteorology*. University of Coimbra, Portugal, pp. 1207-1221.

Xiao, X., D.W. Kicklighter, J.M. Melillo, A.D. McGuire, P.H. Stone and A. P. Sokolov, 1997: Linking a global terrestrial biogeochemical model with a 2-dimensional climate model: Implications for global carbon budget. *Tellus,* **49B**, 18-37.

Xie, P. and P.A. Arkin, 1997: Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Am. Met. Soc.*, **78**, 2539-2558.

Yohe, G.W. and M.E. Schlesinger, 1998: Sea-level change: the expected economic cost of protection or abandonment in the United States. *Clim. Change*, **38**, 447-472.