# GENERAL GUIDELINES ON THE USE OF SCENARIO DATA FOR CLIMATE IMPACT AND ADAPTATION ASSESSMENT

Version 2

June 2007

**Task Group on Data and Scenario Support for**
**Impact and Climate Assessment (TGICA)**

**Intergovernmental Panel on Climate Change**

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## Version 2

## June 2007

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## Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA)

## Intergovernmental Panel on Climate Change

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## Document history

This document, General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment, constitutes "Supporting material" of the Intergovernmental Panel on Climate Change (as defined in the Procedures for the Preparation, Review, Acceptance, Adoption, Approval, and Publication of IPCC Reports). The Guidelines were prepared for consideration by the IPCC at the request of its Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA). This supporting material has not been subject to the formal intergovernmental IPCC review process.

This is the second version of these guidelines. Version 1 was originally drafted by Timothy Carter (Finnish Environment Institute), with later contributions from Mike Hulme and Murari Lal. The document was reviewed by the following members of the Task Group on Scenarios for Climate Impact Assessment (TGCIA): X. Dai, P. Desanker, F. Giorgi, L.J. Mata, L.O. Mearns, J.F.B. Mitchell, T. Morita, R. Moss, D. Murdiyarso, J.D. Pabon-Caicedo, M.L. Parry, R.J. Scholes and P.H. Whetton. With the development of specialist *Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments* and *Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods*, as well as important changes in the scope and content of information held at the IPCC Data Distribution Centre, the newly constituted IPCC Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA) requested Carter to revise and update the document. Comments and contributions were received from: Elaine Barrow, Luis Mata, Cynthia Rosenzweig and Stuart Gaffin. The report was then reviewed by Knut Alfsen, Brad Bass, Jean Palutikof and Bernard Seguin from the TGICA  The final version was published in June 2007.

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**IPCC-TGICA**, 2007: *General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment*. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 66 pp.

# 1. INTRODUCTION

## 1.1. Purpose of this document

In 1997, the Intergovernmental Panel on Climate Change (IPCC) formed the Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA)[1] whose role is to provide regional climate change information with particular focus on capacity building for future IPCC assessments. These Guidelines represent part of an initiative by the Task Group to improve consistency in the selection and application of scenarios[2] in climate impact and adaptation assessments and, in so doing, to reduce the time lag of information exchange between the different scientific communities engaged in climate change research. They offer guidance on the interpretation and application of scenario data in impact and adaptation assessment. They also provide user support for the IPCC Data Distribution Centre (DDC), which has been established under the direction of the Task Group to make freely available a number of recent global data sets of baseline and scenario information on climatic, environmental and socio-economic conditions.

This is a completely revised version of the original Guidelines, which first appeared in December 1999. Since that time a new set of emissions scenarios (Special Report on Emissions Scenarios, SRES – Nakićenović *et al*., 2000) and new chapters on scenarios (Mearns *et al*., 2001; Carter *et al*., 2001, 2007; Morita *et al*., 2001; Nakićenović *et al*., 2007) have been prepared by the IPCC. Furthermore, large amounts of new information related to the SRES scenarios have been added to the Data Distribution Centre and more detailed guidance material on specific topics described in this document has been developed or is under development by the TGICA in parallel with these generic guidelines, concerning:

- Climate scenarios developed from regional climate model experiments (Mearns *et al*., 2003)
- Climate scenarios developed using statistical downscaling techniques (Wilby *et al*., 2004)
- Global and regional sea level scenarios
- Socio-economic scenarios, including population, gross domestic product and land-use change
- Scenarios of atmospheric composition, including carbon dioxide concentration, tropospheric and near-surface ozone abundance and sulphur concentration and deposition

These can (or will) be found on the DDC and are referenced at appropriate points in this document, the individual sections of which have been designed as stand-alone introductions to different sets of information on the DDC website.

## 1.2. Background

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative statement on climate change – its causes, impacts and possible response strategies. It produced three major assessments of climate change in 1990, 1995 and 2001, and a fourth will be published late in 2007. The Third Assessment Report (TAR), comprised three volumes prepared, respectively, by Working Groups I, II and III of the IPCC, on the scientific basis of climate change (IPCC, 2001a), climate change impacts, adaptation and vulnerability (IPCC, 2001b) and climate change mitigation (IPCC, 2001c).

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[1] Formerly known as the Task Group on Scenarios for Climate Impact Assessment (TGCIA)

[2] The term scenario is used in this report to indicate "a coherent, internally consistent and plausible description of a possible future state of the world" (IPCC, 1994).

One conclusion of the Working Group I TAR was that the globally averaged surface air temperature is projected by global climate models to warm 1.4 to 5.8°C by 2100 relative to 1990 (IPCC, 2001a, p. 13). The upper part of this range is higher than previous projections reported in the Second Assessment Report, and Working Group II was forced to concede in its report that "the available literature has not yet investigated climate change impacts, adaptation, and vulnerability associated with the upper end of the projected range of warming" (IPCC, 2001b, p. 3). This admission reflects a time lag and inconsistency problem that has characterised the IPCC assessments.

At the core of the problem is the structure of the IPCC assessment itself, in which the three volumes are prepared in parallel. This has resulted in a mismatch of information and assumptions between the Working Groups. Thus, while Working Group I reviewed the most recent published projections of future climate change, based on transient coupled ocean-atmosphere general circulation model (AOGCM) simulations and a new set of scenarios of future greenhouse gas (GHG) and aerosol emissions, these results were not available to the impacts community in preparing their assessments, which were simultaneously reviewed by Working Group II. Instead, most of these impact studies relied on climate projections from earlier GCM simulations based on previous emissions scenarios. Similarly, the simplified assumptions used in climate model simulations about changes in the radiative forcing of the climate due to changing GHG and aerosol concentrations represent only a limited subset of the plausible atmospheric conditions under a range of emissions scenarios reviewed by Working Group III.

Another difficulty faced by reviewers in attempting to summarise and synthesise the results of impact studies for successive IPCC reports has been the lack of consistency in projections. Different climate projections have been adopted in different studies, in different regions (or within the same region), and in different sectors. Moreover, even where the same climate projections were assumed, these might not be applied in the same way in different impact studies. Finally, some studies are also inconsistent in their methods of projecting changes in climate alongside concurrent changes in related socio-economic and environmental conditions.

The Task Group and Data Distribution Centre were established to address these problems, and this document is designed to guide the reader through the various types of information available for impact and adaptation research and its application and interpretation. Box 1, taken from the Third Assessment Report (Carter et al., 2001), provides definitions for some of the key terms used in the guidelines and on the DDC, as these are widely used in the scientific literature, but often with varying interpretations.

## 1.3. The IPCC Data Distribution Centre (DDC)

The IPCC Data Distribution Centre (DDC) was established in 1998, following a recommendation by the TGICA, to facilitate the timely distribution of a consistent set of up-to-date scenarios of changes in climate and related environmental and socio-economic factors for use in climate impact and adaptation assessment. One of the clear objectives is to encourage new studies that can feed into the IPCC assessment process.

Data are being provided by the DDC over the World Wide Web and on CD-ROM. All research groups supplying data sets have agreed to these being in the public domain. The data are provided free of charge, but all users are requested to register to ensure both that the data are used for public scientific research rather than for commercial applications and also that they can be informed of possible modifications, additions and other new developments at the DDC.

The DDC is a shared operation between the British Atmospheric Data Centre (BADC) in the United Kingdom[3], the Max-Planck-Institut-für-Meteorologie in Germany and the Center for International

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[3] The BADC took over this role in 2007 from the Climatic Research Unit (CRU), University of East Anglia, UK

**Box 1: Definitions of terms**

***Projection***. The term "projection" is used in two senses in the climate change literature. In general usage, a projection can be regarded as any description of the future and the pathway leading to it. However, a more specific interpretation has been attached to the term "climate projection" by the IPCC when referring to model-derived estimates of future climate.

***Forecast/Prediction***. When a *projection* is designated "most likely" it becomes a forecast or prediction. A forecast is often obtained using physically-based models, possibly a set of these, outputs of which can enable some level of confidence to be attached to projections.

***Scenario***. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world (IPCC, 1994). It is not a *forecast*; rather, each scenario is one alternative image of how the future can unfold. A *projection* may serve as the raw material for a scenario, but scenarios often require additional information (e.g., about *baseline* conditions). A set of scenarios is often adopted to reflect, as well as possible, the range of uncertainty in projections. Other terms that have been used as synonyms for scenario are "characterisation", "storyline" and "construction".

***Baseline/Reference***. The baseline (or reference) is any datum against which change is measured. It might be a "current baseline", in which case it represents observable, present-day conditions. It might also be a "future baseline", which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

Earth Science Information Network (CIESIN) at Columbia University, New York, USA. In addition, several regional centres have agreed to serve as mirror sites for the data archive, as well as offering specialised regional user support on top of the basic DDC functions, including translation of key documentation. Technical inputs from other centres or organizations with experience in the preparation and distribution of scenarios have also been solicited, and links are made to these groups from the DDC site.

The DDC provides three main types of data and guidance, which meet certain criteria established by the TGICA. They are introduced briefly here and described in more detail in subsequent sections of these Guidelines:

1. Socio-Economic Data and Scenarios. This information is required for describing socio-economic development and adaptation capacity. The reference data include country and regional-level indicators of socio-economic and resource variables. The scenario data supplied extend to 2100 and are based on the assumptions underlying the new set of emissions scenarios developed for the IPCC Special Report on Emissions Scenarios (SRES - Nakićenović *et al*., 2000). Data are also available for the previous six emissions scenarios prepared by the IPCC in 1992 (the IS92 scenarios - Leggett *et al*., 1992). Links to related guidance material developed by other agencies are also provided.
2. Climate Observations and Scenarios. The climate observations comprise 1961-1990 mean monthly data over global land areas for nine variables on a 0.5° latitude/longitude grid, together with decadal anomalies from this mean for the period 1901-1995. This data set is currently being updated to 2000 and interpolated to a finer resolution (10 x 10 arc minutes). Pointers are provided to other relevant global climatologies. Monthly averaged results from climate change simulations performed by a number of climate modelling centres are also available. The results have been extracted from transient AOGCM simulations which include both greenhouse gas only and greenhouse gas and sulphate aerosol forcings. Results from control simulations, ensembles and time-slice experiments are also being provided, where possible. Explanations of these model simulations are provided later in this document.

3. Data and Scenarios for Other Environmental Changes. These include baseline data and projections for global mean $CO_2$ concentration, global and regional sea-level rise, regional ground-level ozone concentration, sulphate aerosol concentration and sulphur deposition. All of these scenarios were developed for the IPCC Third Assessment Report based on the SRES emissions scenarios (Nakićenović *et al.*, 2000). Detailed documentation and guidance is also provided for the use of these data.

## 1.4. Structure and objectives of these Guidelines

The Guidelines have three main objectives:

1. To introduce and describe the information and analytical tools being provided by the Data Distribution Centre

2. To offer guidance on how to interpret the baseline and scenario data held by the DDC and elsewhere, in order to facilitate the informed selection and use of data in impact and adaptation assessments

3. To highlight and illustrate key steps and procedures that are commonly required in applying baseline and scenario data in impact and adaptation assessments

Building on earlier published guidelines for climate impact and adaptation assessment (e.g., IPCC, 1994; Feenstra et al., 1998; WCC'93, 1994), the main scenario elements provided by the DDC are presented schematically in **Figure 1**. They reflect two alternative and often complementary pathways for carrying out scenario-based assessments: a top-down approach involving the interpretation and downscaling of global-scale scenarios to regional level, and a bottom-up approach, that builds scenarios by aggregating from the local to regional scales. The scenario elements are organised according to the structure of the DDC web pages. The two approaches are described in more detail in the following sections.

**Figure 1** also displays an element that is not currently provided for by the Data Distribution Centre: Observed Impacts (violet box). Previously, the main emphasis of the IPCC DDC has been on the provision of information to assist the conduct of model-based impact and adaptation studies and to facilitate estimates of the impacts of projected climate change. However, the IPCC has already concluded that recent regional changes in temperature have had discernible impacts on the natural environment (e.g., shrinkage of glaciers, thawing of permafrost, and earlier flowering of trees and egg-laying in birds). There is also emerging evidence that some social and economic systems have been affected by recent increasing frequency of floods and droughts in some areas (IPCC, 2001b). Thus, there is an emerging opportunity for impact analysts to compare their projections of impacts against actual observations. For this reason, the TGICA is currently considering how best to use the DDC to direct researchers to data and methods concerning observed impacts.

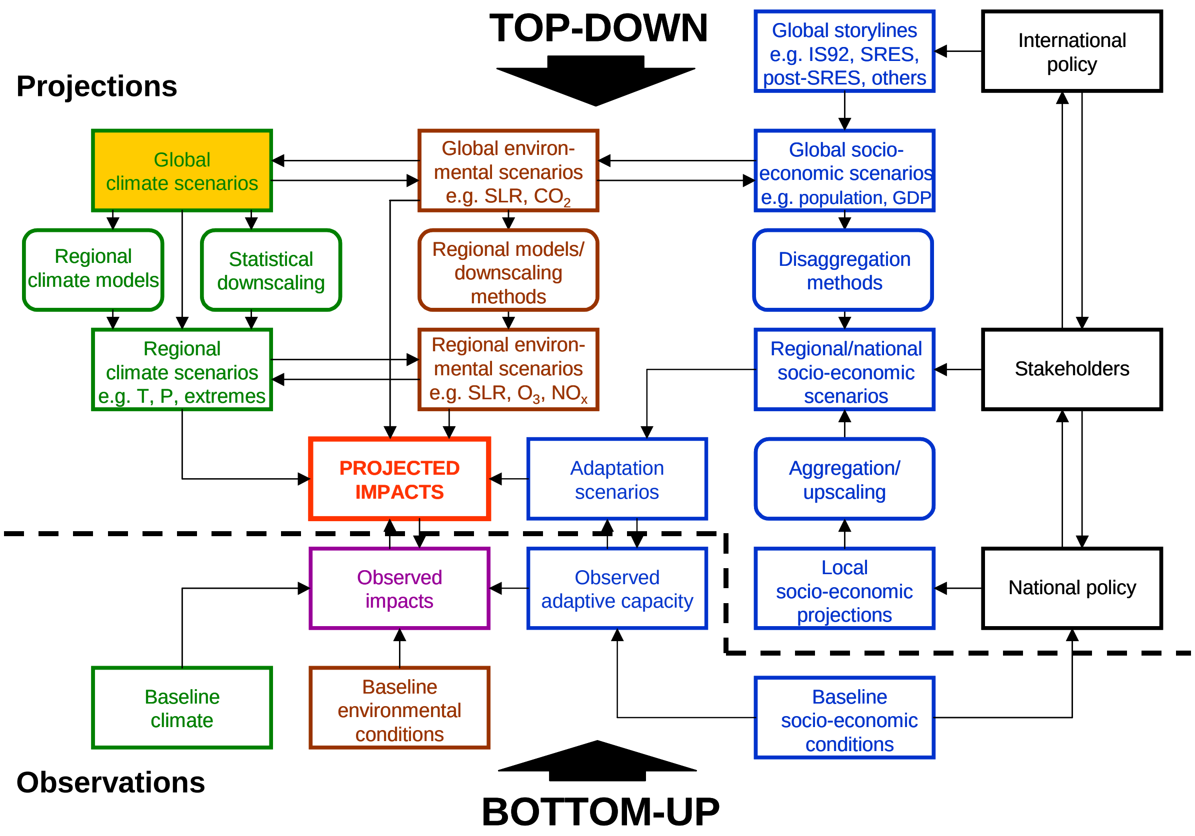

**Figure 1.** Schema of the main scenario elements and guidance material available from the IPCC Data Distribution Centre (DDC). Information above the dashed line comprises projections; below the line observations. For explanation, see text.

# 2. SOCIO-ECONOMIC DATA AND SCENARIOS

## 2.1. Why do we need socio-economic scenarios?

The main purposes of socio-economic scenarios in the assessment of climate impacts, adaptation and vulnerability are:

- to characterise the demographic, socio-economic and technological driving forces underlying anthropogenic greenhouse gas emissions which cause climate change; and
- to characterise the sensitivity, adaptive capacity and vulnerability of social and economic systems in relation to climate change (Carter et al., 2001).

Though greater emphasis in these guidelines is placed on the second objective, the DDC provide information supporting both, recognising that the scenarios underpinning impact and adaptation studies should also be consistent with those assumed for emissions and hence for climate and for other environmental scenarios. Many key parameters such as population and economic growth are common to both types of exercise.

The major underlying cause of rapid changes in atmospheric composition is human economic activity, in particular emissions of greenhouse gases and aerosols, and changing land cover and land use. Socio-economic scenarios that project the major driving factors of change are important for several reasons:

- They improve our understanding of the key relationships among factors that drive future emissions.
- They provide a realistic range of future emissions of net greenhouse gas and aerosol precursors, which can be converted to atmospheric concentrations and associated radiative forcing of the atmosphere, required for estimating future climate change.
- They assist in assessing the relative importance of relevant trace gases and aerosol precursors in changing atmospheric composition and hence climate.
- They offer a consistent framework of projections (albeit at global or aggregate regional scales) that can be applied in climate change impact assessments.

The IPCC Data Distribution Centre disseminates socio-economic information describing the present-day situation and information relating to two sets of emissions scenarios: the SRES scenarios (Special Report on Emissions Scenarios – Nakićenović et al., 2000) prepared for the IPCC Third Assessment Report (2001) and the IS92 scenarios, prepared for the earlier Second Assessment Report (1996). These have a projection period out to 2100 (see below).

### *2.1.1. Socio-economic baseline statistics on the DDC*

The IPCC has published a set of baseline statistics for 195 countries that are representative of the early to mid 1990s. These tabulated data are also available from the Data Distribution Centre. The data were collated from a variety of sources, such as the World Bank, UNEP and FAO, and they comprise a range of factors organised into seven categories (IPCC, 1998):

- <u>Population and human development:</u> total population, current and projected (2025) population density, total urban population, urban population in coastal cities
- <u>Economic Conditions:</u> Gross Domestic Product (GDP) per capita, GDP annual growth rate, GDP from agriculture, from industry and from services
- <u>Land cover/land use:</u> total land area, arable and permanent cropland, permanent pasture, forest and woodland, other land

- Water: water resources per capita, annual withdrawals for domestic, industrial and agricultural use
- Agriculture/food: irrigated land, agricultural labour force, total labour force, stocks of cattle, sheep, goats, pigs, equines, buffalo and camels
- Energy: total commercial energy consumption, commercial hydroelectric consumption, traditional fuel consumption
- Biodiversity: known and endemic mammal, bird and plant species

Clearly these are only selected, summary data and individual impact studies are likely to require information on other factors or at a higher spatial resolution. The original sources of the IPCC data set may be able to provide additional country-level information. Otherwise, national or regional sources of data will need to be accessed.

## 2.2. Socio-economic scenarios

### *2.2.1. The SRES emissions scenarios*

The IPCC published a set of emissions scenarios in 2000 for use in climate change studies (Special Report on Emissions Scenarios – SRES). The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The report adopted the following terminology:

- Storyline: a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces.
- Scenario: projections of a potential future, based on a clear logic and a quantified storyline.
- Scenario family: one or more scenarios that have the same demographic, politico-societal, economic and technological storyline.

The SRES team defined four narrative storylines, labelled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally (**Figure 2**). Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways.

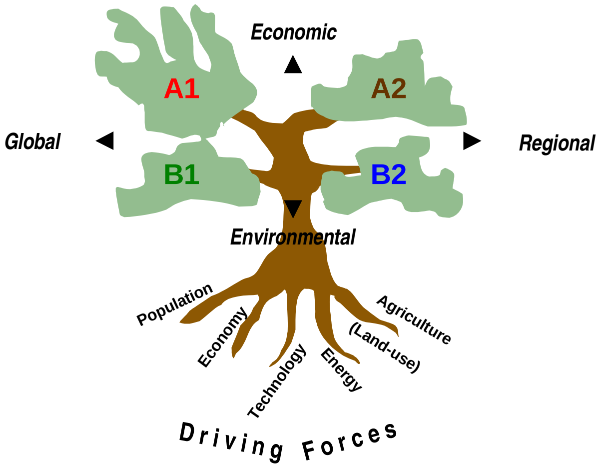

**Figure 2**. The four IPCC SRES scenario storylines (after Nakićenović *et al.*, 2000).

In simple terms, the four storylines combine two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization (**Figure 2**). The storylines are summarized as follows (Nakićenović et al., 2000):

- *A1 storyline and scenario family*: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- *A2 storyline and scenario family*: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
- *B1 storyline and scenario family*: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource-efficient technologies.
- *B2 storyline and scenario family*: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

The basic features of each of the four storylines included quantitative projections of major driving variables such as population and economic development taken from reputable international sources (e,g, United Nations, World Bank and IIASA). The storylines were then fully quantified using integrated assessment models[1], resulting in families of scenarios for each storyline. In all, 40 scenarios were developed by six modelling teams (**Figure 3**).

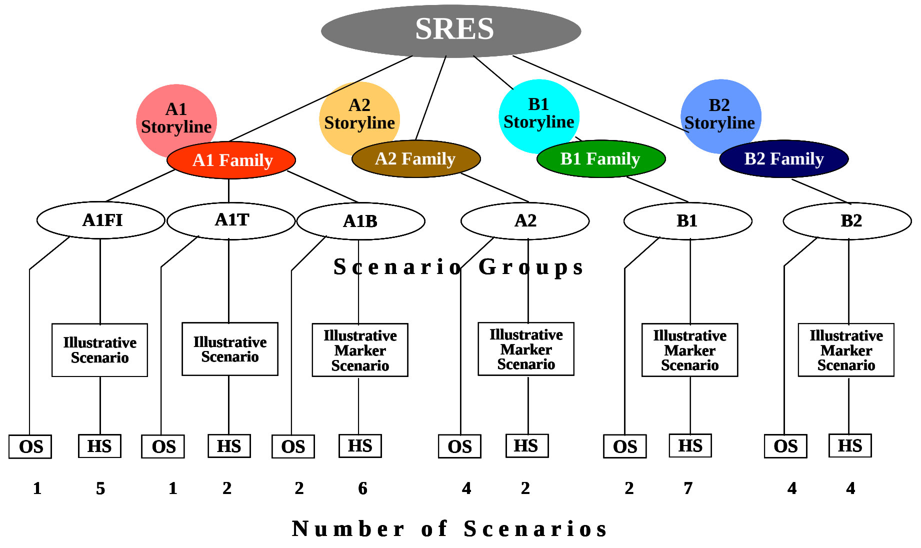

**Figure 3**. Structure of the storylines and scenarios in the IPCC Special Report on Emissions Scenarios, SRES (after Nakićenović *et al.* 2000)

All scenarios were designated as equally valid, with no assigned probabilities of occurrence. Six groups of scenarios were drawn from the four families: one group each in the A2, B1 and B2 families, and three groups in the A1 family, characterising alternative developments of energy technologies: A1FI (fossil intensive), A1T( predominantly non-fossil) and A1B (balanced across energy sources). Illustrative scenarios[2] were selected by the IPCC to represent each of the six scenario groups. Some attributes of these are shown in **Table 1**. The DDC provides quantitative descriptions of the SRES

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[1] Integrated assessment models are computer-based mathematical models used to simulate the social and economic factors that drive greenhouse gas emissions, the effects of greenhouse gas emissions on the global biosphere and climate, and the feedbacks of changes in the biosphere and climate on economies and societies.

[2] Four illustrative scenarios, one for each scenario family, were released in draft form as "marker scenarios" in 1998 so that they could be applied in global climate model simulations in preparation for the IPCC Third Assessment Report. Some of the climate model projections held in the IPCC DDC are based on these preliminary scenarios rather than the final approved SRES scenarios, though differences are relatively minor.

scenarios for variables such as population, GDP and emissions of greenhouse gases and aerosols from different sources, as well as an interpretation – using simple models (cf. Box 5) – of what these different emissions scenarios signify for future global temperature and sea-level change. The assumptions underlying these emissions scenarios (i.e. population, economic growth, etc.) are also described in the online documentation of SRES and are summarised at global scale in **Table 1**.

**Table 1**. Some aspects of the SRES emissions scenarios and their implications for carbon dioxide ($CO_2$) concentration, global temperature and sea-level rise by 2050 and 2100 compared to the IS92a emissions scenario (Leggett *et al.*, 1992). Data in columns 2-4 are taken from Nakićenović *et al.* (2000). Calculations in columns 6-7 are relative to 1990. $\Delta T$ is change in mean annual temperature averaged across simple climate model runs emulating the results of seven AOGCMs with an average climate sensitivity of 2.8°C. $CO_2$ concentrations were estimated using the same model runs. Sea-level rise estimates are based on the temperature changes. SRES-min and SRES-max are minimum and maximum estimates across all 40 SRES scenarios (35 fully quantified scenarios for $CO_2$, $\Delta T$ and sea level). High and low estimates of $CO_2$ concentration and temperature change account for uncertainties in climate sensitivity (across the range 1.7-4.2°C). The sea-level rise range also accounts for uncertainties in model parameters for land ice, permafrost and sediment deposition. Note that scenario values are mutually consistent along all rows except for SRES-min and SRES-max (Source: Carter *et al.*, 2001).

| **Emissions scenario** | **Global population (billions)** | **Global GDP[1] ($10^{12}$ US\$ $a^{-1}$)** | **Per capita income ratio[2]** | **$CO_2$ concentration (ppm)** | **Global $\Delta T$ (°C)** | **Global sea-level rise (cm)** |
|---|---|---|---|---|---|---|
| **1990** | 5.3 | 21 | 16.1 | 354 | 0 | 0 |
| **2000** | 6.1-6.2[3] | 25-28[3] | 12.3-14.2[3] | 367 [4] | 0.2 | 2 |
| **2050** | | | | | | |
| SRES A1FI | 8.7 | 164 | 2.8 | 573 | 1.9 | 17 |
| SRESA1B | 8.7 | 181 | 2.8 | 536 | 1.6 | 17 |
| SRES A1T | 8.7 | 187 | 2.8 | 502 | 1.7 | 18 |
| SRESA2 | 11.3 | 82 | 6.6 | 536 | 1.4 | 16 |
| SRESB1 | 8.7 | 136 | 3.6 | 491 | 1.2 | 15 |
| SRESB2 | 9.3 | 110 | 4.0 | 478 | 1.4 | 16 |
| IS92a | 10.0 | 92 | 9.6 | 512 | 1.0 | – |
| SRES-max | 8.4 | 59 | 2.4 | 463 | 0.8 | 2 |
| SRES-min | 11.3 | 187 | 8.2 | 623 | 2.6 | 29 |
| **2100** | | | | | | |
| SRES A1FI | 7.1 | 525 | 1.5 | 976 | 4.5 | 49 |
| SRESA1B | 7.1 | 529 | 1.6 | 711 | 2.9 | 39 |
| SRES A1T | 7.1 | 550 | 1.6 | 569 | 2.5 | 37 |
| SRESA2 | 15.1 | 243 | 4.2 | 857 | 3.8 | 42 |
| SRESB1 | 7.0 | 328 | 1.8 | 538 | 2.0 | 31 |
| SRESB2 | 10.4 | 235 | 3.0 | 615 | 2.7 | 36 |
| IS92a | 11.3 | 243 | 4.8 | 721 | 2.4 | – |
| SRES-min | 7.0 | 197 | 1.4 | 478 | 1.4 | 14 |
| SRES-max | 15.1 | 550 | 6.3 | 1099 | 5.8 | 80 |

### 2.2.2. *Post-SRES "stabilisation" scenarios*

The SRES scenarios should be regarded as baseline, non-intervention scenarios, since they do not include policies explicitly designed to account for climate change. Researchers are beginning to consider scenarios that are designed to mitigate climate change, termed "post-SRES" scenarios (Morita

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[1] Gross domestic product (trillion 1990 US$ per year)

[2] Ratio of developed countries and economies in transition (UNFCCC-defined Annex I) to developing countries (Non-Annex I)

[3] Modelled range across the six illustrative SRES scenarios

[4] Observed 1999 value (Prentice *et al.*, 2001)

*et al*., 2001). These start with the SRES reference pathways but then depart from them in order to achieve certain mitigation targets (e.g. stabilisation of atmospheric $CO_2$ concentration at a pre-specified level). Interestingly, although they are non-intervention scenarios, some of the SRES scenarios closely resemble mitigation scenarios because they assume policies that promote emissons reduction for other reasons than climate. These similarities have been analysed by Swart et al. (2002) who suggested that, in the absence of climate model projections based directly on stabilisation scenarios, some projections based on SRES emissions scenarios could be used a surrogates for stabilisation scenarios[1]. For instance, the radiative forcing which can be associated with stabilisation at 750 ppm is very similar to that associated with the A1B base case. Their other suggestions for surrogate scenarios are given in **Table 2**. They also point out that there is no surrogate in the SRES scenarios for stabilisation at 450 ppm, which is one of the levels that has been considered by policy-makers.

**Table 2**. The six SRES illustrative scenarios and the stabilisation scenarios (parts per million $CO_2$) they most resemble (based on Swart *et al*., 2002).

| SRES illustrative scenario | Description of emissions | Surrogate stabilisation scenario |
|---|---|---|
| A1FI | High end of SRES range | Does not stabilise |
| A1B | Intermediate case | 750 ppm |
| A1T | Intermediate/low case | 650 ppm |
| A2 | High case | Does not stabilise |
| B1 | Low end of SRES range | 550 ppm |
| B2 | Intermediate/low case | 650 ppm |

### *2.2.3. The IS92 emissions scenarios*

Prior to the development of the SRES scenarios, the IS92 emissions scenarios were widely applied in impact and adaptation assessments. Six alternative scenarios (IS92a to f) were published in the 1992 Supplementary Report to the IPCC Assessment (Leggett *et al*., 1992). These scenarios embodied a wide array of assumptions affecting how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted. The different worlds that the scenarios imply vary widely in terms of economic, social and environmental conditions, and the resulting range of possible greenhouse gas futures spans almost an order of magnitude.

The assumptions for the IS92 scenarios came mostly from the published forecasts of major international organisations or from published expert analyses. Most of these were subject to extensive review. The premises for the IS92a and IS92b scenarios most closely resembled and updated those underpinning the earlier SA90 scenario used in the First Assessment Report of the IPCC in 1990. IS92a was widely adopted as a standard scenario for use in impact assessments, although the original IPCC recommendation was that all six IS92 emissions scenarios be used to represent the range of uncertainty in emissions (Alcamo *et al*., 1995). Population rises to 11.3 billion by 2100 and economic growth averages 2.3 % per annum between 1990 and 2100, with a mix of conventional and renewable energy sources being used. The highest greenhouse gas emissions result from the IS92e scenario that combines, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and eventual phase out of nuclear power. At the other extreme, IS92c has a $CO_2$ emissions path that eventually falls below its 1990 starting level. It assumes that population first grows, then declines by the middle of next century, that economic growth is low, and that there are severe constraints on fossil fuel supply.

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[1] These are reasonable approximations bearing in mind the uncertainty ranges of emissions scenarios and the fact that AOGCM experiments are not expected to lead to significantly different results for small differences in greenhouse gas concentrations (e.g. below 50 ppm) and associated radiative forcing (Swart et al., 2002).

**Table 3** summarises some of the main assumptions of the IS92 scenarios at global scale. The Data Distribution Centre also provides tabular listings for nine major world regions. Also shown in **Table 3** are the atmospheric composition associated with these scenarios, and their climatic and sea-level consequences. The latter estimates were made using a set of simple models described in Box 5.

Few of the IS92 socio-economic scenarios have been used directly in impact assessments, and since the SRES scenarios are now available it is suggested that these rather than the IS92 scenarios be adopted in any new studies. The IS92 scenarios are described here mainly as background information for the set of climate scenarios based on these emissions that are available from the DDC.

**Table 3**. Summary of the IS92 scenarios and their estimated environmental consequences. IS92 emissions used in calculations are taken from IPCC (1994). Model calculations are by the IPCC Second Assessment Report version of MAGICC (Wigley and Raper, 1992; Version 2.3, May 1997). Changes are with respect to the 1961-90 average. Aerosol effects are included.

| | | **IS92 scenarios for 2100** | | | | | |
|---|---|---|---|---|---|---|---|
| **Scenario estimates** | **1990** | **IS92a** | **IS92b** | **IS92c** | **IS92d** | **IS92e** | **IS92f** |
| Population (billion) | 5.252 | 11.3 | 11.3 | 6.4 | 6.4 | 11.3 | 17.6 |
| Economic growth rate (annual GNP; % p.a.) | - | 2.3 | 2.3 | 1.2 | 2.0 | 3.0 | 2.3 |
| $CO_2$ concentration (ppm)[1] | 354 | 708 | 685 | 471 | 542 | 954 | 820 |
| Global annual-mean temp. change (°C)[2] | - | 2.18 | 2.13 | 1.47 | 1.75 | 2.64 | 2.52 |
| Range (°C)[3] | - | 1.50-3.14 | 1.46-3.06 | 1.29-2.18 | 1.18-2.56 | 1.83-3.73 | 1.74-3.59 |
| Global mean sea-level rise (cm)[2] | - | 51 | 50 | 40 | 45 | 57 | 56 |
| Range (cm)[3] | - | 20-90 | 20-89 | 14-76 | 16-82 | 24-98 | 23-96 |

## 2.3. Applying socio-economic scenarios

The methods employed to describe future socio-economic conditions in an impact study alongside concurrent future climate and other environmental changes depend a lot on the scale of analysis. A distinction can be drawn between *top-down* and *bottom-up* approaches to scenario development, although many assessments are likely to require elements of both approaches.

### *2.3.1. The "top-down" approach*

For assessments conducted at global and sub-continental scale, it may be quite appropriate to apply socio-economic projections produced by international agencies such as the United Nations and World Bank. The SRES and IS92 scenarios are examples of scenarios pertaining to such large regions. Some of these are, in fact, aggregated from projections at national scale, so there may also be scope to conduct analysis at national scale, even if the results are expressed in aggregate form. This "top-down" approach (cf. **Figure 1**) has been pursued in several recent global studies of water resources (e.g., Alcamo *et al*., 1997; Arnell, 1999, 2001), ecosystems (e.g., White *et al*., 1999), food security (e.g., Parry *et al*., 1999, Fischer *et al*., 2002), coastal impacts (e.g., Nicholls *et al*., 1999), human health (Martens *et al*., 1999), and environmental risks in general (e.g., Alcamo *et al*., 2001; Parry *et al*., 2001). Box 2 (from Carter *et al*., 2001) illustrates how one set of global studies applied socio-economic scenarios alongside scenarios of land use, climate and other environmental changes.

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[1] Best-guess assumptions for the carbon cycle
[2] Assuming 2.5ºC climate sensitivity
[3] Based on 1.5ºC and 4.5ºC climate sensitivity range

## Box 2: An illustration of multiple scenario use in a global-scale impact study

In this assessment, the prospective effects of unmitigated climate change during the 21st century were estimated at a global scale in five sectoral studies (**Table 4**). Each study had different scenario requirements, though some were common to several studies. For example, the ecosystems study estimated potential biomass on the basis of scenarios of climate, $CO_2$ concentration and nitrogen deposition, but it ignored future land-cover and land-use changes that would be expected regardless of climate change. In contrast, the study on food security examined the effects on crop productivity of the same scenarios of climate (though for fewer variables) and $CO_2$ concentration, it too ignored likely land-cover and land-use changes, it did not consider effects of nitrogen deposition, but it adopted a range of socio-economic and technological scenarios to evaluate the number of persons at risk from hunger.

Notably, across all the studies the scenarios adopted were designed to be mutually consistent. For instance, the population and GDP scenarios were those adopted in constructing the IS92a emissions scenario (Leggett *et al.*, 1992). An approximation of the IS92a emissions scenario was used to force the HadCM2 and HadCM3 general circulation models that were employed to construct the climate and sea-level scenarios (Hulme *et al.*, 1999b). Other scenarios were chosen to be broadly consistent with these assumptions. The scenarios were required as inputs to global impact models, and results from these are described elsewhere in this report. Finally, it should also be noted that while these studies are compatible and consistent, they are not integrated across sectors. For example, climate-induced changes in water resources for irrigation are not accounted for in estimates of future food security.

**Table 4**. Summary of the scenarios adopted in an assessment of global impacts on five sectors (Parry and Livermore, 1999)

| | **Impacts** | | | | |
|---|---|---|---|---|---|
| **Scenario type (up to 2100)** | Ecosystems [a] | Water resources [b] | Food security [c] | Coastal flooding [d] | Malaria risk [e] |
| **Socio-economic/technological**: | | | | | |
| Population | – | √ | √ | √ | √ |
| Gross Domestic Product | – | – | √ | √ | – |
| GDP/capita | – | – | √ | √ | – |
| Water use | – | √ | – | – | – |
| Trade liberalisation | – | – | √ | – | – |
| Yield technology | – | – | √ | – | – |
| Flood protection | – | – | – | √ | – |
| **Land-cover/land-use change** | – | – | – | √ | – |
| **Environmental**: | | | | | |
| $CO_2$ concentration | √ | – | √ | – | – |
| Nitrogen deposition | √ | – | – | – | – |
| **Climate**: | | | | | |
| Temperature | √ | √ | √ | – | √ |
| Precipitation | √ | √ | √ | – | √ |
| Humidity | √ | √ | – | – | – |
| Cloud cover/radiation | √ | √ | – | – | – |
| Windspeed | – | √ | – | – | – |
| Diurnal temperature range | √ | – | – | – | – |
| **Sea level** | – | – | – | √ | – |

a White *et al.* (1999); b Arnell (1999); c Parry *et al.* (1999); d Nicholls *et al.* (1999); e Martens *et al.* (1999)

The original SRES scenarios were presented only for world "macro-regions" (Nakićenović *et al.*, 2000)[1], and are hence too coarse in resolution for most impact and adaptation studies. To address this problem, there have been several recent attempts to disaggregate these scenarios to national-scale estimates of population and GDP (e.g., Gaffin *et al.*, 2004; 2005; van Vuuren *et al.*, 2005).

### *2.3.2. The "bottom-up" approach*

Many impact and adaptation studies have an exclusively local focus, or require geographically explicit information before aggregating results to national or regional scale. For such studies, it is often inappropriate to attempt to use simple downscaling approaches to obtain local estimates from global projections such as the SRES and IS92 scenarios. For example, population trends at national scale, and over large regions may be upward, but this may mask important trends in migration from rural to urban areas. Nationally-averaged scenarios of per capita income or wealth may distort large disparities in the ratio between rich and poor.

Of course, if a sensible assessment of vulnerability to climate change is to be conducted at the community level, then projections of community development should be compatible with ongoing and prospective trends. In order to obtain credible scenarios at the local and regional scale, historical data and information about ongoing trends are of great importance. Furthermore, qualitative and anecdotal information from local resource managers, policy makers and other stakeholders can provide very useful supplementary material. In some cases, this may be the only source of information available. However, the role of local stakeholders becomes even more important in projecting trends into the future. Here, some reference to national estimates downscaled from global scenarios (see the "top-down" approach, above) may provide a framework for scenario development, but the plausibility and credibility of scenarios will ultimately be judged by experts at local scale. This "bottom-up" approach to scenario development requires access to local knowledge and data, and provision of such information is well outside the scope of the DDC. However, some guidance on the formulation of socio-economic scenarios at local scale is offered, for example, by UNDP-GEF (2003), and guidance on scenarios for adaptation is under development by the TGICA.

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[1] The four SRES macro-regions are: OECD90 – members of the Organization of Economic Co-operation and Development in 1990; Annex II countries as defined by the UN Framework Convention on Climate Change (UNFCCC, 1992); REF – countries in Eastern Europe and the Former Soviet Union undergoing economic reform (Annex I countries outside Annex II); ASIA – all developing (non-Annex I) countries in Asia; ALM – rest of the world, including all developing (non-Annex I) countries in Africa, Latin America and the Middle East.

# 3. CLIMATE DATA AND SCENARIOS

In order to have a basis for assessing future impacts of climate change, it is necessary to obtain a quantitative description of the changes in climate to be expected (climate scenarios). However, before considering future climate it is first important to characterise the present-day or recent climate in a region – often referred to as the climatological baseline. The choice of both baseline and scenarios can strongly influence the outcome of a climate impact assessment, and both issues are treated in turn in the following sections.

## 3.1. The climatological baseline

In order to characterise the present-day or recent climate in a region, good quality observed climatological data are required for a given baseline period. Issues to consider in selecting the climatological baseline include the types of data required, duration of the baseline period, sources of the data and how they can be applied in an impact assessment.

### *3.1.1. Data needs of the impacts community*

The baseline climatological information required by impact analysts varies enormously from study to study. Some options include:

- <u>Variables:</u> The most common variables applied in impact studies are surface (screen height) observations of air temperature and precipitation. However, many impact models require a larger set of surface variables as input, for example, solar radiation, humidity, windspeed, soil temperature and snowcover. In addition, for certain scenario construction procedures (e.g. statistical downscaling from GCM outputs), daily upper air data, mean sea-level pressure or circulation indices may also be needed. Derived variables, such as accumulated temperature, evapotranspiration and runoff, are rarely required in impact studies, as these are usually computed directly from primary observations. However, some indices may be useful for identifying important large scale climatic variations, including the Southern Oscillation Index (related to El Niño/La Niña events), the North Atlantic Oscillation (associated with mid-latitude atmospheric circulation), the strength of the Asian monsoon, and indices of large volcanic eruptions and solar activity.
- <u>Spatial scale:</u> Data requirements may be for a single site (e.g. for testing complex impact models such as crop climate models), a region (e.g. a dense network of sites over a river catchment) or the whole globe (e.g. for modelling human disease risk using interpolated data over a grid).
- <u>Temporal resolution:</u> This may range from annual through seasonal and monthly means to daily or sub-daily time steps. In some cases long-term averages may suffice (e.g. for mapping vegetation distribution) but in others annual time series are essential (e.g. for computing peak demand for space heating or cooling). Finally, studies of disasters often require knowledge of the distribution of extremes in certain time windows (e.g. for computing the risk of storm surges).

### *3.1.2. Baseline period*

The baseline period is usually selected according to the following criteria (IPCC, 1994):

- representative of the present-day or recent average climate in the study region;
- of a sufficient duration to encompass a range of climatic variations, including a number of significant weather anomalies (e.g. severe droughts or cool seasons);
- covering a period for which data on all major climatological variables are abundant, adequately distributed over space and readily available;
- including data of sufficiently high quality for use in evaluating impacts;
- consistent or readily comparable with baseline climatologies used in other impact assessments.

A popular climatological baseline period is the non-overlapping 30-year "normal" period as defined by the World Meteorological Organization (WMO). The current WMO normal period is 1961-1990. As well as providing a standard reference to ensure comparability between impact studies, other advantages of using this baseline period include:

- The period ends in 1990, which is the common reference year used for climatic and non-climatic projections by the IPCC in the First, Second and Third Assessment Reports.
- It represents the recent climate, to which many present-day human or natural systems are likely to have become reasonably well adapted (though there are exceptions, such as vegetation zones or groundwater levels, that can have a response lag of many decades or more relative to the ambient climate).
- In most countries, the observed climatological data are most readily available for this period, especially in computer-coded form at a daily time resolution.

Nevertheless, in selected cases there may be difficulties with adopting this baseline period, including:

- In some countries there is better access to data from an earlier period (e.g. 1951-1980 or 1931-1960).
- In some, though not all, regions more recent periods may already contain a significant warming trend which may be greenhouse gas related. Globally, it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record, since 1862 (IPCC 2001a, p. 2). Moreover, recent years have also been characterised by a high frequency of El Niño events, some of them very strong.
- Climatological data from the 1990s and 2000s will certainly be required for the calibration and testing of many impact models. Moreover, 1961-1990 is already being superseded by 1971-2000 as a new standard 30-year averaging period, and some national meteorological agencies have published statistics for this period. Nevertheless, it commonly takes between 1 and 5 years for these normals to become widely available worldwide and, in addition, the 1971-2000 period is not an official WMO normal period. The next official WMO normal period will be 1991-2020.
- A 30-year period may not be of sufficient duration to reflect natural climatic variability on a multidecadal timescale, which could be important in considering long-term impacts.

### *3.1.3. Obtaining baseline climatological data*

There are a number of alternative sources of baseline climatological data that can be applied in impact assessments. These are not mutually exclusive, and include:

- National meteorological agencies and archives
- Supranational and global data sets
- Climate model outputs
- Weather generators

#### *3.1.3.1. National meteorological agencies and archives*

The most common source of observed climatological data applied in impact assessments is the national meteorological agencies. It is these agencies that usually have responsibility for the day-to-day operation and maintenance of national meteorological observational networks for purposes of weather forecasting and other public services. They are also relied upon to transmit surface and upper air observations from key "synoptic" sites in real time over the global telecommunications system for use in numerical weather prediction models. It is usual for these observations, along with data from other climatological and hydrological stations, to be processed and stored in archives by the responsible agency. Many agencies also routinely interpolate station data onto a regular grid, for a range of spatial applications.

In many cases, summary statistics are published in yearbooks or as climatological normals (for 30-year periods), although there can be time lags of several months or years between observations being collated, quality controlled, analysed and published. However, most data used in impact assessments nowadays are required in digital form. These data can usually be obtained by potential users, but under a variety of terms (including cost) that are highly country and case specific. To illustrate the great diversity of data availability, in a survey of 39 national meteorological agencies in Europe, the cost of obtaining a comparable set of 30-year mean monthly climatological normals varied from no charge to as much as 297 US$ per variable per station (Hulme, 1994).

Data are commonly available from national agencies at time resolutions ranging from hourly to monthly, and while adequate monthly data can frequently be obtained from global or regional data sets (see below) station data at a daily resolution or higher are usually obtained from national sources.

#### *3.1.3.2. Supranational and global data sets*

As well as serving national needs, climatological data from different countries have also been combined into various supranational and global data sets. These have been developed to serve various needs, including:

- Monitoring of observed variations in global and regional climate and detection of anthropogenically-induced climate change
- Testing and development of numerical weather prediction models
- Validation of global climate models, to compare simulated with observed climate
- Regional and global-scale climate impact assessments, as inputs to impact models

The data sets include observations of surface variables at a monthly time step over land and ocean, surface and upper air observations at a daily time step from sites across certain regions and, for recent decades, satellite observations. Many of these data sets are available as mean values, for various periods, often interpolated to a regular grid. However, with improved processing and storage capacity, there are now a number of historical data sets providing annual time series of gridded or site observations.

A selection of data sets that are available in the public domain (e.g. through the Internet) are listed in **Table 5**. One of these, the CRU Global Climate Data set, is being made directly available for use from the Data Distribution Centre (see below).

#### *3.1.3.3. Climate model outputs*

There are two types of information from global climate models that may also be useful in describing the climatological baseline: reanalysis data and outputs from GCM and RCM simulations.

<u>Reanalysis data</u>**:** These are fine resolution gridded data which combine observations with simulated data from numerical models. Through a process known as data assimilation, the observations (available only sparsely and irregularly over the globe), along with data from satellites and information from a previous model forecast, are input into a short-range weather forecast model. This is integrated forward by one time step (typically 6 hours) and combined with observational data for the corresponding period. The result is a comprehensive and dynamically consistent three-dimensional gridded data set (the "analysis") which represents the best estimate of the state of the atmosphere at that time. The assimilation process fills data voids with model predictions and provides a suite of constrained estimates of unobserved quantities such as vertical motion, radiative fluxes, and precipitation.

Large quantities of past observational data that were used operationally as inputs to earlier versions of weather forecasting models have subsequently been "reanalysed" using the current generation of numerical models to produce high resolution data sets. Examples are also included in **Table 5**. These data sets are primarily used by atmospheric scientists for model development and testing. However, impact analysts and scenario developers are increasingly finding uses for such data, for instance, by examining observed relationships between reanalysed upper air fields and surface variables to produce regional climate scenarios downscaled from GCM outputs (e.g. Kaas and Frich, 1995). It should be noted, however, that some reanalysis variables, especially precipitation, are unreliable and should not normally be used as proxies for observed climate data (Widmann and Bretherton, 2000)

**Table 5**. Some public domain sources of baseline climatological data (illustrative, not comprehensive). Links to many sites can be found at the IPCC Data Distribution Centre[1]

| Type of baseline data | Source |
|---|---|
| Various types | World Data Center - A, Meteorology |
| Observed climate | The CRU Global Climate Data set (IPCC Data Distribution Centre)<br>Global Historic Climatology Network (GHCN)<br>International Research Institute for Climate Prediction/Lamont-Doherty Earth Observation at University of Columbia<br>British Atmospheric Data Centre (BADC)<br>Global Precipitation Climatology Centre (GPCC)<br>National Centre for Atmospheric Research (NCAR) Data Support System<br>Climatic Research Unit (CRU) data<br>Climate Diagnostics Centre at NOAA<br>Comprehensive Ocean-Atmosphere Data Set (COADS) at NOAA |
| Reanalysis data | NCEP Re-analysis Data<br>ECMWF |
| GCM control simulations | IPCC Data Distribution Centre |
| Weather generators | LARS Weather generator<br>ClimGen Climatic Data Generator |

Outputs from GCM and RCM simulations: Another model-based source of information on the present-day climate is multi-century control simulations from AOGCMs. These simulations attempt to represent the dynamics of the global climate system unforced by anthropogenic changes in atmospheric composition. For some regions and on some time-scales these model estimates of natural variability are quite similar both to observations (Tett *et al*., 1997) and to climatic fluctuations reconstructed from proxy records over the past millennium (Jones *et al*., 1998). Since observations with a reasonable global coverage barely extend beyond one century in duration, model control simulations offer an alternative source of data enabling impact analysts to investigate the impact of multi-decadal variations in climate. Control simulation data from seven AOGCMs are currently available from the Data Distribution Centre.

Unforced (control) AOGCM outputs can be very useful for representing natural climate variability. However, comparison of these with observed climate for the late 20th century would be somewhat misleading, as they do not account for the historical radiative forcing that is believed to have affected global climate and is discernible in the observational record. A rigorous test of the performance of climate models would be to use forced model outputs for the baseline period as direct inputs to impact models. Previous attempts at this have shown that the discrepancies between AOGCM outputs and observed climate are too large to provide useful estimates of present-day impacts (e.g. Mearns et al., 1992). However, recent experiments at higher resolution using AGCMs or regional climate models

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[1] http://ipcc-ddc.cru.uea.ac.uk/obs/index.html

(RCMs) nested within AOGCMs or AGCMs, suggest that the use of direct model outputs may soon become worthy of consideration by impact analysts. This is currently being tested (e.g., see Christensen et al., 2002), and though high resolution model outputs may provide reliable information when driven by realistic boundary conditions (e.g. using reanalysis data), it is still GCMs that supply the boundary conditions for climate change simulations, and these are prone to large errors.

#### *3.1.3.4. Weather generators*

A fourth method of characterising the baseline climate is to apply stochastic weather generators (see Box 1). These are computer models that generate synthetic series of daily or sub-daily resolution weather at a site conditional on the statistical features of the historically observed climate. The use of a weather generator (WG) offers several advantages in impact assessment, including:

- The possibility to substitute large quantities of daily observational station data, which are often required as an input to impact models, with a simple model requiring a few parameters describing the statistical properties of the distributions of these values.
- The opportunity to obtain representative weather time series in regions of data sparsity, by interpolating the statistical distribution parameters obtained by running a weather generator using observed data from the nearest climate stations.
- The ability to generate time series of unlimited length, which may be useful in long-term (e.g. multiple-century) or ensemble simulations with impact models. Note, however, that more sophisticated methods are required to reproduce observed inter-annual and longer-term variability (e.g. El Niño/Southern Oscillation or North Atlantic Oscillation events), but weather generators have been successfully conditioned on ENSO phases (Wang and Connor, 1996; Woolhiser et al., 1993) and NAO signals (Wilby, 1997).
- The option to alter the statistical characteristics (parameters) of selected variables according to scenarios of future climate change, representing not only mean changes but also changes in climatic variability.

There are also potential limitations or hazards in using weather generators that should be noted:

- They are seldom able to describe all aspects of the climate accurately, especially persistent events like droughts and warm spells, rare events like heavy rainfall and decadal- or century-scale variations. A weather generator is only able to reproduce events which exist in the observed climate record used to calibrate the generator. Use of as long a climate record as possible in the calibration process means that the generator may be more successful at simulating events such as droughts, warm spells and heavy rainfall. However, one of the main assumptions in stochastic weather generation is that a stationary climate record is used to calibrate the model. If trends exist in the observed data (such as a warming trend which may be apparent in some station records), these must be removed before calibration is undertaken or the generator is likely to perform poorly.
- They rely on statistical correlations between climatic variables derived from historical observations that may not be valid under a changed climate.
- They are usually designed for use, independently, at individual locations and few account for spatial correlation of climate (see Box 1).

There are several well documented WGs available in the public domain that are available for use by impact analysts. Two of these are also included in **Table 5**.

## Box 3: Stochastic weather generators

### *Description*

A stochastic weather generator (WG) produces synthetic time series of weather data of unlimited length for a location based on the statistical characteristics of observed weather at that location. Models for generating stochastic weather data are conventionally developed in two steps (Hutchinson 1987). The first step is to model daily precipitation and the second step is to model the remaining variables of interest, such as daily maximum and minimum temperature, solar radiation, humidity and windspeed conditional on precipitation occurrence. Different model parameters are usually required for each month, to reflect seasonal variations both in the values of the variables themselves and in their cross-correlations.

### *The "Richardson" and "serial" types*

Perhaps the best known approach for developing weather generators was reviewed by Richardson (1981), and WGs based on the approach are often referred to as the "Richardson-type". At the first step, the estimation of precipitation involves first modelling the occurrence of wet and dry days using a Markov procedure, and then modelling the amount of precipitation falling on wet days using a functional estimate of the precipitation frequency distribution. The remaining variables are then computed based on their correlations with each other and with the wet or dry status of each day. The Richardson-type of generator has been used very successfully in a range of applications in hydrology, agriculture and environmental management.

One criticism of the Richardson-type WG is its failure to describe adequately the length of dry and wet series (i.e. persistent events such as drought and prolonged rainfall). These can be very important in some applications (e.g. agricultural impacts). For this reason an alternative, "serial approach" has been developed (Racsko *et al.*, 1991), which first models the sequence of dry and wet series of days and then models other weather variables like precipitation amount and temperature as dependent on the wet or dry series.

### *Using WGs in impact assessment*

The decision to apply a weather generator in an impact assessment may be determined by one or more of the following requirements:

- Long time series of daily weather, which are not available from observational records
- Daily weather data in a region of data sparsity
- Gridded daily weather data for spatial analysis (e.g. of risk)
- The ability to investigate changes in both the mean climate and its inter-daily variability

Once the decision is made, a suitable WG should then be selected. The criteria for selection will depend upon what models are available and how their documented features suit the needs of the impact assessment. It may be necessary to test a number of models to assess their suitability.

After selecting a model, several steps of analysis are required to parameterise and test the WG:

1. *Data collection* - observed daily climatological data for the variables and site(s) of interest should be collected, quality controlled and correctly formatted. If the WG is to be parameterised for a 1961-1990 baseline period, as much data as possible from this period will be required. On the other hand, if it is important to model low frequency, high magnitude events, it will be desirable to obtain the longest possible observed time series. For spatial applications, between-site consistency of the observational time period may also be important.
2. *Parameterisation* - the parameters of the model are estimated using methods documented for the weather generator. If spatial analysis is also being undertaken, this will require parameter estimation at many sites and subsequent interpolation of the parameters to a grid or other spatial field. Some WG programs have automatic procedures for parameter estimation.

3. *Model testing* - time series of weather are generated and their statistics analysed and compared with the observed data on which they were based. The significance of any discrepancies between the WG-derived and observed series can be assessed by running both series through an impact model. Again, automatic model testing procedures are built in to some public domain WG programs.
4. *Climate scenarios* - if the WG is to be used to create weather time series representing a changed climate, procedures will also be required for applying climate change information (e.g. on climate variability change from GCMs) as adjustments to the parameters of the WG. Some WG software also handles climate scenarios.

***Applying WGs over space***

Weather generators using different approaches have been tested and applied in climate impact assessment (e.g. Wallis and Griffiths, 1995; Harrison *et al*., 1995), and the approaches have also been compared (e.g. Johnson *et al.*, 1996; Semenov *et al.*, 1998; Qian *et al.*, 2004). While they are most commonly applied at sites, methods have also been developed to interpolate the site parameters of WGs over space, facilitating spatial analysis (e.g. of risk). However, because WG time series are usually site-independent and ignore the observed spatial correlation of climate, this can limit the value of some spatial impact assessments.

For example, a WG may simulate the occurrence of 3 prolonged droughts in a 30 year time series at location A. It may also simulate the same number of droughts at a nearby location B, but in different years. On the other hand, the observed climate at both locations may also show three drought years, but it is likely that these are the same years at both locations, since drought is commonly a widespread phenomenon. Thus, while the WG may provide an accurate statistical representation of the observed situation at each individual site (i.e. the risk of drought and its local impact), taken together, the droughts are not simultaneous and the aggregate impact (e.g. on water resources or agriculture) is likely to be less severe than in the real situation, where widespread drought affects a large area.

A further discussion of this problem and of efforts being made to develop stochastic space-time weather models can be found in Hutchinson (1995). Examples of WG approaches that attempt to preserve the spatial correlations of extremes occurrence include Palutikof et al. (2002), Wilby *et al*. (2003) and Wilks (1999a, b). An account of the role of WGs in climate scenario development is also provided in Mearns et al. (2001).

### 3.1.4. Applying baseline climatological data

The primary objective in applying baseline data in an impact assessment is to characterise the sensitivity of the exposure unit to present-day climate. This commonly involves first, using part of the data to calibrate and test impact models and second, running the models with input data from the entire baseline period to estimate reference impacts.

Once the baseline data have been obtained, there are several options available for applying them in an impact assessment. A number of these are described below.

#### *3.1.4.1. Extreme event analysis*

Analysis of the baseline climate is a key step in studies that focus on the vulnerability of an exposure unit to climatic variability. Both the impacts themselves and possible adaptive responses to climatic variability are often closely related to the magnitude and frequency of extreme events. Thus, a special focus on these events is often merited in the baseline analysis. Three possible options include:

- A focus on the absolute climatic extreme in the record (e.g. a drought, cold year, heavy rainfall event, gale), which might be justified, for example, if the frequency of such events is anticipated to increase in the future. It might be defined directly, as an extreme in the observational climate record, or from a climatic index (e.g. the Southern Oscillation Index to indicate El Niño events).

Alternatively, it could be defined as the climatic conditions responsible for an extreme impact, either recorded or simulated.

- A focus on infrequent but recurrent extreme events, which are anomalies that occur more frequently than the absolute extremes, but still cause significant impacts. Due to their greater frequency, they may be more important in shaping the adaptive responses of an exposure unit (for example, the effects of typhoons in low lying coastal areas). Any increase in their frequency might have damaging, perhaps irreversible effects. For example, an early set of studies on the effects of drought on agriculture in semi-arid regions focused on the 1-in-10 year anomaly (Parry *et al.*, 1988).
- A focus on consecutive anomalies, the impacts of which by themselves might be absorbed by an exposure unit, but in succession may have disproportionately greater consequences. For example, one year of drought may force a subsistence farmer to draw on savings or take out loans to pay for the following year's seed, relying on a good crop the following year to make up the shortfall. In this case, a second drought-related crop failure can lead to financial ruin. An example of clustering in precipitation and temperature anomalies in the United Kingdom, which imposed severe stress on the level and distribution of water resources, is presented by Marsh and Turton (1996)

#### *3.1.4.2. Applying time series of baseline observations*

Probably the most common method of defining the baseline climate is to apply climatic time series for a 30-year period either at individual sites or interpolated to a grid. In cases for which a longer period baseline than 30 years is required (for example, to estimate the growth of trees or the risk from storm surges) one option is to apply long-term observations, if they are available. More commonly they are not, so a second option might be to apply a repeating observed 30-year baseline time series over the required time period. Problems with this approach include the possibility that trends or cycles in the baseline period are repeated (unrealistically) throughout the extended series, as well as the likelihood that the 30-year baseline period does not encompass the full range of climatic variability that might be expected in a longer-term series.

#### *3.1.4.3. Applying time series of synthetic data*

In impact studies that make use of synthetic time series from weather generators, an important distinction needs to be made between the *precision* and the *accuracy* of the generated statistics. Since there is a random component in the selection of values, the statistics of one time series can differ from those of another of identical length for the same location. The magnitude of this difference depends on the variable in question and the length of the series. As the time series is lengthened, its statistics will converge to a stable set of values (i.e. the precision will be improved). In contrast, the accuracy of the time series describes how well the series reproduces the statistics of the corresponding observations. This can be evaluated by comparing the statistics of very long (and precise) synthetic series with the observed series.

Thus, while the accuracy of the WG can only be improved by modifying the generator itself, the precision of the time series can be enhanced by employing a longer time series. Specifying a suitable length of series often involves a compromise between, on the one hand, obtaining an acceptable precision for the climatological data (and the impacts derived from these data) and, on the other hand, maintaining the volume of data generated at a manageable level. This compromise is of particular importance when generating time series of data regionally, over a regular grid. In this case, the spatial coherence of the generated climatic statistics and of the computed regional impacts is closely dependent on the precision of the time series. Note that spatial coherence refers here to long-term climatic statistics rather than daily weather. As explained in Box 1, most WGs produce a daily weather series at a point that is independent of the series at neighbouring locations.

#### *3.1.4.4. GCM control simulations and baseline climate*

A mention should also be made of the analysis of outputs from the control simulations of GCMs in relation to the baseline climate in a region. Two points can be noted, which relate to GCM validation and use of the GCM control simulation in impact assessments.

- GCM validation: One of the criteria commonly used in selecting a GCM to be used in constructing regional climate scenarios for impact assessment is the performance of the GCM in simulating the present-day climate in the region. This is evaluated by comparing the model outputs with observed climate in the target region, and also over larger scales, to determine the ability of the model to simulate large scale circulation patterns. Examples of graphical comparisons between GCM outputs and observed climate for the 1961-1990 period for subcontinental world regions can be found in Ruosteenoja et al. (2003). Other measures of GCM performance are described in section 3.2.3.1.

- Use of the GCM control in impact assessments: In most impact applications, the baseline climate is represented by observations or synthetic data based on observations. GCM information is only used to define the change in climate between the present-day and some future condition. However, data from GCM control simulations have been applied directly as the input to impact models in a few exploratory studies (e.g. Mearns et al., 1992; Mavromatis and Jones, 1999). Furthermore, century-scale control simulations have been used to characterise the natural variability of climate that shorter observational time series cannot show. For example, a recent impact study estimated the simulated runoff and wheat yields across Europe for the baseline observed climate, 1961-1990, using a hydrological model and a crop growth simulation model (Hulme *et al.*, 1999a). The baseline climate was then adjusted according to the variations in climate between eight, non-overlapping 30-year periods of an AOGCM control simulation. The range of results based on these eight plausible baseline climates was then compared with estimates of runoff and yield under a changing climate, to establish whether the impacts of anthropogenic climate change were significantly different from the impacts under natural climatic variability.

### *3.1.5. Accessing baseline climatological data from the Data Distribution Centre*

The DDC cannot meet all the possible demands for observed climate data that impacts assessors may need. What is provided are pointers to some existing climate data sets that are in the public domain, as well as access to a new gridded global land climate data set and some analysis and plotting tools.

The Climatic Research Unit (CRU) Global Climate Data set contains gridded monthly surface climate variables for the period 1901-2000 and is described in Box 4. One reason why gridded datasets of observed data are valuable is because, in contrast to point observations, they can be compared directly with model data, which are also gridded. Whereas point observations from a site are subject to numerous local factors, such as terrain, aspect and surface cover, the process of gridding station data inevitably involves the spatial smoothing of information. Similarly, gridded data from climate models are representative of conditions over a whole grid box. The CRU Global Climate Data can be viewed using the DDC "Data Visualisation" software, and selected components of the data set can be downloaded. The data set can be used to examine climate variability over the twentieth century, to evaluate the simulations of various GCMs over the period 1961-1990 and to combine observed data with GCM projections. Some of the options available include:

- Viewing observed fields, which are maps of observed surface climate variables over land areas for 1961-1990 and other periods. It is also possible to compare the observed fields with modelled 1961-90 mean fields projected onto the same grid.
- Viewing observed time series, which enables time series plots of observed climate to be displayed for the period 1901-2000 for a user-defined region of the global land surface, and for a selection of variables and months or seasons.

- Viewing observed and GCM fields combined, which allows the user to combine the observed 1961-90 global land fields with a user-defined GCM change field to generate a future climate field for any timeslice and variable.

A list of other climatological data sets is also included in the DDC (with links to Web sites on the Internet - and see **Table 5**). The list is not comprehensive, and is continually being updated. Moreover, its inclusion implies no judgement about the validity or reliability of the data, nor does it imply that these data sets have been "approved" by the IPCC. Users should make their own evaluation based on the available documentation and provenance of each data set.

## Box 4: The CRU global climate data set

The CRU Global Climate Data set, available through the IPCC DDC, consists of a multi-variate 0.5º latitude by 0.5º longitude resolution mean monthly climatology for global land areas, excluding Antarctica. Together with a mean climatology, which is strictly constrained to the period 1961-1990, there is a monthly time series at the same resolution for the period 1901-2000 (New *et al.*, 2000, updated). The mean 1961-1990 climatology comprises a suite of eleven surface variables: precipitation (PRE) and wet-day frequency (WET); mean, maximum and minimum temperature (TMP, TMX, TMN); vapour pressure (VAP) and relative humidity (REH); sunshine percent (SUN) and cloud cover (CLD); frost frequency (FRS); and wind speed (WND). The time series component comprises all variables except sunshine per cent, frost frequency and wind speed. These are still under development.

### The mean 1961-90 climatology

The mean climate surfaces have been constructed from a new data set of station 1961-1990 climatological normals, numbering between 19,800 (precipitation) and 3615 (windspeed). The station data were interpolated as a function of latitude, longitude and elevation using thin-plate splines. The accuracy of the interpolations were assessed using cross-validation and by comparison with other climatologies (New *et al.*, 1999). Examples of mean temperature and precipitation surfaces are shown in **Figure 4**.

### The anomaly timeseries

The anomaly time series were constructed using historic anomalies derived from the monthly data holdings of the Climatic Research Unit and the Global Historic Climatology Network (GHCN). For the purposes of developing monthly gridded time series, the variables were classified as either primary or secondary. For the primary variables - PRE, TMP, TMX, TMN - sufficient data were available to enable interpolation directly from the station time series. In the case of secondary variables - CLD, VAP, REH, WET - the available station time series were sparsely sampled in space and time. These variables had to be derived indirectly from gridded time series of primary variables. Station data that were available for secondary variables were used to develop relationships to the primary variables, and to validate the derived gridded time series.

### The full global climate data set

To calculate monthly time series, grids of monthly anomalies relative to 1961-90 were calculated for each variable and applied to their respective 1961-90 climatology. The anomaly approach was adopted because the network of station normals was much more comprehensive than the network of station time series. The spatial variability in mean climate was best captured by the denser network of station normals, while the more sparse network of primary variable time series captured as much temporal variability as possible.

### Viewing and availability

Selected fields and time series from this climatology can be viewed through the Data Visualisation pages of the DDC. Decade-mean and 30-year mean monthly fields can also be downloaded. Access to the full year-by-year monthly data set is achieved by lodging a request with the Climate Impacts LINK Project at the Climatic Research Unit.

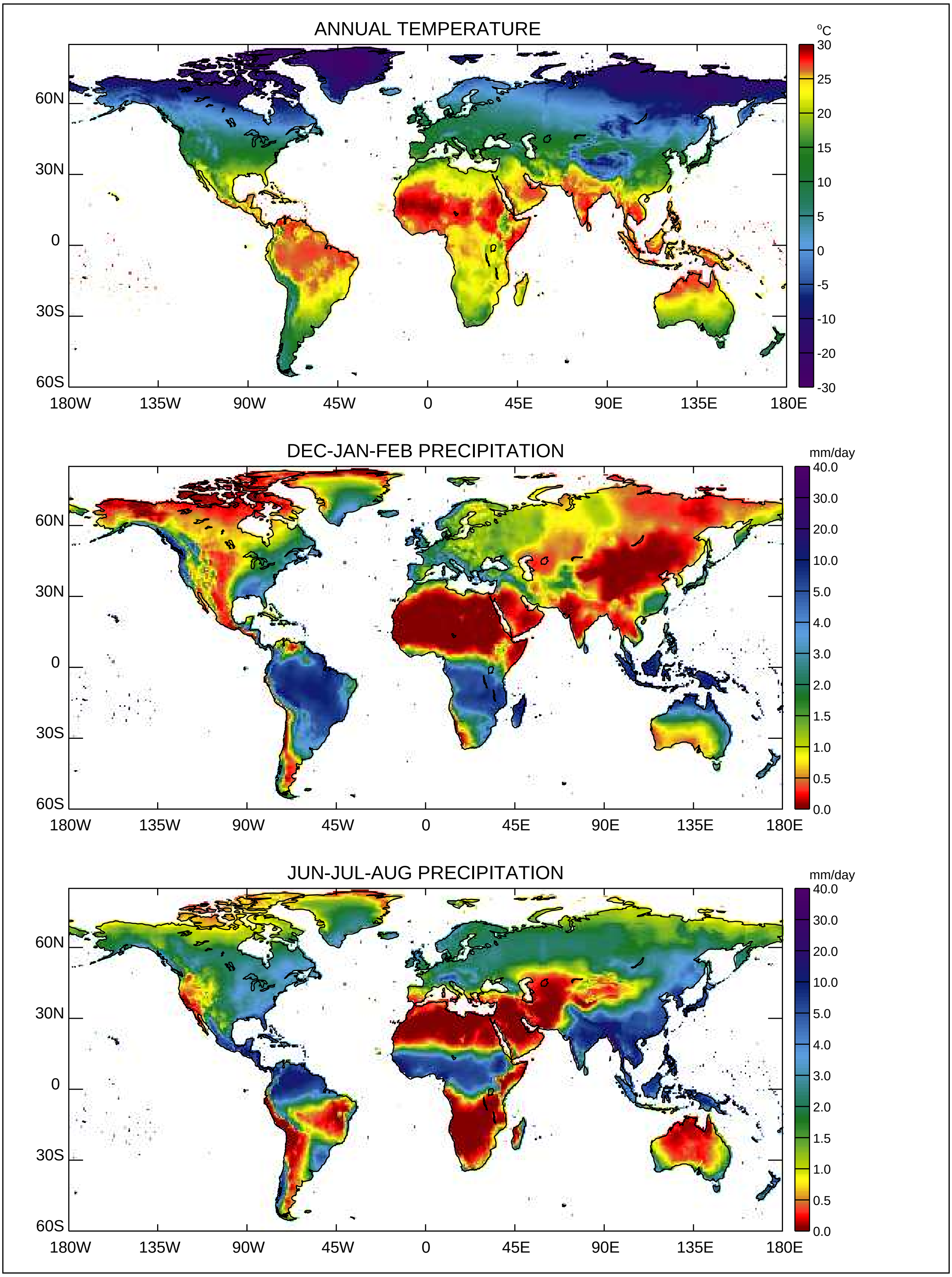

**Figure 4**. Observed global land mean climate fields for 1961-1990 extracted from the New *et al*. (1999) data set. Top: annual mean temperature (°C); middle: December-February mean precipitation rate (mm d$^{-1}$); bottom: June-August mean precipitation rate (mm d$^{-1}$). Source: Hulme *et al.* (1999b)

## 3.2. Climate scenarios

Although there is increasing confidence among atmospheric scientists that increased atmospheric greenhouse gas concentrations will increase global temperatures, there is much less confidence in estimates of how the climate will change at a regional scale (Giorgi et al., 2001). However, it is precisely at this regional or local level (e.g. at the scale of a farm, a river catchment or even an individual organism) that climate change will be felt. Since no method yet exists of providing confident predictions of climate change at these scales, an alternative approach is to specify a number of plausible future climates. These are termed "climate scenarios".

Climate scenarios are plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases and other pollutants and with our understanding of the effect of increased atmospheric concentrations of these gases on global climate. A range of scenarios can be used to identify the sensitivity of an exposure unit to climate change and to help policy makers decide on appropriate policy responses. It is important to emphasise that, unlike weather forecasts, climate scenarios are not predictions. Weather forecasts make use of enormous quantities of information on the observed state of the atmosphere and calculate, using the laws of physics, how this state will evolve during the next few days, producing a prediction of the future - a forecast. In contrast, a climate scenario is a plausible indication of what the future could be like over decades or centuries, given a specific set of assumptions. These assumptions include future trends in energy demand, emissions of greenhouse gases, land use change as well as assumptions about the behaviour of the climate system over long time scales. It is largely the uncertainty surrounding these assumptions which determines the range of possible scenarios.

The choice of climate scenarios and related non-climatic scenarios is important because it can determine the outcome of a climate impact assessment. Extreme scenarios can produce extreme impacts; moderate scenarios may produce more modest effects (Smith and Hulme, 1998). It follows that the selection of scenarios can also be controversial, unless the fundamental uncertainties inherent in future projections are properly addressed in the impact analysis.

### *3.2.1. Criteria for selecting climate scenarios*

Four criteria that should be met by climate scenarios if they are to be useful for impact researchers and policy makers are suggested in Smith and Hulme (1998):

- <u>Criterion 1: Consistency with global projections</u>. They should be consistent with a broad range of global warming projections based on increased concentrations of greenhouse gases. This range is variously cited as 1.4°C to 5.8°C by 2100 (IPCC, 2001a), or 1.5°C to 4.5°C for a doubling of atmospheric $CO_2$ concentration (IPCC, 1990; 1996 - otherwise known as the "equilibrium climate sensitivity" - IPCC, 2001a).
- <u>Criterion 2: Physical plausibility</u>. They should be physically plausible; that is, they should not violate the basic laws of physics. Hence, changes in one region should be physically consistent with those in another region and globally. In addition, the combination of changes in different variables (which are often correlated with each other) should be physically consistent.
- <u>Criterion 3: Applicability in impact assessments</u>. They should describe changes in a sufficient number of variables on a spatial and temporal scale that allows for impact assessment. For example, impact models may require input data on variables such as precipitation, solar radiation, temperature, humidity and windspeed at spatial scales ranging from global to site and at temporal scales ranging from annual means to daily or hourly values.
- <u>Criterion 4: Representative</u>. They should be representative of the potential range of future regional climate change. Only in this way can a realistic range of possible impacts be estimated.

An additional criterion can be added to this list:

- Criterion 5: Accessibility. They should be straightforward to obtain, interpret and apply for impact assessment. Many impact assessment projects include a separate scenario development component which specifically aims to address this last point. The DDC and this guidance document are also designed to help meet this need.

### *3.2.2. Types of climate scenarios*

Before discussing different types of climate scenarios, it is worth pointing out that not all climate change impact and adaptation studies require a scenario component. For example, a lot of information can be obtained on the vulnerability and adaptive capacity to important regional climatic variations such as the El Niño–Southern Oscillation (ENSO) phenomenon simply by using data from past events. Although scenarios might be helpful in indicating the likely trends in ENSO-events, they are probably not essential. From the point of view of adaptation, efficient coping strategies for the events when they occur combined with skilful short-term forecasting of their onset and decay, may well be the most effective responses to such possible future changes.

Several types of climate scenario have been used in previous impact studies. These fall into three main classes: synthetic scenarios, analogue scenarios and scenarios based on outputs from GCMs.

#### *3.2.2.1. Synthetic scenarios*

Synthetic scenarios describe techniques where particular climatic (or related) elements are changed by a realistic but arbitrary amount, often according to a qualitative interpretation of climate model simulations for a region. For example, adjustments of baseline temperatures by +1, 2, 3 and 4°C and baseline precipitation by ±5, 10, 15 and 20 per cent could represent various magnitudes of future change. An early illustration of this approach is presented in Terjung *et al.* (1984). Most studies have adopted synthetic scenarios of constant changes throughout the year (e.g. Rosenzweig *et al.*, 1996 – see **Figure 5**), but some have introduced seasonal and spatial variations in the changes (e.g. Rosenthal *et al.*, 1995), and others have examined arbitrary changes in inter-annual, within-month and diurnal variability as well as changes in the mean (e.g. Williams *et al.*, 1988; Mearns *et al.*, 1992, 1996; Semenov and Porter, 1995).

The advantages of synthetic scenarios are:

- They are simple to apply by impact analysts, transparent and easily interpreted by policy makers and non-specialists (fulfilling criterion 5).
- They capture a wide range of possible changes in climate, offering a useful tool for evaluating the sensitivity of an exposure unit to changing climate (meeting criteria 3 and 4). Since individual variables can be altered independently of each other, synthetic scenarios also help to describe the relative sensitivities to changes in different climatic variables. Moreover, they can assist in identifying thresholds or discontinuities of response that might occur under a given magnitude or rate of climate change. For instance, a small amount of warming might promote the growth of a plant species, but above a critical threshold of warming heat stress may occur.
- Different studies can readily apply the same synthetic scenarios to explore relative sensitivities of exposure units. This is potentially useful for comparing and synthesizing the potential effects of climate change over different sectors and regions (cf. **Figure 5**).

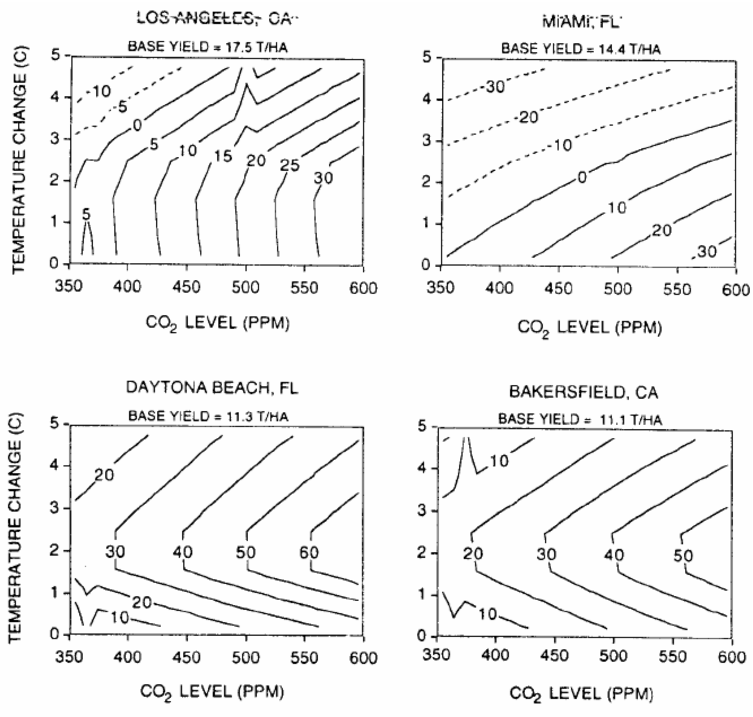

**Figure 5**. Sensitivity of citrus (Valencia orange) yield to elevated temperature and $CO_2$ concentration at four sites in the United States. Contours indicate percentage yield changes relative to base yields at current temperatures and $CO_2$ concentration, and are interpolated from means of 28 simulated years for each synthetic scenario combination. Source: Rosenzweig *et al.* (1996)

The major disadvantage of synthetic scenarios is their arbitrary nature. They seldom present a realistic set of changes that are physically plausible, commonly representing adjustments as being uniform over time and space and inconsistent among variables (hence violating criterion 2). Moreover, some scenarios may be inconsistent with the uncertainty range of global changes (criterion 1). However, this limitation can be overcome if the selection of synthetic scenarios is guided by information from GCMs. The application of "guided sensitivity analysis" is discussed further in Section 5.3, below.

### *3.2.2.2. Analogue scenarios*

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

#### Temporal analogues

Temporal analogues make use of climatic information from the past as an analogue of possible future climate. They are of two types: palaeoclimatic analogues based on information from the geological record, and analogues selected from the historical instrumental record, usually within the past century. Both have been used to identify periods when the global (or regional) temperatures have been warmer than they are today. Other features of the climate during these warm periods (e.g. precipitation, windspeed), if available, are then combined with the temperature pattern to define the scenario climate. This can provide a potentially rich data set of observed, and therefore physically plausible, climate (thus satisfying criteria 2 and 3).

Palaeoclimatic analogues are based on reconstructions of past climate from what are known as proxy indicators. These proxy indicators include, for example, evidence from fossil plant or animal remains, sedimentary deposits, tree rings, pollen, spores, plant macrofossils and diatoms in lake sediments, buried soils and peatlands. Each proxy indicator represents a unique response of natural systems and processes to climate conditions, and there are unique limitations associated with each proxy. For example, lake sediments tend to house detailed records of climate during dry periods, when lakes are low and sensitive, whilst high water levels tend to buffer the impacts of temperature and precipitation fluctuations.

Palaeoclimatic analogues of global warming have typically focussed on reconstructions of past climate from fossil evidence, with three periods receiving particular attention (Budyko, 1989; Shabalova and Können, 1995): the mid-Holocene (5000 to 6000 years BP[1]) - when Northern Hemisphere temperatures are estimated to have been about 1°C warmer than today, the Last (Eemian) Interglacial (125000 years BP) - about 2°C warmer, and the Pliocene (three to four million years BP) - about 3-4°C warmer. During these periods, global temperatures relative to present conditions may have been similar to changes anticipated during the next century (fulfilling, in part, criterion 1).

More recently, other proxy indicators, such as tree rings and evidence from lake sediments, have been recognised as not only having value for the construction of palaeoclimatic analogues, but also in extending climate records in regions where the instrumental records are short, thus providing valuable information about natural climate variability. For example, records of past lake salinity, inferred from fossil diatoms, can be used to reconstruct historical precipitation (**Figure 6**). Tree rings are also extremely valuable proxy indicators and depending on their source location can be used to infer past temperature or precipitation conditions (**Figure 7**). Some proxy indicators may not necessarily be related directly to a particular climate variable, but can also be used to infer, for example, changes in a climate-related variable, such as stream flow. Information from palaeoclimatic reconstructions can be used as analogues for the future where they represent anticipated future conditions.

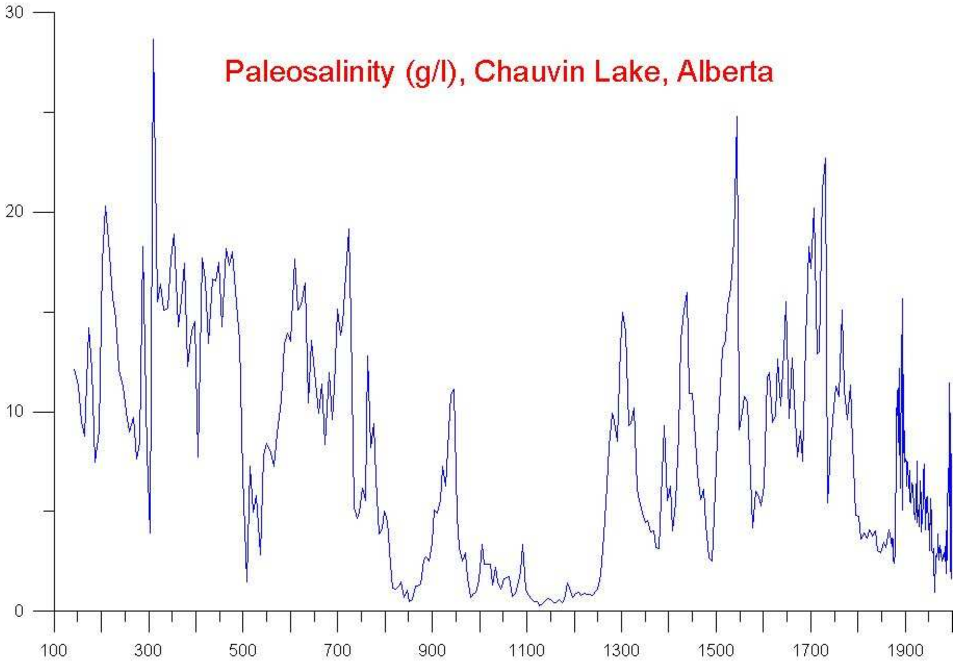

**Figure 6**. A record of past salinity from Chauvin Lake, east-central Alberta, Canada, as inferred from fossil diatoms extracted from a lake sediment core (Sauchyn *et al*., 2002). Lake water salinity reflects fluctuations in lake level, with greatly elevated salinity representing the most arid conditions and low lake levels. In this example, analysis of aerial photographs between 1940 and the present demonstrated that levels of this particular lake have varied in accordance with historical changes in precipitation.

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[1] BP = Before Present

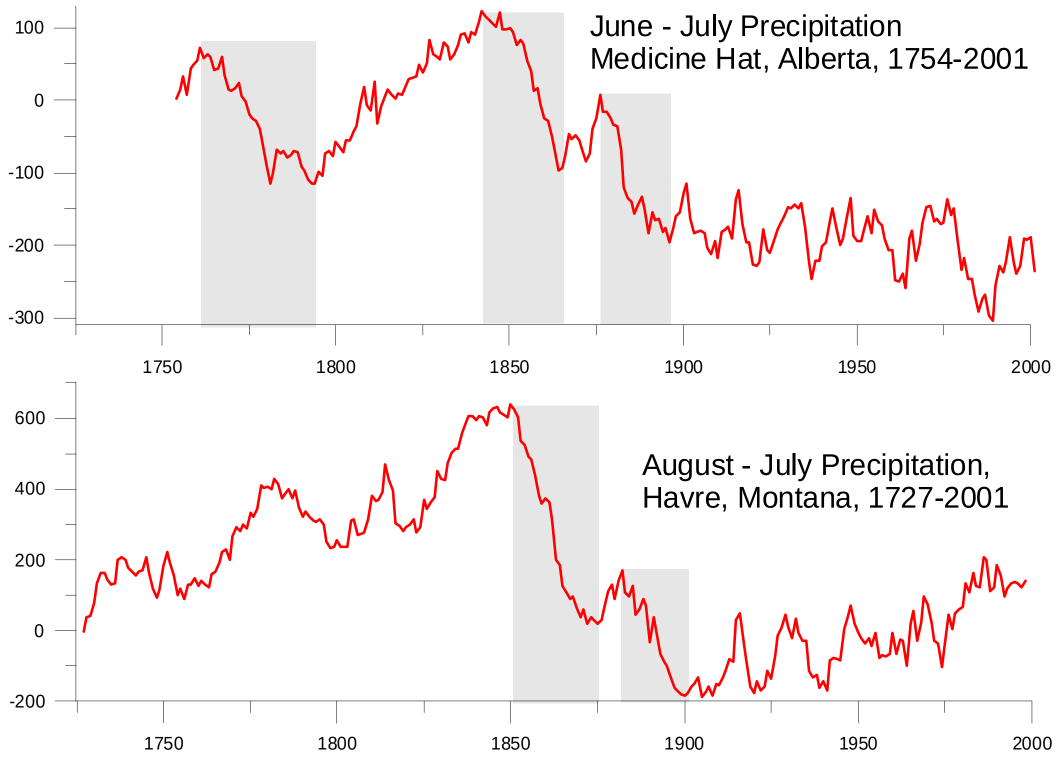

**Figure 7**. Cumulative departures of reconstructed precipitation from median values for two locations in the northern Great Plains: Medicine Hat, Alberta, Canada and Havre, Montana, USA (Sauchyn *et al*., 2003). These plots illustrate the shift in climate variability whereby long periods of consistent drying (highlighted in grey) preceded the twentieth century and thus most of the instrumental weather records in this region.

Instrumentally-based analogues have been used to identify past periods of observed global-scale warmth as an analogue of a greenhouse gas induced warmer world. Scenarios are often constructed by estimating the difference between the regional climate during the warm period and that of the long term average or that of 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. A popular example is the dry 1930s period in central North America, which was a period of great hardship coinciding with a depressed economy and widespread soil erosion. It has been adopted in several studies as a possible analogue of future conditions (e.g. Warrick, 1984; Williams *et al*., 1988; Rosenberg *et al*., 1993). For instance, in the Upper Midwest of the United States very dry conditions were accompanied by mean temperatures some 1°C warmer than the 1951-1980 baseline (see **Figure 8**). A further method employs observed atmospheric circulation patterns as analogues, as illustrated by an analysis of the effects of extreme anticyclonic weather on United Kingdom water resources (Wilby *et al*., 1994).

The major disadvantage of using temporal analogues for climate scenarios is that past changes in climate were unlikely to have been caused by increasing greenhouse gas concentrations (criterion 1). Palaeoclimatic changes from earlier time periods, e.g., the Last Interglacial, were probably caused by variations in the Earth's orbit around the Sun, whilst more recent palaeoclimatic changes (i.e., within the last millennium) are most likely related to naturally occurring changes in atmospheric circulation, as are changes in the earlier part of the instrumental record, such as the 1930s drought in North America. These different 'boundary conditions' mean that we cannot be confident that the characteristics of a greenhouse gas-induced future climate which is, say, 3°C warmer than current conditions, will resemble those of a past climate which is also estimated to have been 3°C warmer than the present day. However, the impact response to a warming of a particular magnitude is likely to be similar, regardless of the mechanism of that warming.

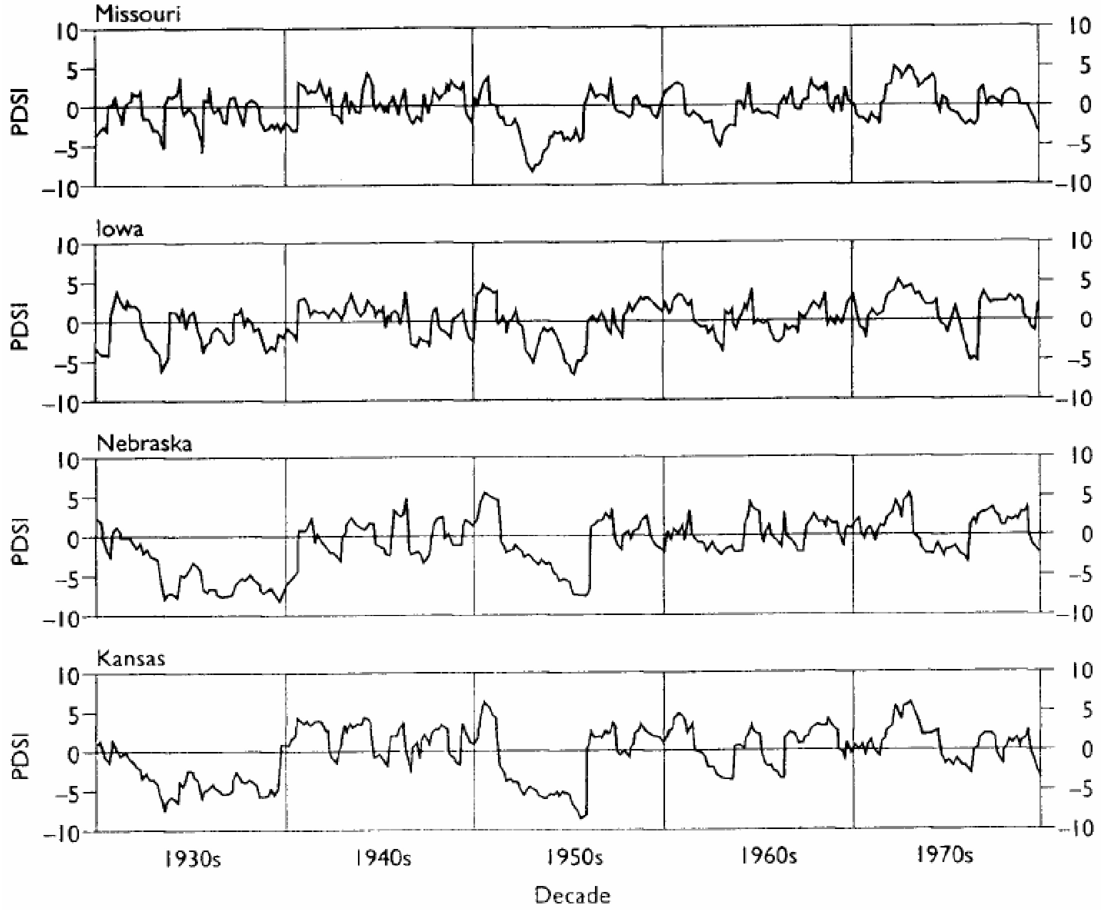

**Figure 8**. Palmer Drought Severity Index (PSDI) for the US Corn Belt, 1930-1980. Note that negative values denote water deficiency. Source: Rosenberg *et al.* (1993)

There are many caveats associated with the use of palaeoclimatic reconstructions, including concerns related to their quality (Covey, 1995), their incomplete geographical coverage and to dating of material from the geological record (especially in the more distant past). However, for some proxies, such as tree-rings, it is possible to date the annual chronologies exactly. Also, typically, only mean temperature and precipitation information is available, thus limiting the use of these data in the construction of climate change scenarios (violation of criterion 3). For studies in which only temperature or precipitation information is required, however, palaeoclimatic analogues (particularly those derived from tree-ring information) have utility.

Additionally, some climate proxies are only able to provide details of the average, and then often only seasonal, conditions prevailing in the past and so may have limited utility if climate variability and extremes are important factors for the exposure unit under study. However, some proxies are best suited to providing information about extreme events since these are typically best preserved (e.g., in the stratigraphic record for geological sequences). For some proxies it is also only a question of resampling the record to get higher resolution information, including, potentially, information about extreme events. Palaeoclimate records are the best source of information on climatic variability because instrumental records are unlikely to capture the full range of variability and GCMs generally do not simulate sufficient variability.

Concerns have also been raised regarding the fact that the reconstructed climate may be, in many cases, a steady-state, or ‘equilibrium’, climate with respect to long-term processes of vegetation response to climate and this may be quite different in character to the transient climate changes anticipated during the 21st century. However, there are many palaeoclimate records which exhibit discontinuous changes and so, where there are long high resolution records with a reasonable spatial coverage, it may be possible to construct analogues which are more likely to resemble the nature of the anticipated future climate change.

Finally, the more reliable palaeoclimate reconstructions tend to indicate climate changes which lie at the "low end" of the range of anticipated future climate warming, so temporal analogue scenarios derived from this type of information may not represent the range of possible future climate conditions (violation of criterion 4). Although conditions during the Pliocene period are estimated to have been 3-4°C warmer than today, thus representing more mid-range estimates of future warming, less data are available from this period and accurate dating of those data which do exist is problematic. However, local climate reconstructions (e.g., from tree-rings) typically exhibit larger variability than reconstructions from a larger spatial area, and so these have potential for the construction of analogue scenarios which exhibit larger warming. Despite the fact that many palaeoclimate reconstructions lie at the low end of the anticipated future warming, they are still able to provide valuable information about the response of particular exposure units *en route* to that anticipated warming.

#### Spatial analogues

Spatial analogues are regions which today have a climate analogous to the study region in the future. For example, Bergthórsson *et al*. (1988) used northern Britain as a spatial analogue for the potential future climate over Iceland. In this way, modelled estimates of the effects of climatic warming on grass growth in Iceland, based on extrapolation of local relationships, could be compared against the present-day response of grass to temperature and fertilizer application in Britain. The approach is severely restricted, however, by the frequent lack of correspondence between other important features (both climatic and non-climatic) of the two regions (for instance, the daylength in the summer is shorter in northern Britain than in Iceland). Hence, it is unlikely that the present-day combination of climatic and non-climatic conditions prevailing in an analogue region today would be a physically plausible scenario for conditions in the study region in the future, hence violating criterion 2.

### *3.2.2.3. Scenarios from general circulation model outputs*

#### General circulation models

Numerical models (general circulation models or GCMs), representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations (criterion 1). While simpler models have also been used to provide globally- or regionally-averaged estimates of the climate response, only GCMs, often in conjunction with nested regional models or other downscaling methods (see section 3.2.3.2), have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis (IPCC, 1994), thus fulfilling criterion 2.

GCMs depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans (**Figure 9**). Their resolution is thus quite coarse relative to the scale of exposure units in most impact assessments, hence only partially fulfilling criterion 3.

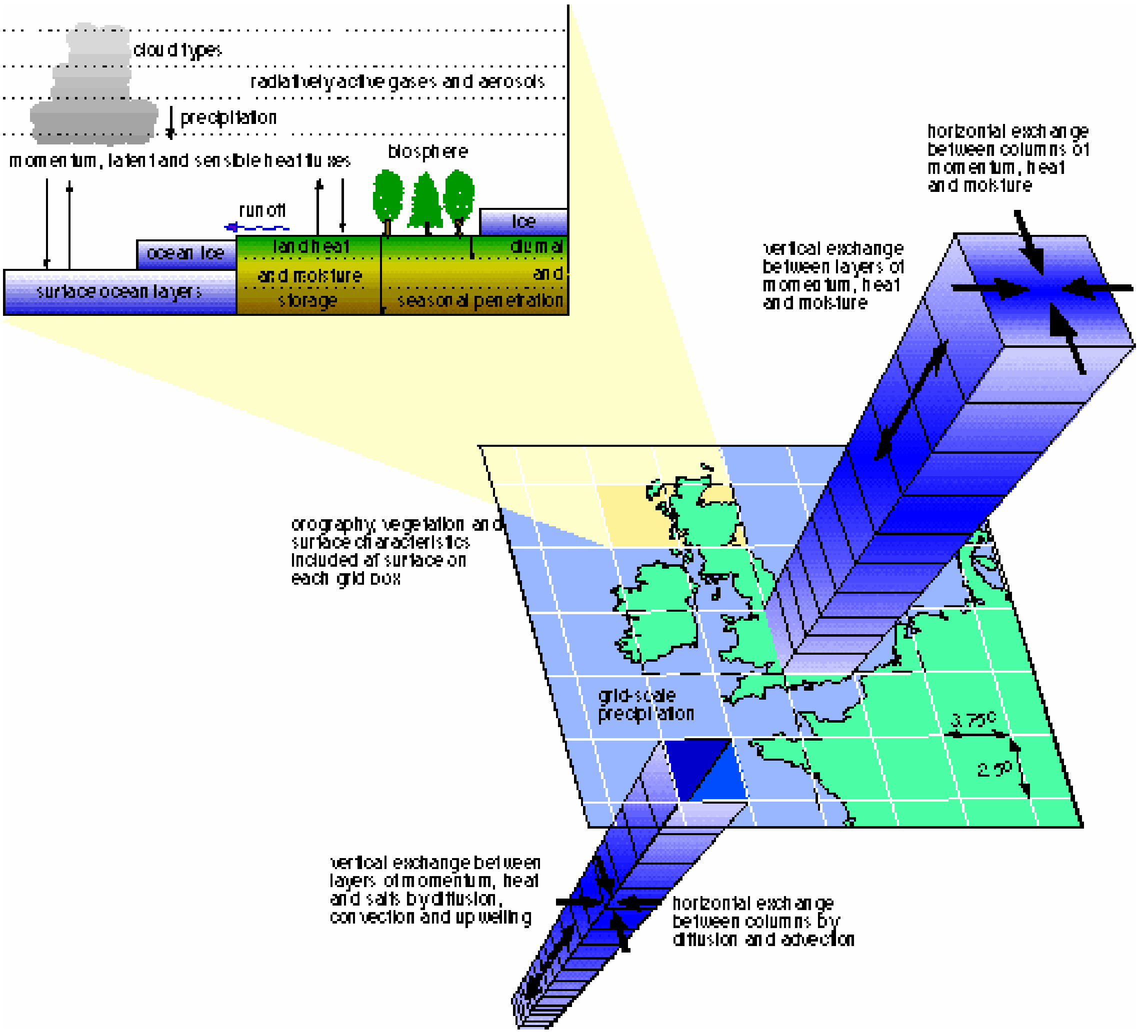

**Figure 9**. Conceptual structure of a coupled atmosphere-ocean general circulation model. Source: Viner and Hulme (1997).

Moreover, many physical processes, such as those related to clouds, also occur at smaller scales and cannot be properly modelled. Instead, their known properties must be averaged over the larger scale in a technique known as parameterization. This is one source of uncertainty in GCM-based simulations of future climate. Others relate to the simulation of various feedback mechanisms in models concerning, for example, water vapour and warming, clouds and radiation, ocean circulation and ice and snow albedo. For this reason, GCMs may simulate quite different responses to the same forcing, simply because of the way certain processes and feedbacks are modelled.

However, while these differences in response are usually consistent with the climate sensitivity range described in criterion 1, they are unlikely to satisfy criterion 4 concerning the uncertainty range of regional projections. Even the selection of all the available GCM experiments would not guarantee a representative range, due to other uncertainties that GCMs do not fully address, especially the range in estimates of future atmospheric composition. This is discussed further in section 5.

All models are first run for a control simulation assuming a constant atmospheric composition. Early GCM control runs assumed a $CO_2$ concentration characteristic of the 1970s or 1980s (e.g. 330 ppm). Control simulations with more recent models assumed pre-industrial levels of greenhouse gases. GCMs have been used to conduct two types of "experiment" for estimating future climate: equilibrium-response and transient-response experiments.

### Equilibrium-response experiments

Versions of almost all GCMs have been used to conduct experiments to evaluate the equilibrium response (new stable state) of the global climate following an abrupt increase (a doubling or occasionally a quadrupling) of atmospheric $CO_2$ concentration or its radiative equivalent including all greenhouse gases. These simulations are fairly straightforward to conduct and are useful for intercomparing model results. However, they are not very realistic. The actual change in atmospheric composition is neither continuous nor is it likely to stabilise in the foreseeable future. Furthermore, different parts of the climate system respond differently to radiative forcing and will approach equilibrium at different rates, and may never approximate the composite equilibrium conditions modelled. GCMs used for equilibrium experiments generally have only a very simple representation of the oceans. No results from 2 x $CO_2$ climate change experiments are provided by the IPCC DDC.

### Transient-response experiments

The most advanced GCMs are coupled atmosphere-ocean models (AOGCMs) which link, dynamically, detailed models of the ocean with those of the atmosphere. Since these can represent the ocean circulation, AOGCMs are able to simulate the time lags between a given change in atmospheric composition and the response of climate. They can also represent some of the important large scale transfers of heat and moisture attributable to ocean currents. With these features, they can be used in more realistic simulations of the transient-response of climate to a time dependent change in greenhouse gas concentrations. Hence they can provide useful information on the rate as well as the magnitude of climate change. In addition, they have also been used to assess the effects of regional sulphate aerosol loading (a negative forcing) in combination with greenhouse gas forcing.

The earliest transient-response experiments simulated the response of climate to radiative forcing from the present into the future (typically 100 years or more). However, because these failed to account for the historical forcing of rising greenhouse gases during the last century, but rather started the forcing from an assumed equilibrium condition at the present, the GCMs probably underestimated the change in climate during the first few decades beyond the present – the so-called "cold start" problem (Hasselmann *et al.*, 1993).

In contrast, most contemporary AOGCM simulations begin by modelling historical forcing due to greenhouse gases and aerosols since the eighteenth or nineteenth century ("warm start" experiments), enabling comparisons to be made between modelled and observed climate over this period. Simulations then continue into the future under a scenario of future atmospheric composition. The DDC includes results of simulations that assume a forcing of 1% per year in equivalent $CO_2$ concentration (which approximates the radiative forcing expected under the IS92a emissions scenario), with or without aerosols, as well as results of simulations assuming radiative forcing approximating the SRES emissions scenarios, including aerosol effects. Multiple or "ensemble" simulations have also been conducted with some models to investigate the effect of slightly different, but equally plausible, initial conditions on the climate response to an identical radiative forcing. Examples of these are also available from the DDC.

### Aerosol experiments

It is only since the 1990s that the effects of atmospheric aerosols (derived from fossil fuel combustion and biomass burning) on climate have been recognised and included in GCM experiments (e.g. Charlson *et al.*, 1992; Taylor and Penner, 1994). Aerosols can affect climate both directly, by scattering and absorbing solar radiation, and indirectly, by altering the properties and lifetime of clouds. The net effect of aerosols is to cool the surface - a negative radiative forcing.

Until recently, nearly all long term climate simulations that considered aerosols modelled only the direct effects. To do this it was necessary for the models to reproduce the geographical variation in aerosol concentrations. Unlike most greenhouse gases, which are well mixed in the atmosphere, aerosol concentrations are greatest over industrial regions, and their patterns can change from decade-to-decade depending on sources and volumes of emissions. In recent years, simulations incorporating the indirect effects of aerosols have also been reported (e.g. Takemura et al., 2005), and the global aerosol model inter-comparison project, AEROCOM, was initiated in order to improve the understanding of uncertainties in model estimates (Kinne et al., 2003).

AOGCM experiments which account for both the negative forcing associated with historically observed concentrations of aerosols and greenhouse gas forcing over the same period have achieved a close correspondence of global mean temperature changes compared to observations (e.g. Mitchell *et al*., 2001 – **Figure 10**). These experiments have also been projected into the future on the basis of the assumed concentrations of sulphate aerosols, usually under the assumption of the IS92a or SRES scenario $SO_2$ emissions profiles. The effect on climate when aerosols are included, compared to experiments forced by greenhouse gases only, is to suppress global warming. However, none of the SRES emissions scenarios shows regional $SO_2$ concentrations as high as for the IS92a scenario, and by the end of the 21st century all scenarios show that the effects of greenhouse gas forcing dominate over the aerosol effect.

What can be concluded from GCMs about future climate?

As general background information, it is useful to repeat here some of the main conclusions about future climate drawn from the results of GCM experiments conducted to date (Kattenberg *et al*., 1996; Cubasch et al., 2001):

- Greater surface warming of the land than the oceans in winter.
- A minimum warming around Antarctica and in the northern Atlantic associated with deep-water formation.
- Maximum warming at high northern latitudes in late autumn and winter associated with reduced sea ice and snow cover.
- Little warming over the Arctic in summer.
- Little seasonal variations of warming at low latitudes or over the southern oceans.
- A reduction in diurnal temperature range over land in most seasons and most regions.
- An increase in anomalously high temperature events and a decrease in anomalously low temperatures.
- An enhanced global mean hydrological cycle.
- Increased precipitation at high latitudes in winter.
- Probable increases in intense precipitation events in many regions.

GCM outputs available from the DDC

One of the main goals of the Data Distribution Centre was to make available to the impacts community a set of recent GCM outputs that both reflect the state-of-the-art of model experiments and provide a representative range of results from different GCMs. To this end, the IPCC TGICA defined a set of criteria that were applied to identify a small number of GCM experiments whose results could be deposited at the IPCC DDC. Models should (Parry, 2002):

- be full 3D coupled ocean-atmospheric GCMs,
- be documented in the peer reviewed literature,
- have performed a multi-century control run (for stability reasons), and
- have participated in CMIP2 (Second Coupled Model Intercomparison Project).

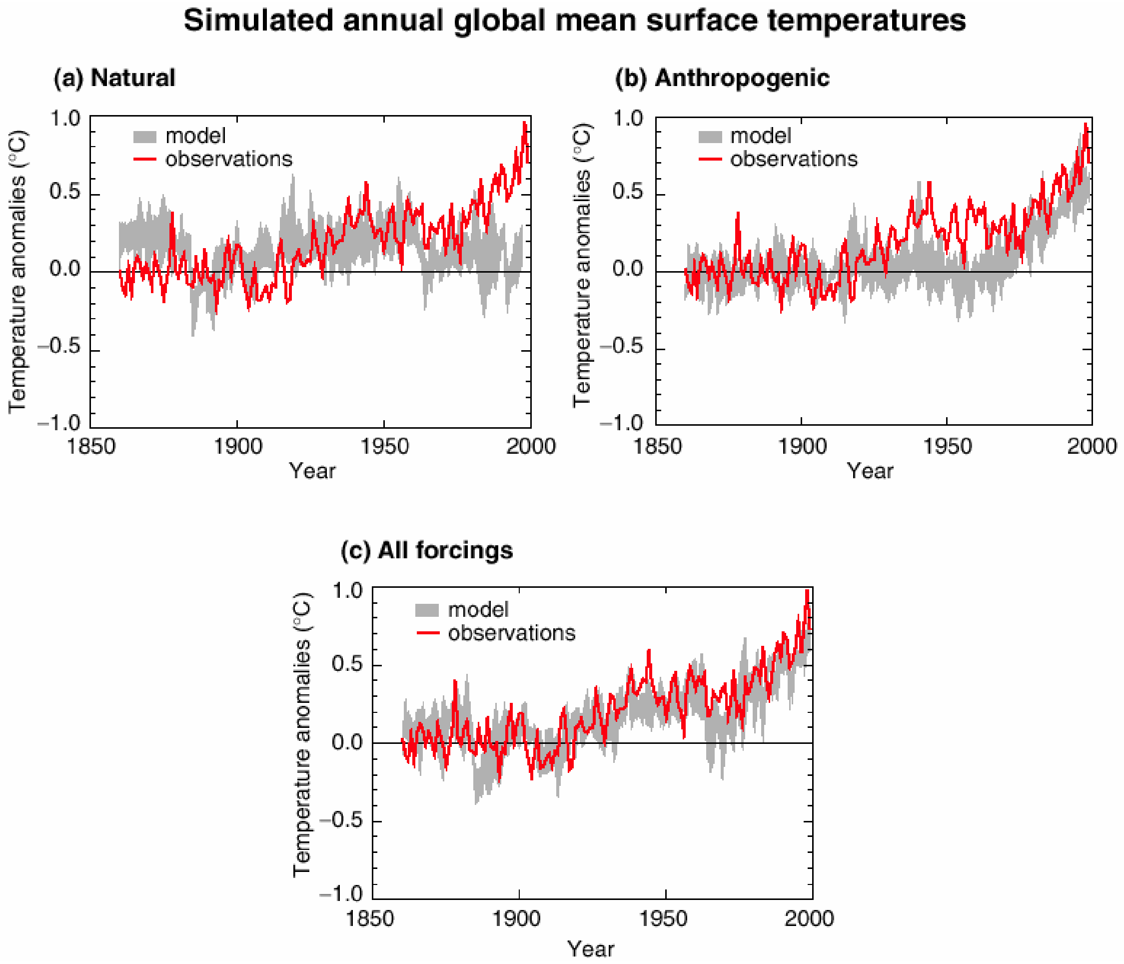

**Figure 10**. Global mean surface temperature anomalies relative to the 1880-1920 mean from the instrumental record compared with ensembles of four simulations with the HadCM3 coupled ocean-atmosphere climate model forced (a) with solar and volcanic forcing only, (b) with anthropogenic forcing including well mixed greenhouse gases, changes in stratospheric and tropospheric ozone and the direct and indirect effects of sulphate aerosols, and (c) with all forcings, both natural and anthropogenic. The thick line shows the instrumental data while the thin lines show the individual model simulations in the ensemble of four members. Source: Mitchell et al. (2001).

In addition, the models preferably should:

- have performed a 2 x $CO_2$ mixed layer run,
- have participated in AMIP (Atmospheric Model Intercomparison Project),
- have a resolution of at least T40, R30 or 3° latitude x 3° longitude, and
- consider explicit greenhouse gases (e.g. $CO_2$, $CH_4$, etc.).

On the basis of these criteria, results of experiments at seven modelling centres are currently held by the DDC **Table 6**). Other results from model simulations assessed for the IPCC Fourth Assessment Report (AR4) are in the process of being added (June 2007). Summary information on each model experiment can be found at the DDC Web site and in comprehensive tables in McAvaney et al. (2001) and Cubasch et al. (2001). Note that data from ensemble and time slice experiments are also available for some models. Monthly averaged results from each model have been lodged with the IPCC DDC. For each AOGCM the following core variables can be found on the DDC, provided on a global grid that varies from model to model – cloud, diurnal temperature range, precipitation, radiation, mean temperature, minimum temperature, vapour pressure and wind. Some other variables can also be obtained for individual experiments.

**Table 6**. Coupled atmosphere-ocean general circulation models for which climate change simulations held by the IPCC Data Distribution Centre as of mid-2005). A wider set is represented for the AR4 model projections.

| **Modelling centre** | **Country** | **Model(s)** |
|---|---|---|
| Commonwealth Scientific and Industrial Research Organisation (CSIRO) | Australia | CSIRO-Mk2 |
| Max Planck Institüt für Meteorologie (formerly Deutsches Klimarechenzentrum, DKRZ) | Germany | ECHAM4/OPYC and ECHAM3/LSG |
| Hadley Centre for Climate Prediction and Research | UK | HadCM2 and HadCM3 |
| Canadian Centre for Climate Modelling and Analysis (CCCMA) | Canada | CGCM1 and CGCM2 |
| Geophysical Fluid Dynamics Laboratory (GFDL) | USA | GFDL-R15 and GFDL-R30 |
| National Centre for Atmospheric Research (NCAR) | USA | NCAR DOE-PCM |
| Center for Climate Research Studies (CCSR) and National Institute for Environmental Studies(NIES) | Japan | CCSR-NIES |

The full sets of monthly results from these experiments (and more detailed technical information) can be obtained from the DDC GCM Archive, although daily fields are only available directly from the respective modelling centres. DDC software allows the user to plot 30-year mean change fields from these experiments, comparing them with each other and with the 1961-1990 observed climatology. Ensemble members can also be plotted, as well as ensemble means.

### *3.2.3. Applying climate scenarios in impact assessment*

Having described some of the options available for developing climate scenarios and the scenario information available from the DDC, the next vital step in an impact assessment is the selection, interpretation and application of appropriate scenarios.

#### *3.2.3.1. Selecting model outputs*

Many climate change experiments have been performed with GCMs. Therefore, if GCM-based scenarios are to be constructed, it is not easy to choose suitable examples for use in impact assessments.

There have always been some limitations on the breadth of choice: some experiments may not have been fully archived in an accessible and public form, in some cases the required variables have not been available and in many cases the impact assessors have simply not been aware of the potential sources of information. However, several research centres now serve as repositories of GCM information (e.g. the National Center of Atmospheric Research, USA; the Climatic Research Unit, UK; the Commonwealth Scientific and Industrial Research Organization, Australia). Some of these have also developed software for extracting, displaying and comparing information from different GCMs (e.g. see Hulme *et al*., 2000; Jones, 1996 and Box 5, below). The IPCC Data Distribution Centre complements these existing sources.

Thus, assuming that the user is in a position to select from a large sample, which results should be chosen? Four criteria for selection are suggested in Smith and Hulme (1998): vintage, resolution, validity and representativeness of results.

Vintage

In general, recent model simulations are likely (though by no means certain) to be more reliable than those of an earlier vintage. They are based on recent knowledge, incorporate more processes and feedbacks and are usually of a higher spatial resolution than earlier models. Therefore, it is of some concern that results from equilibrium experiments conducted as long ago as the early 1980s are still occasionally adopted in impact assessments without reference to more recent experiments. Moreover, one of the problems often encountered in evaluating impact studies is knowing exactly which version of a GCM has provided the scenario information. Part of this is due to poor reporting by the impact analysts, but part can also be attributed to confusing documentation of the model outputs. For instance, there are many sets of results available from different experiments conducted by the same modelling group, and quite often these have been denoted using the same model name or acronym.

### Resolution

As climate models have evolved and computing power has increased, there has been a tendency towards increased resolution. Some of the early GCMs operated on a horizontal resolution of some 1000 km with between 2 and 10 levels in the vertical. More recent models are run at nearer 250 km spatial resolution with perhaps 20 vertical levels (more in some ocean models). However, although higher resolution models contain more spatial detail (i.e. complex topography, better-defined land/sea boundaries, etc.) this does not necessarily guarantee a superior model performance.

### Validity

A more persuasive criterion for model selection is to adopt the GCMs that simulate the present-day climate most faithfully, on the premise that these GCMs would also yield the most reliable representation of future climate. Several large impact assessment projects have used this approach (e.g. Smith and Pitts, 1997).

The approach involves comparing GCM simulations that represent present-day conditions with the observed climate. The GCM run is typically the control simulation of an equilibrium GCM experiment, but for transient experiments, the modelled period corresponding to the observed data (e.g. 1961-1990) is adopted. The modelled and observed data are projected to the same grid, and statistical methods employed to compare, for example, mean values, variability and climatic patterns. Where the GCM is coarser than the observed grid, comparisons of modelled and observed data should take place on the GCM grid, rather than interpolating the GCM data to a finer resolution grid to match the observed data. "Scaling up" the observed data to the same resolution as the GCM grid is a more robust and defensible procedure than interpolating coarse resolution data to a finer grid. Useful statistical measures of similarity between the modelled and observed pattern of climate include the spatial pattern correlation coefficient (e.g. Hulme, 1991; Whetton *et al*., 1996), Reliability Ensemble Averaging (REA) method (Giorgi and Mearns, 2002) and Climate Prediction Index (CPI) (Murphy et al., 2004).

However, it should be noted that the relative performance of GCMs can depend critically on the size of the region (i.e. small regions at sub-grid-scale are less likely to be well described than large regions at continental scale), on its location (i.e. the level of agreement between GCM outputs varies a lot from region to region) and on the variables being analysed (for instance, regional precipitation is more variable and more difficult to model than regional temperature). Indeed, rather than searching for the best performing model, perhaps the most valuable function of a model intercomparison study is to exclude those models whose performance is unacceptably poor, especially in estimating features of the climate that are of critical importance for the impact application. Furthermore, it should also be remembered that the models giving the best pattern correlation coefficients for the simulation of the present day may not necessarily be the models providing the most reliable predictions.

Many international model intercomparison projects have been conducted and reported, often focusing on regions that are relevant to impact assessment. Comparison of models with observations is a key component of these projects, and impact assessors are encouraged to consult these before undertaking their own analysis. Most of these projects are ongoing and are well documented on the Internet[1]. They include:

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[1] See list and links at: http://www.clivar.org/science/mips.htm

- AEROCOM - Global Aerosol Model Intercomparison Project[1]
- AMIP - Atmospheric Model Intercomparison Project I (1990-1996) and II (1996-)
- CMIP - The Coupled Model Intercomparison Project
- ENSIP - ENSO (El Niño/Southern Oscillation) Intercomparison Project
- GRIPS - GCM-Reality Intercomparison Project for SPARC (Stratospheric Processes And their Role in Climate)
- PILPS - Project for Intercomparison of Landsurface Parameterization Schemes
- PIRCS - Project to Intercompare Regional Climate Simulations
- SIMIP - Sea-ice Model Intercomparison Project
- SMIP - Seasonal Model Intercomparison Project
- STOIC - Study of Tropical Oceans in Coupled Models

The scope for selection has been increased with the advent of ensemble experiments, which assume an identical radiative forcing but slightly different initial conditions. Since each ensemble experiment is equally plausible, it is important to know how their results compare. In selecting from ensemble members, one option is to average the members to provide a composite ("consensus") climate. However, internal consistency may be compromised through this procedure, so it is advisable to use all ensemble members separately in an impact assessment, if possible.

The Data Distribution Centre has provided graphical and statistical tools to facilitate the intercomparison of information from AOGCMs (including ensembles) and the observed CRU Global Climate Data set. Moreover, intercomparisons of the model results held on the DDC for future changes in surface air temperature and precipitation have also been presented for sub-continental world regions by Giorgi and Francisco (2000), Giorgi et al. (2001), Carter et al. (2000) and Ruosteenoja et al. (2003).

Representativeness of results

If results from more than one GCM are to be applied in an impact assessment (and given the known uncertainties of GCMs, this is strongly recommended), another criterion for selection is to examine the representativeness of the results. Alternative GCMs can display large differences in estimates of regional climate change, especially for variables like precipitation, which frequently show wetter conditions in a region in some models and drying in others.

Where several GCMs are to be selected, it might be prudent, therefore, to choose models that show a range of changes in a key variable in the study region (for example, models showing little change in precipitation, models showing an increase and models showing a decrease). The selections may not necessarily be the best validated models (see above), although some combination of models satisfying both criteria could be agreed upon. For example, a study in southern Africa adopted three GCMs: a core scenario based on the GCM that, out of a sample of 11 examined, correlated best with the observed climate, and two other scenarios from GCMs that captured the extreme range of regional precipitation changes obtained in the 11 experiments (Hulme *et al*., 1996 – see **Figure 11**). The simple GCM intercomparison tools provided by the DDC provide an opportunity to assess the representativeness of outputs from different climate models.

A note of caution is required in interpreting a modelled change in climate between the present and future. While conflicting results are commonly reported from different models, it is not always clear that they each represent a genuine greenhouse gas signal. Many early impact assessments relied on transient GCM outputs based on 10-year averaged climate. Given the substantial inter-decadal climatic variability exhibited by most GCMs, it was often difficult to distinguish a climate change signal from the background noise. For this reason, it is strongly recommended that at least a 30-year period be employed for averaging GCM output data, to dampen the effects of inter-decadal variability.

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[1] http://nansen.ipsl.jussieu.fr/AEROCOM/

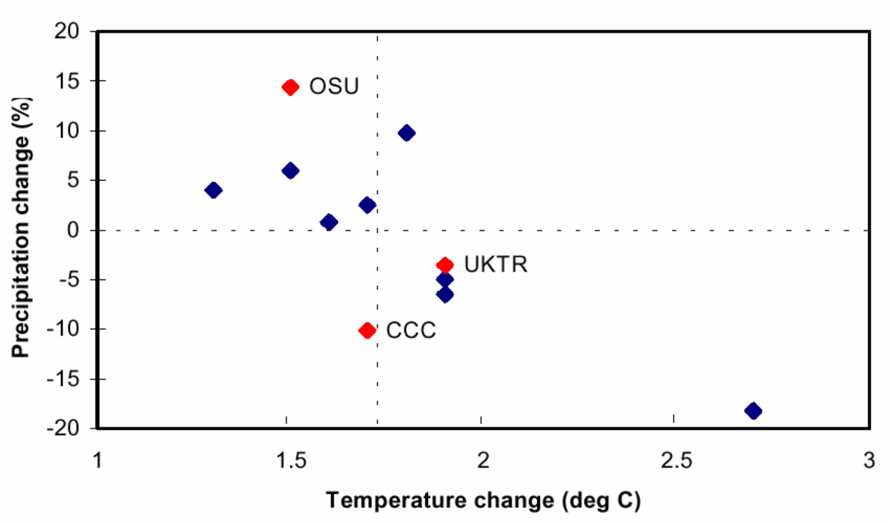

**Figure 11**. Changes in average annual temperature and precipitation for the 2050s relative to 1961-1990 from eleven GCM experiments for a 10° latitude/longitude region of southern Africa centred on Zimbabwe. The three experiments indicated in red were selected as scenarios. Source: Hulme (1996).

### *3.2.3.2. Constructing scenarios*

Once GCM outputs have been selected for use in an impact study, there are numerous procedures available for processing and applying the data (i.e. constructing the scenarios). The procedure chosen can itself have a strong influence on the actual climate changes imposed on an exposure unit.

#### Constructing change fields

GCM outputs are not generally of a sufficient resolution or reliability to be applied directly to represent the present-day climate. Instead, it is usual for baseline observational data to be used, which are commonly in the form of time series of daily or monthly data for several variables over a period such as 1961-1990.

A scenario of future climate is obtained by adjusting the baseline observations by the difference (or ratio) between period-averaged results for the GCM experiment (usually 10 or 30 year periods are used) and the corresponding averages for the GCM control simulation. In transient experiments, the simulated baseline period (e.g. 1961-1990) is used in place of the control-run results. Differences are usually applied for temperature changes (e.g. 2040-2069 minus 1961-1990) while ratios are commonly used for precipitation change (e.g. 2040-2069 divided by 1961-1990), though differences may be preferred in some cases. When this procedure is completed across some or all of the model grid boxes, a pattern of differences or ratios known as a "change field" is produced.

Change fields of 30-year averages for eight variables have been computed from the monthly outputs of all experiments held in the Data Distribution Centre. In this case, changes for all variables are expressed as *differences* relative to the present, where the present refers to model simulated 1961-1990 climate.

#### Downscaling

One of the major problems in applying GCM projections to regional impact assessments is the coarse spatial scale of the gridded estimates in relation to many of the exposure units being studied. Several methods have been adopted for developing regional GCM-based scenarios at the sub-grid scale, a procedure variously known as “regionalisation” or "downscaling" (see, for example, Giorgi and Mearns, 1991; Wilby and Wigley, 1997; Giorgi et al., 2001).

*Using original grid box information.* The simplest method of applying GCM changes is to use values for the nearest grid box to the study area. There are several drawbacks of this method. First, because of the lack of confidence in regional estimates of climate change, it has been suggested that the minimum effective spatial resolution should be defined by at least four, and probably more GCM grid boxes (e.g. von Storch *et al*., 1993). Second, sites in close proximity but falling in different grid boxes, while having a very similar baseline climate, may be assigned a quite different scenario climate. Third, a site on land may fall within the bounds of a GCM grid box defined (due to its coarse spatial resolution) as ocean (and *vice versa*). The climate response over land grid boxes is known to differ from that over ocean boxes.

*Interpolating grid box outputs*. The simplest method of downscaling is to interpolate the change fields to the site or region of interest from nearby grid boxes (e.g. Harrison *et al*., 1995; Neilson, 1998). This overcomes the problem of discontinuities in changes between adjacent sites in different grid boxes, but it also introduces a false geographical precision to the estimates. Most impact applications consider one or more fixed time horizon(s) in the future (e.g. the 2020s, 2050s and 2080s have been chosen as 30-year time windows for storing change fields in the DDC). Some other applications may require time-dependent information on changes, such as vegetation succession models that simulate transient changes in plant composition (e.g. VEMAP members, 1995).

*Statistical downscaling.* More sophisticated downscaling techniques calculate sub-grid scale changes in climate as a function of larger-scale climate or circulation statistics. Some approaches utilise statistical relationships between large-area and site-specific surface climates (e.g. Wigley *et al*., 1990) or between large-scale upper air data and local surface climate (e.g. Karl *et al*., 1990; Winkler *et al*., 1997; Crane and Hewitson, 1998). Others have examined relationships between atmospheric circulation types and local weather (e.g. Hay *et al*., 1992; Conway *et al*., 1996; Brandsma and Buishand, 1997). When applied to daily GCM data, these techniques can provide daily climate scenarios for specific sites or regions.

Statistical downscaling is much less computationally demanding than physical downscaling using numerical models (see below), offering an opportunity to produce ensembles of high resolution climate scenarios. Nevertheless, some approaches can still require large amounts of observational data to establish statistical relationships for the present-day climate, and a high degree of specialist knowledge and skill is needed to apply statistically downscaled results sensibly in impact assessments. Moreover, they are based on a fundamental assumption that the observed statistical relationships will continue to be valid under future radiative forcing, i.e. they are time-invariant. This proposition is questioned by Wilby (1997), who found significant variations in relationships developed for daily precipitation using data from different periods during the past century in the United Kingdom. Another important weakness of circulation based downscaling methods is that the scenarios produced are relatively insensitive to future climate forcing (see Wilby and Wigley, 1997). For more detailed guidance on statistical downscaling, see Wilby *et al* (2004).

*High resolution experiments.* Another method of obtaining more localised estimates of future climate is to conduct experiments with numerical models at high resolution over the region of interest. This can be done in several ways. One method is to run a full GCM at higher resolution for a limited number of years in "time slice" experiments. Another method involves running a GCM at varying resolution across the globe, with the highest resolution over the study region ("stretched grid" experiments). A third method makes use of a separate high resolution limited area model (LAM), using conventional GCM outputs (control simulation and experiment) to provide the boundary conditions for the LAM (the "nesting" approach). There are also examples of "double nesting", in which a fine resolution LAM is nested in a LAM, which has itself first been nested in a GCM (e.g. Whetton *et al*., 1997). Finally, statistical and dynamical downscaling methods can be combined to produce very high resolution climatic scenarios and land-atmosphere feedbacks (e.g. Zhang and Foufoula-Georgiou, 1997).

## Box 5: Using simple models to estimate global mean temperature and sea-level change

GCMs are the most comprehensive tools for estimating the response of climate to radiative forcing. However, they are also computationally and resource intensive, with a single experiment typically requiring several person-years to design, run, analyse and release. Moreover, one experiment provides information, albeit detailed, on only one possible scenario of the future.

An alternative method of examining climate response to radiative forcing is to use simpler models that generalise many of the processes simulated explicitly by a GCM. A system of simple global models (MAGICC) has been used by the IPCC for its 1990, 1995 and 2001 assessments to investigate the effects of different emissions scenarios (Wigley and Raper, 1992; IPCC, 1997). It comprises the following components (**Figure 12**):

- Gas models for each of the main greenhouse gases, which convert emissions into atmospheric concentrations and subsequently compute radiative forcing. Values of key parameters of each model can be adjusted across a representative uncertainty range.
- An upwelling diffusion-energy balance (UD/EBM) climate model, which computes global mean temperature response to a given radiative forcing. The parameters of the model can be altered to represent uncertainties in GCMs. For example, the climate sensitivity can be selected from a range of values, along with a factor accounting for the differential heating of land and ocean (observed in GCM results). This latter parameter is important for estimating the thermal expansion component of sea-level rise.
- Ice melt and thermal expansion models, which are used to compute sea-level change.

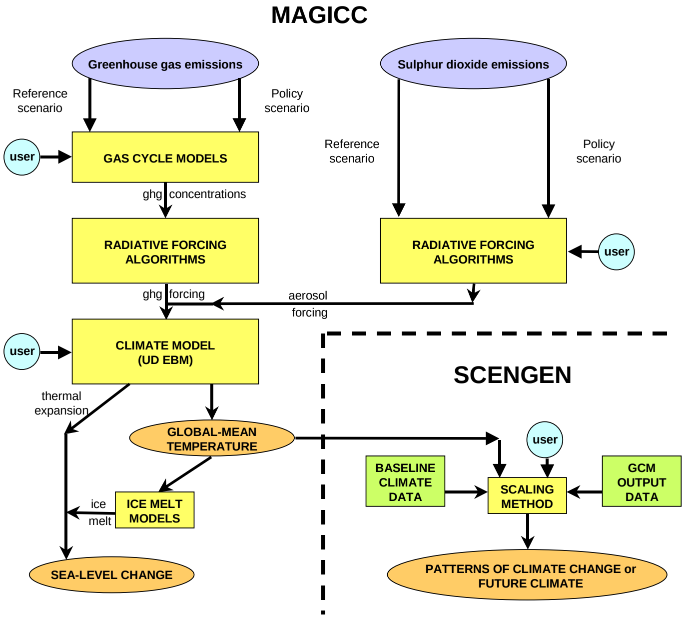

**Figure 12.** Schematic diagram of the MAGICC/SCENGEN model system (after Hulme *et al*., 2000)

This model system was used to estimate atmospheric concentrations, global temperature changes and sea-level rise for the IS92 and SRES scenarios in Tables 3 and 1, respectively. There are several advantages to be gained by using simple models of this kind:

- They are simple to operate.
- They are computationally fast, and can be used to examine a large number of scenario simulations.
- They produce scenarios of greenhouse gas emissions, atmospheric concentrations, radiative forcing, temperature response and sea-level rise that are physically consistent.
- They can provide timely information for policy makers, for instance, enabling comparisons to be made of the effects on climate of alternative measures to limit greenhouse gas emissions.
- They can be linked with GCM outputs to develop regional climate scenarios (e.g. SCENGEN in **Figure 12**).

Regional models have been used to conduct climate change experiments for many regions of the world, including parts of North America, Asia, Europe, Australia and southern Africa. These approaches were reviewed by the IPCC (Kattenberg *et al*., 1996) and an intercomparison project for regional climate simulations (PIRCS) was listed in section 3.2.3.1.

These methods of obtaining sub-grid scale estimates (commonly down to 50 km resolution or less) are able to account for important local forcing factors such as surface type and elevation, which conventional GCMs are unable to resolve. They have the advantage of being physically based, but are also highly demanding of computer time. For this reason, until recent years there had been very few simulations for a sufficient period of simulated years to allow meaningful climate change statistics to be extracted. Furthermore, the commonest approach, nesting, is still heavily reliant on specialised GCM outputs for its boundary conditions - the GCMs do not always provide good simulations of the large scale flow and there can be inconsistencies between the behaviour of the physical parameterizations in the driving model and in the finer grid of the regional model.

Nonetheless, the situation is changing rapidly, and a number of long-period simulations with LAMs for a few regions of the world, which overcome some of the problems described above, are now available for use in impact assessment. An early example of impact studies that made use of such information was reported by Mearns *et al*. (1997). The recently completed PRUDENCE project compared the performance of more than ten LAMs nested in several GCMs over Europe, and also evaluated their utility for application in impact studies (Christensen *et al*. 2002). Although outputs from LAM experiments are not being made available from the DDC, they can be obtained by contacting the respective modelling groups[1].

More detailed guidance on the construction of scenarios from regional climate model outputs is provided in Mearns *et al*. (2003).

#### *3.2.3.3. Interpreting GCM results and their uncertainties*

Sources of uncertainty

Model intercomparison studies, such as those presented above, provide valuable information on the differences between GCM projections and the reasons for these differences. However, the range of GCM results is unlikely to be indicative of the full range of uncertainties about future climate. Three main sources of uncertainty can be identified:

1. Uncertainties in future greenhouse gas and aerosol emissions. The IS92 and SRES emissions scenarios described exemplify these uncertainties, with each scenario implying different levels of atmospheric composition and hence of radiative forcing.
2. Uncertainties in global climate sensitivity, due to differences in the way physical processes and feedbacks are simulated in different models. This means that some GCMs simulate greater mean global warming per unit of radiative forcing than others.
3. Uncertainties in regional climate changes, which are apparent from the differences in regional estimates of climate change by different GCMs for the same mean global warming (see, for example, **Figure 11**).

While the results of GCM experiments probably capture a large part of the uncertainty ranges in 2 and 3, they certainly do not encapsulate the range of emissions described in 1. Due to constraints of time and resources, only a limited number of GCM experiments can be conducted. In addition, many experiments have been specifically designed to be directly comparable with other models, to aid model development, and their assumed forcing is very similar.

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[1] For example, the PRUDENCE model outputs are available online at: http://prudence.dmi.dk/

An alternative approach for estimating the effects of emissions uncertainties on climate is to use simple models. These enable the user to explore, very rapidly, the consequences for global mean temperature of large numbers of possible emissions scenarios. The approach is described in more detail in Box 4.

A combined approach to represent uncertainty

A combined approach, using information both from simple models and from GCMs, offers the possibility to represent the three types of uncertainty described above. In this approach, the *magnitude* and *timing* of global mean temperature change are supplied by the simple model, on the basis of a given emissions scenario, and the regional *pattern* of change in temperature and other climatic variables is supplied by a GCM. The approach comprises three stages (Smith and Hulme, 1998):

1. The standardised pattern of climate change from the GCM is estimated by dividing individual grid box changes by the global mean warming of that model experiment, yielding a ratio. Changes are computed between the present and future climate as simulated by the GCM. For instance, this might be the change between the model simulated 1961-1990 and 2070-2099 (centred on 2085) periods of a transient experiment.
2. The magnitude of global warming by a specified date in the future is estimated from the simple model for a given emissions scenario and a given climate sensitivity.
3. The patterns of changes in different climatic variables (i.e. the ratios computed in stage 1) are multiplied by the global warming value from stage 2 in a procedure known as "pattern-scaling".

In this way it is possible to generate regional climate scenarios that combine the uncertainties represented by the emissions scenarios, uncertainties about the climate sensitivity and uncertainties related to the regional pattern of climate change. An example of how this approach can be applied in sensitivity studies is shown below.

A fundamental assumption of the scaling approach is that while the magnitude of climate change alters over time in proportion to the global warming, the pattern of change from the GCM remains constant. This is problematic for two reasons. First, it can be difficult to establish whether the pattern of change represents a climatic response to radiative forcing or is simply an artefact of natural climatic variability. It may take many decades of a transient experiment before the climate change "signal" emerges from the "noise" of year-to-year variability.

A second problem is that regional climate may not respond coherently to increased radiative forcing, and hence the pattern of change may not be constant over time. For instance, it has been shown that the pattern of precipitation change can vary substantially during a transient simulation, sometimes changing sign. However, these results may be related to the high natural variability of precipitation. A pattern correlation analysis to compare an AOGCM experiment assuming 0.5%/year increase in emissions with an experiment assuming a 1%/year increase concluded that the regional pattern of temperature change was fairly similar at different periods during both simulations, while the pattern of precipitation change was much more variable (Mitchell *et al*., 1999). It should also be noted that the assumption of a consistent emerging pattern of change is the basis of recent detection studies that have produced evidence of an anthropogenic "fingerprint" in observations of the climate (Santer *et al*., 1996). Pattern scaling methods are harder to apply in the case of combined greenhouse gas and aerosol climate change fields; in this case, regionally-scaled aerosol patterns may need to be defined and combined with greenhouse gas only patterns (Schlesinger *et al*., 2000). An evaluation of the pattern-scaling technique for results from AOGCMs is presented by Mitchell (2003), and an approach for application with regional climate model outputs is suggested by Ruosteenoja *et al*. (2005).

Guided sensitivity analysis

The use of synthetic scenarios, which are arbitrary adjustments to the baseline climate, was identified above as an alternative to applying GCM-based scenarios. These scenarios can be used to explore the sensitivity of an exposure unit to a range of climatic variations. One way of refining this type of analysis, is to make use of the combined information from GCMs and simple models to define a credible range of plausible changes in regional climate, which can guide sensitivity analysis (Hulme and Brown, 1998).

This idea is illustrated in **Figure 13** for grid boxes over central India. 14 GCM outputs were standardised to a global mean warming of 1.4°C by 2050, based on a simple model (Box 4) assuming the IS92a emissions scenario and a climate sensitivity of 2.5°C. Their scaled regional estimates are plotted as temperature and precipitation changes relative to the baseline (solid circles). The straight lines represent the range of estimates obtained under extreme combinations of greenhouse gas emissions and climate sensitivity. For example, the largest changes are obtained under a combined scenario of high emissions (IS92e) and high climate sensitivity (+4.5°C); the lowest changes under low emissions (IS92c) and low sensitivity (+1.5°C).

The estimated range of natural variability (±2 standard deviations of 30 year smoothed data) is also shown in **Figure 13** for comparison with the simulated changes in climate, using both a century of observations (at the origin - open circle) and a 240-year control simulation (± 2 sd either side of the Hadley Centre AOGCM greenhouse gas-only simulation - open square). The Hadley Centre GHG plus aerosols experiment is also shown for comparison (solid square). The resulting envelope of temperature and precipitation changes embraces much of the current uncertainty in future estimates over central India. In this example, all experiments indicate a warming, in most cases significant relative to natural variability (i.e. the width of the horizontal error bars). In addition, all but two of the GHG-only experiments indicate an increase in precipitation, most of them significant (vertical bars). However, both the Hadley Centre experiments and one other experiment show a decrease in precipitation. Indeed, the aerosols experiment shows the most marked warming and drying of all the 16 models portrayed, in contrast to the finding globally that temperature increases are suppressed by aerosols (**Figure 13**).

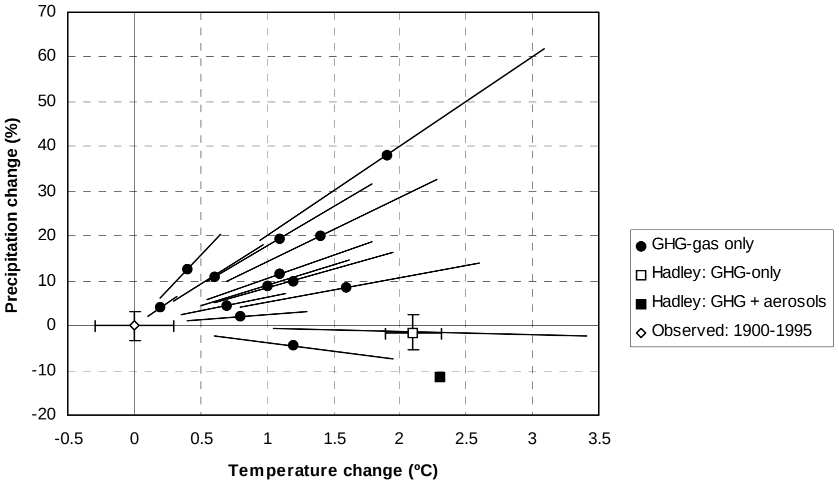

**Figure 13**. Temperature and precipitation change by 2050 relative to 1961-1990 over central India. Source: Parry and Carter (1998), modified from a draft version of Hulme and Brown (1998).

One of the criticisms of scenario analyses such as those portrayed in **Figure 13**, which attempt to account for the three types of uncertainty described above, has been that all plausible projections of future climate are implicitly accorded an equal probability of occurrence. Jones (2000) argues that this assumption is erroneous, and that outcomes at the extremes of the uncertainty range are less probable (on statistical grounds) than outcomes towards the centre of the range. He illustrates this with an example of an impact study which combined a sensitivity analysis with a probability analysis of the likelihood of various combinations of temperature and precipitation change in Australia based on a combination of simple model and GCM outputs. The objective of the study was to assess the risk of exceeding a threshold demand for annual irrigation (12 Mlha$^{-1}$), which would require an adaptive response. The sensitivity study evaluated the percentage of years in which the threshold is exceeded for arbitrary combinations of changes in temperature and precipitation. Superimposing probability plots of expected climate changes (based on a Monte Carlo analysis of combinations of outcomes across the range of uncertainty) onto the sensitivity graph yielded an estimate of the changing risk of exceeding the irrigation threshold between 1990 and 2100 (**Figure 14**). Further analysis established that, for instance, by 2030 there is only a 5% probability that the climate will have changed enough to produce an exceedance of the threshold in 20% of years. However, by 2070, the probability of the required climate change occurring has risen to 80%.

### *3.2.3.4. Changes of means and variability*

Outputs from GCMs are usually applied as monthly or seasonal adjustments to the baseline climate in impact assessments, assuming no change in climatic variability between the baseline and future climate. Thus the pattern of diurnal, day-to-day and inter-annual variability of climate remains unchanged (unless inadvertent adjustments are made to the baseline climatic variability - see section 5.4.5, below). However, sensitivity studies that altered the variability of climate across a plausible range have demonstrated that changes in climatic variability can be just as important for an exposure unit, if not more so, than changes in the mean climate (e.g. Katz and Brown, 1992; Semenov and Porter, 1995). So what do GCMs tell us about future climatic variability?

Unfortunately, there is still great uncertainty about GCM estimates of future climatic variability. Some of the key issues are discussed in Kattenberg *et al*., (1996), and a summary table was produced for the IPCC Third Assessment Report (**Table 7**). Some of the generalised conclusions are reproduced below.

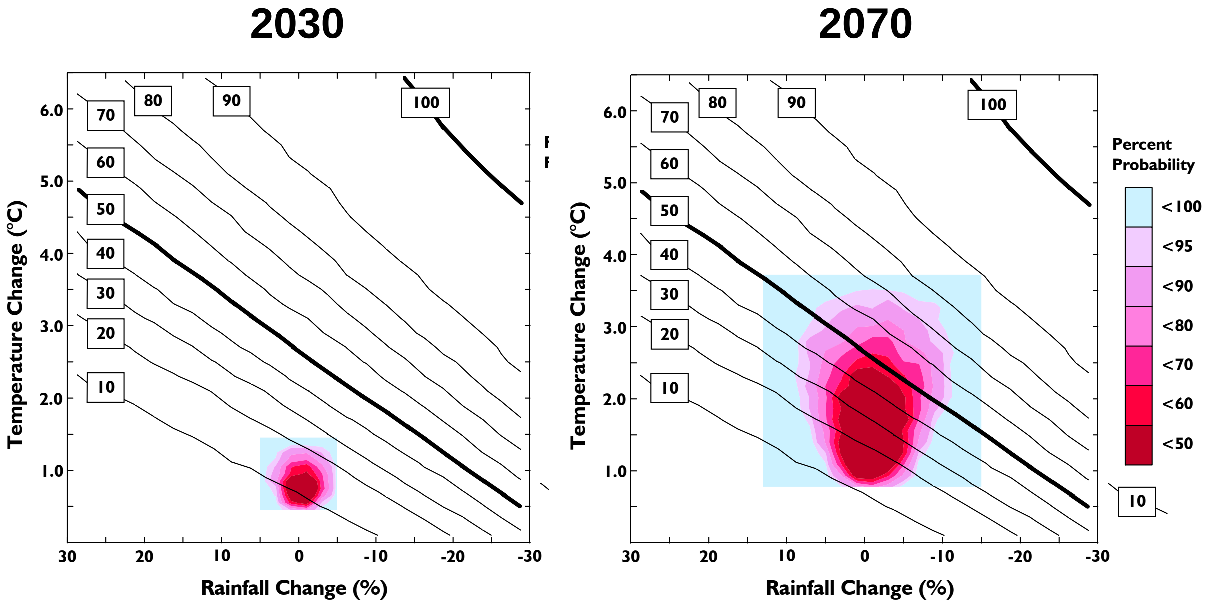

**Figure 14**. Cumulative probability plots for climate scenarios and probability of exceedence of an annual irrigation threshold for 2030 and 2070 in northern Victoria, Australia. High percentages on the cumulative probability scale indicate a low probability (e.g. <100 represents an occurrence probability of between 0 and 5%). Source: Jones (2000).

### Interannual variability

Perhaps the most important source of interannual variability in the tropics and beyond is the ENSO phenomenon. However, it is not clear whether ENSO events will change character as a response to global warming, though recent simulations with the ECHAM4 GCM indicated an increase in the frequency of ENSO events (Timmermann *et al.*, 1999) and there is a suggestion from other model results that precipitation variability associated with ENSO events may be enhanced, especially over tropical continents (Trenberth and Hoar, 1997). There is also growing evidence that interannual temperature variability may decrease in northern mid-latitudes in winter.

### Severe storms and cyclones

There is little agreement between GCMs about possible changes in the frequency, intensity and track of mid latitude storms under climatic warming (Kattenberg *et al*., 1996). The situation is similar regarding future changes in tropical typhoons, although a recent study coupling GCM outputs with a high resolution forecast model in the western Pacific simulates an increase of storm intensity for a doubling of $CO_2$ (Knutson *et al*., 1998).

### Precipitation variability

There is more evidence to suggest that precipitation variability may change in the future. The hydrological cycle is likely to be more intense under a warmer climate and several models have shown an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events (e.g. Fowler and Hennessy, 1995). At the same time, some models also project more frequent or severe drought periods over land areas.

### Diurnal temperature range

Annual trends during 1950-2004 averaged over 71% of the terrestrial surface for which data are available, show an increase in minimum temperatures of 0.20 ºC decade$^{-1}$ and maximum temperatures of 0.14 ºC decade$^{-1}$ (Vose et al., 2005). This represents a narrowing of the diurnal temperature range (DTR) by –0.07 K decade$^{-1}$, though this narrowing had fallen to virtually zero change from 1979–2004 (Vose et al., 2005). Changes in DTR can be of importance for some exposure units (e.g. crop plants - Williams *et al*., 1988). Since most GCMs, including all of those held at the Data Distribution Centre, provide information on both temperature variables, impact analysts have an opportunity to examine whether changes in the DTR (observed to have varied from region to region) are projected to continue into the future. There have also been some initial attempts to construct statistically downscaled scenarios of DTR (e.g. Kaas and Frich, 1995).

### Scenarios of changing variability

A number of impact studies have used stochastic weather generators (Box 1) or other synthetic methods to develop scenarios combining mean changes with variability changes on the basis of GCM or regional model outputs (e.g. Wilks, 1992; Mearns *et al*., 1997; Semenov and Barrow, 1997). These have focused primarily on changes in daily variability, though some studies have also considered inter-annual variability (e.g. Mearns *et al*., 1996). It should be noted that inadvertent adjustments to the daily variability of certain variables can occur through apparently straightforward mean adjustments of daily baseline observations (e.g. Mearns et al., 1997 have demonstrated this when adjusting baseline precipitation according to monthly mean ratios of GCM-derived 2 x $CO_2$/control precipitation changes). For a more extensive discussion of scenarios of changing variability, see Mearns et al. (2001).

**Table 7**. Estimates of confidence in observed and projected changes in extreme weather and climate events. Source: IPCC (2001a).

| **Confidence in observed changes (latter half of the 20th century)** | **Changes in Phenomenon** | **Confidence in projected changes (during the 21st century)** |
|---|---|---|
| Likely | Higher maximum temperatures and more hot days over nearly all land areas | Very likely |
| Very likely | Higher minimum temperatures, fewer cold days and frost days over nearly all land areas | Very likely |
| Very likely | Reduced diurnal temperature range over most land areas | Very likely |
| Likely over many areas | Increase of heat index over land areas | Very likely over most areas |
| Likely over many Northern Hemisphere mid- to high latitude land areas | More intense precipitation events | Very likely over many areas |
| Likely in a few areas | Increased summer continental drying and associated risk of drought | Likely over most mid-latitude continental interiors. (Lack of consistent projections in other areas) |
| Not observed in the few analyses available | Increase in tropical cyclone peak wind intensities | Likely over some areas |
| Insufficient data for assessment | Increase in tropical cyclone mean and peak precipitation intensities | Likely over some areas |

# 4. OTHER ENVIRONMENTAL DATA AND SCENARIOS

## 4.1. Environmental baselines

Concurrent with variations in climate, there are also variations in other environmental conditions that can have a direct effect on an exposure unit. Strictly speaking, the baseline period for these ought to be consistent with that of the climatological baseline. In fact, many impact studies assume environmental conditions to be fixed at constant values representative of a single year. For instance, in previous IPCC assessments, 1990 has been designated as the reference year.

Some of the more important environmental factors are outlined below under three categories: atmospheric, water and terrestrial conditions.

### *4.1.1. The atmospheric environment*

A number of gases and other atmospheric constituents may have important effects on the exposure unit. Some of these gases, and their effects, are described below.

*4.1.1.1. Carbon dioxide:*

Perhaps the most important gas in the atmosphere, from the point of view of the impacts analyst, is carbon dioxide. $CO_2$ concentration is commonly required as a direct input to models of plant growth, since it can affect both the growth and water use of many plants through its first-order (direct) effect on photosynthesis and stomatal conductance. As well as having direct effects on vegetation and biomass, it is also the major greenhouse gas associated with global climate change. In any scenario building exercise, the $CO_2$ concentrations adopted should be consistent with concentrations during the climatological baseline period. $CO_2$ is well mixed in the atmosphere, so observations of concentrations from a single site (e.g. see **Table 8**, below) are adequate for most impact applications.

**Table 8**. Annual- and decadal-mean $CO_2$ concentrations (ppm) observed at Mauna Loa, Hawaii (1959-2004). 1961-1990 mean concentration is 333.3 ppm. Source: CDIAC (2006).

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | *Mean* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1950** | - | - | - | - | - | - | - | - | - | 315.8 | - |
| **1960** | 316.7 | 317.5 | 318.3 | 318.8 | 319.4 | 319.9 | 321.2 | 322.0 | 322.9 | 324.5 | ***320.1*** |
| **1970** | 325.5 | 326.2 | 327.3 | 329.5 | 330.1 | 331.0 | 332.0 | 333.7 | 335.3 | 336.7 | ***330.7*** |
| **1980** | 338.5 | 339.8 | 342.0 | 342.6 | 344.2 | 345.7 | 347.0 | 348.8 | 351.3 | 352.8 | ***345.3*** |
| **1990** | 354.0 | 355.4 | 356.2 | 357.0 | 358.9 | 360.9 | 362.6 | 363.8 | 366.7 | 368.3 | ***360.4*** |
| **2000** | 369.5 | 371.0 | 373.1 | 375.6 | 377.4 | | | | | | |

Conventionally, the baseline $CO_2$ concentration is assumed fixed at a given level. This might be the reference concentration in which plants have been grown in $CO_2$ enrichment experiments. Alternatively, it might be the default value assumed in an impact model, usually a value representative of the late 20th century. However, a word of caution is necessary when testing impact models for conditions over a 30-year or longer baseline period. $CO_2$ concentrations have increased rapidly since 1960 (**Table 8**), and if the exposure unit is responsive to $CO_2$, this temporal trend should be accounted for. For example, mean $CO_2$ concentration has increased by 11.5% between 1961 and 1990 (**Table 8**). Model estimates of plant growth and yield in 1961 should thus assume 1961 $CO_2$ concentration in combination with 1961 climate. For century-long simulations of tree growth, this effect may be even more important.

There may also be some applications in which the seasonal and/or diurnal variation of $CO_2$ concentration should be accounted for. Data on these variations can be found on the Internet pages and in volumes published by the Carbon Dioxide Data and Information and Analysis Center (e.g. CDIAC, 2006[1]). The consistency between $CO_2$ concentrations and climate projections is discussed further below (Section 4.3.1).

#### *4.1.1.2. Tropospheric ozone*

Another gas of importance in some impact studies is tropospheric ozone. This is toxic for a wide range of living organisms, its concentrations being highly variable in space and time, registering its highest concentrations over industrial regions or rural areas close to them under certain weather conditions. Time series of ozone concentrations are available for some regions, especially in developed countries. They are usually expressed in terms of background concentrations and peak concentrations. Global model estimates of ozone abundance are presented in Prather et al. (2001) and gridded model results are available from the DDC.

#### *4.1.1.3. Stratospheric ozone*

Concentrations of stratospheric ozone have been measured operationally at many high latitude sites in recent years, especially following the discovery of the seasonal "ozone hole" over Antarctica in 1985. Ozone depletion is associated with increased ultraviolet radiation, which can be harmful for life on earth. Daily forecasts of exposure risk to UV-radiation are issued in many countries at mid to high latitudes, especially during the spring and early summer when levels of stratospheric ozone are generally at a minimum.

#### *4.1.1.4. Sulphur and nitrogen compounds*

Concentrations of sulphur and nitrogen compounds, which are both major contributors to acid precipitation in many parts of the world, are also measured in some regions. Also, the presence of nitrogen in rainfall, even in low quantities, is suspected to play some role (difficult to precisely assess at the present stage) in the increased productivity of Northern Hemisphere forests by some kind of fertilization. Furthermore, it has been estimated that sulphate aerosol concentrations in industrial regions have contributed a cooling effect on climate in some regions in past decades, which has counteracted the warming effect of greenhouse gases. A comprehensive review of sulphate aerosols in the atmosphere is provided by Penner et al. (2001), and some gridded global estimates of sulphur abundances and deposition are available from the DDC.

#### *4.1.1.5. Smoke and particulates*

Smoke and other particulate matter in the atmosphere, bi-products of fossil fuel burning, land clearance and land erosion or other human activities, can have important regional impacts on visibility and human health. These are increasingly being observed using satellites as well as ground based instruments.

### ***4.1.2. The terrestrial environment***

#### *4.1.2.1. Land cover and land use*

On land, data on land cover and land use change are of great importance in many impact studies. Geographical data and time series have been compiled by a number of research groups working at national, continental and global scale, based on satellite imagery, aerial photographs and ground survey. Many data sets have been collected as part of a major international research effort - the Land Use and Land Cover Change Programme (LUCC) of the International Geosphere Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP). For instance, a global integrated model, IMAGE 2, has been used to study the dynamics of land use change. The model was initialised using baseline land use data from 1970. A

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[1] http://cdiac.esd.ornl.gov/cdiac/

continually updated time series of observed global land use up to the 1990s can then be used to test the model's predictions during the period after 1970 (Alcamo *et al*., 1996, 1998). National land cover/land use statistics have also been tabulated by the IPCC and are available from the DDC (see Section 2.2.1).

#### *4.1.2.2. Soil and agricultural practices*

Baseline information is also commonly required on the state of the soil where this has been changing over time, for example, water storage capacity, nutrient status, pH and salinity. Data sources for this information tend to be national or regional in scope.

In agriculture, data on farm management practices are of vital importance in describing the reference conditions. This covers, for instance, the kind of adopted cultivars, the timing and quantities of water brought by irrigation, and of fertilizer applications, use of pesticides and herbicides, tillage practices, stocking rates. Baseline information on these is important, not only because they have been responsible for dramatic increases in productivity in many regions in recent decades, but also because they have contributed to soil erosion or pollution of soils, surface waters and groundwater in many regions. Data for different countries are collected annually by the United Nations Food and Agriculture Organization (FAO, 1992, also see the website www.fao.org).

#### *4.1.2.3. Biodiversity*

There has been considerable concern in recent years about the endangerment and loss of natural species, mainly attributable to human activities. There have been a number of national and international initiatives to document and catalogue biodiversity, and baseline statistics representative of the 1990s have been compiled for each country by the World Conservation Monitoring Centre, were published for an IPCC report on Regional Impacts of Climate Change (IPCC, 1998) and are available from the Data Distribution Centre.

### ***4.1.3. The hydrological environment***

#### *4.1.3.1. Sea level*

One of the key factors to evaluate for many impact studies in low lying coastal regions is the current level of the sea relative to the land. Globally, eustatic sea level (the volume of water in the oceans) appears to have been rising during the past century (Church *et al*., 2001). However, there are large regional deviations in relative sea level from this global trend due to local land movements. Subsidence, due to tectonic movements, sedimentation, or human extraction of groundwater or oil, enhances relative sea-level rise. Uplift, due to post glacial isostatic rebound or tectonic processes, reduces or reverses sea-level rise (**Figure 15**). The main source of information on relative sea level is tide gauge records, and the major global data source is the Permanent Service for Mean Sea Level (PSMSL)[1].

As a reference, most studies of vulnerability to sea-level rise use the mean sea-level at a single date. For instance, studies employing the IPCC Common Methodology (WCC'93, 1994) use the level in 1990 (Nicholls, 1995; Bijlsma, 1996). However, to assess coastal vulnerability to sea-level effects, baseline tide gauge and wave height observations are required. These reflect tidal variations in combination with the effects of weather such as severe storms and atmospheric pressure variations.

For more information on baseline sea level information, see Nicholls et al. (2003).

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[1] http://www.nbi.ac.uk/psmsl/index.html

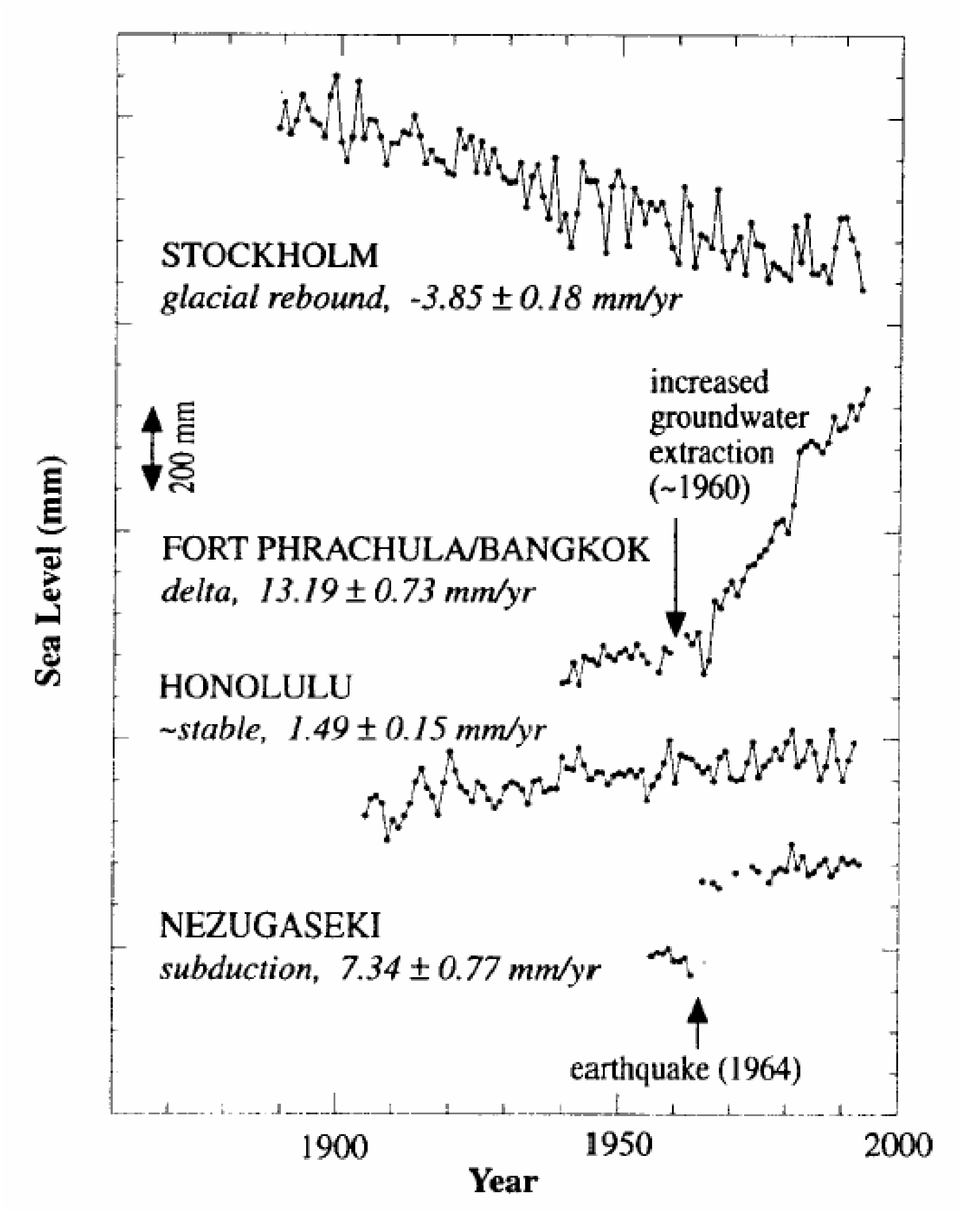

**Figure 15**. Examples of four different trends in observed sea-level change, due to contrasting geological settings. Source: Bijlsma, (1996).

### *4.1.3.2. Inland water levels*

The levels of lakes, rivers and groundwater also vary with time, usually for reasons related to the natural balance between water inflow (due to precipitation and runoff) and losses (due to evaporation and seepage). Human intervention can also affect water levels, through flow regulation and impoundment, land use changes, water abstraction and effluent return and large scale river diversions (Arnell *et al.*, 1996). Sometimes these fluctuations in levels can be very large (often much larger than mean changes anticipated in the future). Thus, where time series are available, it is important to be able to identify the likely causes of fluctuations (i.e. natural or anthropogenic), as this information could influence the selection of an appropriate baseline period.

#### *4.1.3.3. Other characteristics*

Other important water-related characteristics for which baseline data may be required include water temperatures (surface and at different depths), salinity, dissolved oxygen and dissolved organic carbon.

## 4.2. Environmental scenarios without climate change

It is highly probable that future changes in other environmental factors will occur, even in the absence of climate change, which may be important for an exposure unit. Examples include land use in general and especially deforestation or afforestation, changes in grazing pressure from livestock, changes in groundwater level or mean sea-level and changes in air, water and soil pollution. Projections may exist to describe some of these (such as groundwater level), but for others it may be necessary to study past trends and apply expert judgement. Since most of these changes are local or regional in scale, projections are not provided by the DDC. Most factors are related to, and projections should be consistent with, trends in socio-economic factors (see section 2). Greenhouse gases may also change, but they are usually linked to climate (which is assumed unchanged here).

## 4.3. Environmental scenarios with climate change

The two environmental factors that are directly related to a changing climate, and are commonly required in impact assessments, are atmospheric composition and sea-level rise.

### *4.3.1. Scenarios of atmospheric composition*

Projections of atmospheric composition are important for assessing effects, firstly, on radiative forcing of the climate, secondly, on depletion of stratospheric ozone (CFCs), and thirdly, on plant response and human health ($CO_2$, tropospheric ozone and compounds of sulphur and nitrogen). Scenarios for $CO_2$ concentrations have been reviewed by Prentice et al. (2001). Projections for the 21st century consistent with the SRES and IS92 emissions scenarios are given in **Table 1** and **Table 3**, and are also available on the DDC[1]. Global model estimates of tropospheric ozone abundance were reviewed by Prather et al. (2001) and gridded projections up to 2100 are available from the DDC. Atmospheric concentrations and deposition of sulphur aerosols have been reviewed by Penner et al. (2001), and gridded model projections for the 21st century are available from the DDC.

### *4.3.2. Scenarios of sea level*

One of the major impacts projected under global warming is sea-level rise. Global factors such as the expansion of sea water and melting of ice sheets and glaciers all contribute to this effect. Some of the AOGCMs compute relative sea-level rise, but this is only the portion attributable to thermal expansion of sea water, possibly accounting for no more than about one half of the projected change (Warrick *et al.*, 1996). Simple global models that attempt to account for all of these factors can also be used to obtain global estimates. A set of estimates consistent with the SRES and IS92 scenarios and modelled temperature changes (cf. Box 4) are provided in **Table 1** and **Table 3**.

Note that local conditions such as coastal land subsidence, tectonic movements, isostatic uplift, changes in mean atmospheric and oceanic circulation and changes in storminess, waves and tides should also be taken into account in considering the extent of sea-level changes and their regional impacts. Some of these can be projected based on past trends, for example, using tide gauge records.

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[1] SRES emissions data are available at: http://ipcc-ddc.cru.uea.ac.uk/sres/ddc_sres_emissions.html

### *4.3.3. Other environmental scenarios*

Other environmental factors that are directly affected by climate include river flow, runoff, soil characteristics, erosion and water quality. Projections of these often require full impact assessments of their own, or could be included as interactive components within an integrated assessment framework. No projections of these are provided by the DDC.

# 5. SCENARIO CONSISTENCY AND REPORTING

## 5.1. Scenario consistency

In the list of criteria for selecting climate scenarios, provided in Section 3.2.1, one of the key criteria is that it should be physically plausible (Criterion 2). This criterion also applies to the relationship between climate and non-climatic scenarios (and see Lorenzoni et al., 2000). Thus, when constructing scenarios for impact and adaptation assessment, projections of climate should be consistent not only with projections of atmospheric composition and the emissions scenarios upon which they are based, but also with "downstream" projections of sea-level rise. One way of ensuring this is to use simple models such as those described in Box 5.

Carbon dioxide concentration is one of the most important of the non-climatic factors to take into account. Besides being a major greenhouse gas that influences the climate (indirect effect), it is also of great importance for plant growth and productivity (direct effects). It is important that appropriate levels of $CO_2$ concentration are used in conjunction with a given climate change (see, for example, **Table 1** and **Table 3**). If, for example, a study of crop responses to greenhouse warming is carried out, the climate-related indirect effect on crops should be consistent with the atmospheric $CO_2$ concentrations which contribute to the direct effect. This is not straightforward, and unfortunately has been a source of some confusion in past impact studies,. The following points are worth noting:

- In interpreting climate model data, it is important to know the forcing. The forcing may be specified by climate modellers as an equivalent $CO_2$ atmosphere, in which the combined effects of $CO_2$ and other greenhouse gases on the Earth's radiation balance are expressed in terms of $CO_2$ alone. With respect to consistency, this is an important point to note when both indirect and direct effects of $CO_2$ are to be taken into account in an impact study. Where the forcing is expressed in terms of a $CO_2$ equivalent, the indirect effect will be less than if it were $CO_2$ alone, since such gases as methane and nitrous oxide, although they have an atmospheric forcing potential, do not have a direct effect on plants.
- The climate has a lag time of several decades in its response to increasing greenhouse gas concentrations. Thus, at any particular point in time, the climate will not have realized its full, equilibrium, response to the forcing whereas, with respect to the direct effect of $CO_2$ on plants, the impact is immediate.

Similarly, sea-level rise occurs in response to global warming. In the early years of warming this increase is related primarily to thermal expansion of sea water, but increasingly melting of land-based ice will contribute. Scenarios of future sea-level change should also be consistent with estimates of climate change (see Section 4.3.2).

## 5.2. Scenario reporting

In this section suggestions are put forward concerning the presentation and reporting of impact assessments, especially concerning the use of scenarios. Adherence to some of these basic guidelines will greatly assist the reviewing and synthesis of impact studies.

### *5.2.1. Appropriate citation of sources*

Out of courtesy to the scientists involved, the original sources of the baseline data and scenarios used should be cited correctly. For example, although the Data Distribution Centre will be providing data from AOGCMs, the correct sources to cite in referring to these models are publications by the modelling groups themselves, not the DDC or these Guidelines. The DDC has documented each of the models, so the relevant information is readily available. Similarly, the sources of non-climatic scenarios should also be referenced correctly (for example, the source of the SRES scenarios is Nakićenović et al. 2000). If components of these SRES scenarios are to be used (for example, regional population projections) then the original source of the projections should be cited (e.g. United Nations, 1992). Again, the DDC provides guidance on these.

### *5.2.2. Use of standard notation*

Special care should be taken to adopt conventional notation when referring to individual GCM experiments. There are many versions of the the same or similar models in circulation, so it is important to identify models using an accepted acronym. Again, the DDC will provide guidance on these.

### *5.2.3. Description of methods*

The methods adopted to select, interpret and apply the scenarios should be described in full, with proper citation to comparable previous studies employing similar methods. This information is important for evaluating and comparing different impact studies, and for tracing how techniques are evolving over time.

### *5.2.4. Understanding the significance of the results*

Impact studies that employ scenarios should indicate, where possible, the statistical significance of the results. For example, regional scenarios of climate change should be compared with natural variability in the baseline observations or model simulation of the present day. Similarly, the impacts of these scenarios should be contrasted with the impacts of natural variability.

### *5.2.5. Consideration of uncertainties*

At each stage of an impact assessment, there should be a full and proper discussion of the key uncertainties in the results, including those attributable to the input data, impact models, climate scenarios and non-climatic scenarios (Carter, 2001). A rigorous sensitivity analysis can be very helpful in identifying some of the major uncertainties. It is also strongly recommended that users should design and apply multiple scenarios in impact assessments, where these multiple scenarios span a range of possible future climates, rather than designing and applying a single “best-guess” scenario.

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## Appendix 1 IPCC Task Group on Data and Scenario Support for Impact and Climate Assessment

The mandate of the IPCC Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA), formerly the Task Group on Scenarios for Climate Impact Assessment (TGCIA), is to facilitate wide availability of climate change related data and scenarios to enable research and sharing of information across the three IPCC working groups. The TGICA disseminates information in support of IPCC work, as well as IPCC “approved” “adopted,” “accepted,” and “supporting” material (as defined in Appendix A to the Principles Governing IPCC Work). This includes, for example, information on:

- anthropogenic influences on climate
- climatological baselines and observations
- projected future climate
- other environmental, technological, and socio-economic factors and data relevant to impacts, adaptation, vulnerability, and mitigation research

The TGICA does not develop emission, climate, or other types of scenarios for the IPCC, make decisions regarding the choice of such scenarios for use in IPCC assessments, nor undertake modeling or research. The TGICA is accountable to the Panel through the IPCC Bureau and reports to sessions of the Bureau and Panel.

The first full meeting of the TGCIA took place in May 1997. The members of the Task Group are drawn from the climate modelling, impacts and emission scenario communities as well as those working at the interface between the various communities (**Table 9**). It is supported by the Technical Support Units (TSUs) of Working Groups I and II.

Two inventories of climate model studies (actions (i) and (ii)) and an additional inventory of impact studies have been prepared by the TSUs and are freely available. To address action (iii), the Task Group recommended the establishment of a Data Distribution Centre, the preparation of supporting guidance material (this document) and the development of a training programme in the use of scenarios. The training component and the other actions listed above are currently under discussion by the Task Group.

**Table 9.** IPCC Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA)

| **Name** | **Country** |
|---|---|
| Jose Antonio Marengo | Brazil (Co-Chair) |
| Richard Moss | USA (Co-Chair) |
| Ayman F. Abou-Hadid | Egypt |
| Knut Alfsen | Norway |
| Nigel Arnell | United Kingdom |
| Elaine Barrow | Canada |
| Timothy Carter | Finland |
| Seita Emori | Japan |
| Xuejie Gao | P. R. China |
| Bruce Hewitson | South Africa |
| Tom Kram | The Netherlands |
| Emilio Lebre La Rovere | Brazil |
| Rodel Lasco | Philippines |
| Linda Mearns | USA |
| John Mitchell | United Kingdom |
| Anthony Okon Nyong | Nigeria |
| Hugh Pitcher | USA |
| Bernard Seguin | France |
| Serguei Semenov | Russia |
| Robert Chen | USA (Ex-officio) |
| Martin Juckes | United Kingdom (Ex-officio) |
| Michael Lautenschlager | Germany (Ex-officio) |
| Martin Manning | USA (Ex-officio) |
| Leo Meyer | The Netherlands (Ex-officio) |
| Jean Palutikof | United Kingdom (Ex-officio) |

Former members: Jose Daniel Pabon Caicedo, Columbia; Ulrich Cubasch, Germany; Xiaosu Dai, P.R. China; Paul Desanker, USA; Mohamed El-Raey, Egypt; Filippo Giorgi, USA; David Griggs, UK; Murari Lal, India; Mike Hulme, UK; Neil Leary, USA; Ileana Mares, Romania; Luis Jose Mata, Venezuela; Tsuneyuki Morita, Japan; Daniel Murdiyarso, Indonesia; Nguyen Hoang Nghia, Vietnam; Carlos Nobre, Brazil; Maria Noguer, UK; Martin Parry, UK (former Chair); Mezak Ratag, Indonesia; Cynthia Rosenzweig, USA; Robert Scholes, South Africa; Rob Swart, Netherlands; David Viner, United Kingdom; Penny Whetton, Australia