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Developing and Applying Scenarios

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EXECUTIVE SUMMARY

What are Scenarios and What is Their Role?

A scenario is a coherent, internally consistent, and plausible description of a possible future state of the world. Scenarios commonly are required in climate change impact, adaptation, and vulnerability assessments to provide alternative views of future conditions considered likely to influence a given system or activity. A distinction is made between climate scenarios—which describe the forcing factor of focal interest to the Intergovernmental Panel on Climate Change (IPCC)—and nonclimatic scenarios, which provide socioeconomic and environmental "context" within which climate forcing operates. Most assessments of the impacts of future climate change are based on results from impact models that rely on quantitative climate and nonclimatic scenarios as inputs.

Types of Scenarios

Socioeconomic scenarios can serve multiple roles within the assessment of climate impacts, adaptation, and vulnerability. Until recently, they have been used much more extensively to project greenhouse gas (GHG) emissions than to assess climate vulnerability and adaptive capacity. Most socioeconomic scenarios identify several different topics or domains, such as population or economic activity, as well as background factors such as the structure of governance, social values, and patterns of technological change. Scenarios make it possible to establish baseline socioeconomic vulnerability, pre-climate change; determine climate change impacts; and assess post-adaptation vulnerability.

Land-use and land-cover scenarios should be a major component of scenarios for climate change impact and adaptation assessments. A great diversity of land-use and land-cover change scenarios have been constructed. However, most of these scenarios do not address climate change issues explicitly; they focus instead on other issues—for example, food security and carbon cycling. Large improvements have been made since the Second Assessment Report (SAR) in defining current and historic land-use and land-cover patterns, as well as in estimating future scenarios. Integrated assessment models currently are the most appropriate tools for developing land-use and land-cover change scenarios.

Environmental scenarios embrace changes in environmental factors other than climate that will occur in the future regardless of climate change. Because these changes could have an important role in modifying the impacts of future climate change, scenarios are required to portray possible future environmental conditions, such as atmospheric composition [e.g., carbon dioxide (CO_2), tropospheric ozone (O_3), acidifying compounds, and ultraviolet (UV)-B radiation]; water availability, use, and quality; and marine pollution. Apart from the direct effects of CO_2 enrichment, changes in other environmental factors rarely have been considered alongside climate changes in past impact assessments, although their use is increasing with the emergence of integrated assessment methods.

Climate scenarios of three main types have been employed in impact assessments: incremental scenarios, analog scenarios, and climate model-based scenarios. Of these, the most common use outputs from general circulation models (GCMs) and usually are constructed by adjusting a baseline climate (typically based on regional observations of climate over a reference period such as 1961–1990) by the absolute or proportional change between the simulated present and future climates. Most recent impact studies have constructed scenarios on the basis of transient GCM outputs, although some still apply earlier equilibrium results. Regional detail is obtained from the coarse-scale outputs of GCMs by using three main methods: simple interpolation, statistical downscaling, and high-resolution dynamic modeling. The simple method, which reproduces the GCM pattern of change, is the most widely applied in scenario development. In contrast, the statistical and modeling approaches can produce local climate changes that are different from the large-scale GCM estimates. More research is needed to evaluate the value added to impact studies of such regionalization exercises. One reason for this caution is the large uncertainty of GCM projections, which requires further quantification through model intercomparisons, new model simulations, and pattern-scaling methods. Such research could facilitate future evaluation of impacts in a risk assessment framework.

Sea-level rise scenarios are required to evaluate a diverse range of threats to human settlements, natural ecosystems, and landscape in coastal zones. Relative sea-level scenarios (i.e., sea-level rise with reference to movements of the local land surface) are of the most interest for impact and adaptation assessments. Tide gauge and wave height records of 50 years or more are required, along with information on severe weather and coastal processes, to establish baseline levels or trends. Although some components of future sea-level rise can be modeled regionally, using coupled ocean-atmosphere models, the most common method of obtaining scenarios is to apply global mean estimates from simple models. Changes in the occurrence of extreme events such as storm surges and wave set-up, which can lead to major coastal impacts, sometimes are investigated by superimposing historically observed events onto rising mean sea level. More recently, some studies have begun to express future sea-level rise in probabilistic terms, enabling rising levels to be evaluated in terms of the risk that they will exceed a critical threshold of impact.

How Useful have Scenarios Been in Past Impact and Adaptation Assessments?

Study of past assessments has highlighted problems of compatibility in the development and application of scenarios. These problems include difficulties in obtaining credible and compatible projections over long time horizons across different scientific disciplines, inconsistencies in scenarios adopted and their methods of application between different impact assessments, and time lags between reporting of recent climate science and the use of this science in developing scenarios for impact assessment. Furthermore, the use of nonclimatic scenarios at the regional level, alongside more conventional climate scenarios, is only a relatively recent introduction to impact assessment, and methods of scenario development (especially of socioeconomic scenarios) still are at a rudimentary level.

Scenarios of the 21st Century

The IPCC recently completed the *Special Report on Emissions Scenarios* (SRES) to replace the earlier set of six IS92 scenarios developed for the IPCC in 1992. These new scenarios consider the period 1990–2100 and include a range of socioeconomic assumptions [e.g., a global population by 2100 of 7.0–15.1 billion; average gross domestic product (GDP) of $197–550 trillion (1990 US$)]. Their implications for other aspects of global change also have been calculated. For example, mean ground-level O_3 concentrations in July over the industrialized continents of the northern hemisphere are projected to rise from about 40 ppb in 2000 to more than 70 ppb in 2100 under the highest illustrative SRES emissions scenarios. Estimates of CO_2 concentration range from 478 to 1099 ppm by 2100, accounting for the range of SRES emissions and uncertainties about the carbon cycle. This range of implied radiative forcing gives rise to an estimated global warming from 1990 to 2100 of 1.4–5.8°C, assuming a range of climate sensitivities. This range is somewhat higher than the 0.7–3.5°C of the SAR because of higher levels of radiative forcing in the SRES scenarios than in the IS92a-f scenarios, primarily because of lower sulfate aerosol emissions, especially after 2050. The equivalent range of estimates of global sea-level rise (for this range of global temperature change in combination with a range of ice-melt sensitivities) to 2100 is 9–88 cm (compared to 15–95 cm in the SAR).

In terms of *mean changes of climate*, results from GCMs that have been run to date—assuming the new SRES emissions scenarios—display many similarities with previous runs. Rates of warming are expected to be greater than the global average over most land areas and most pronounced at high latitudes in winter. As warming proceeds, northern hemisphere snow cover and sea-ice extent will be reduced. Models indicate warming below the global average in the North Atlantic and circumpolar southern ocean regions, as well as in southern and southeast Asia and southern South America in June–August. Globally, there will be increases in average water vapor and precipitation. Regionally, December–February precipitation is expected to increase over the northern extratropics and Antarctica and over tropical Africa. Models also agree on a decrease in precipitation over Central America and little change in southeast Asia. Precipitation in June–August is expected to increase in high northern latitudes, Antarctica, and south Asia; to change little in southeast Asia; and to decrease in Central America, Australia, southern Africa, and the Mediterranean region.

Changes in the frequency and intensity of extreme climate events also can be expected. Based on the conclusions of the Working Group I report and the likelihood scale employed there, under GHG forcing to 2100, it is very likely that daytime maximum and minimum temperatures will increase, accompanied by an increased frequency of hot days. It also is very likely that heat waves will become more frequent; the number of cold waves and frost days (in applicable regions) will decline. Increases in high-intensity precipitation events are likely at many locations, and Asian summer monsoon precipitation variability also is likely to increase. The frequency of summer drought will increase in many interior continental locations, and it is likely that droughts, as well as floods, associated with El Niño events will intensify. The peak wind intensity and mean and peak precipitation intensities of tropical cyclones are likely to increase. The direction of changes in the average intensity of mid-latitude storms cannot be determined with current climate models.

How can We Improve Scenarios and Their Use?

Methods of scenario construction and application are evolving rapidly, but numerous deficiencies still must be addressed:

- Representing and integrating future nonclimatic (socioeconomic, environmental, and land-use) changes in scenarios for impact assessment
- Treatment of scenario uncertainties
- The requirement for scenario information at higher spatial and temporal resolution
- Representing changes in variability and the frequency of extreme events in scenarios
- Reducing time lags between climate modeling and climate scenario development
- Increasing attention on the construction of policy-relevant scenarios (e.g., stabilization of atmospheric CO_2 concentration)
- Recognizing linkages between scenarios for studies of mitigation, impacts, and adaptation
- Improving guidance material and training in construction and application of scenarios.

3.1. Definitions and Role of Scenarios

3.1.1. Introduction

This chapter examines the development and application of scenarios required for assessment of climate change impacts, adaptation, and vulnerability. Scenarios are one of the main tools for assessment of future developments in complex systems that often are inherently unpredictable, are insufficiently understood, and have high scientific uncertainties. The central goals of the chapter are to set out the different approaches to scenario use, to evaluate the strengths and weaknesses of these approaches, and to highlight key issues relating to scenario application that should be considered in conducting future assessments.

Recognizing the central role of scenarios in impact and adaptation studies, scenarios are treated separately for the first time by Working Group II.[1] This chapter builds on Chapter 13 of the WGI contribution to the Third Assessment Report (TAR), which describes construction of climate scenarios, by embracing scenarios that portray future developments of any factor (climatic or otherwise) that might have a bearing on climate change vulnerability, impacts, and adaptive capacity. A distinction is drawn between climate scenarios, which describe the forcing factor of key interest in this report, and nonclimatic scenarios (e.g., of projected socioeconomic, technological, land-use, and other environmental changes), which provide the "context"—a description of a future world on which the climate operates. Many early impact assessments tended to focus on climate forcing without properly considering the context, even though this might have an important or even dominant role in determining future vulnerability to climate.

In addition to serving studies of impacts, scenarios are vital aids in evaluating options for mitigating future emissions of greenhouse gases (GHGs) and aerosols, which are known to affect global climate. For instance, projections of future socioeconomic and technological developments are as essential for obtaining scenarios of future emissions as they are for evaluating future vulnerability to climate (see TAR WGIII Chapter 2). Thus, although the focus of this chapter is on the development and use of scenarios in impact and adaptation assessment, reference to scenarios that have been developed for purposes of addressing mitigation is important and unavoidable.

There is a varied lexicon for describing future worlds under a changing climate; alternative terms often reflect differing disciplinary origins. Therefore, for the sake of consistency in this chapter, working definitions of several terms are presented in Box 3-1.

[1]Hereafter the Working Group I, II, and III contributions to the Third Assessment Report (TAR) are referred to as WGI, WGII, and WGIII, respectively.

Box 3-1. Definitions

Projection. The term "projection" is used in two senses in this chapter. 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 was attached to the term "climate projection" throughout the Second Assessment Report (SAR) to refer to model-derived estimates of future climate.

Forecast/Prediction. When a *projection* is branded "most likely," it becomes a forecast or prediction. A forecast is often obtained by using deterministic models—possibly a set of such models—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*; 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 often is adopted to reflect, as well as possible, the range of uncertainty in projections. Indeed, it has been argued that if probabilities can be assigned to such a range (while acknowledging that significant unquantifiable uncertainties outside the range remain), a new descriptor is required that is intermediate between *scenario* and *forecast* (Jones, 2000). Other terms that have been used as synonyms for scenario are "characterization" (*cf.* Section 3.8), "storyline" (*cf.* Section 3.2), 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 also might be a "future baseline," which is a projected future set of conditions, excluding the driving factor of interest. Alternative interpretations of reference conditions can give rise to multiple baselines.

3.1.2. Function of Scenarios in Impact and Adaptation Assessment

Selection and application of baseline and scenario data occupy central roles in most standard methodological frameworks for conducting climate change impact and adaptation assessment (e.g., WCC, 1993, 1994; IPCC, 1994; Smith *et al.*, 1996; Feenstra *et al.*, 1998; see Section 2.1). Many assessments treat scenarios *exogenously*, as an input, specifying key future socioeconomic and environmental baselines of importance for an exposure unit,[2] possibly with some aspects of adaptation potential also considered. Other assessments—especially those that use integrated assessment models (IAMs)—generate projections (e.g., of emissions, concentrations, climate, sea level) *endogenously* as outcomes, requiring only prior specification of the key driving variables (e.g., economic development, population). Outputs from such assessments might be applied themselves as scenarios for downstream analysis. Moreover, in IAMs, some of the original driving variables may be modified through modeled feedbacks.

Scenarios are widely used in climate change-related assessments. For some uses, scenarios are qualitative constructions that are intended to challenge people to think about a range of alternative futures that might go beyond conventional expectations or "business as usual" (BAU). Some of the socioeconomic and technological assumptions underlying GHG emissions scenarios are of this type (see TAR WGIII Chapter 2). For other uses, scenarios may be mainly quantitative, derived by running models on the basis of a range of different input assumptions. Most assessments of the impacts of future climate change are based on results from impact models that rely on quantitative climate and nonclimatic scenarios as inputs. Some scenario exercises blend the two approaches. However, not all impact assessments require a scenario component; in some cases, it may be sufficient that system sensitivities are explored without making any assumptions about the future.

3.1.3. Approaches to Scenario Development and Application

The approaches employed to construct scenarios vary according to the purpose of an assessment. For instance, scenarios may be required for:

- Illustrating climate change (e.g., by depicting the future climate expected in a given region in terms of the present-day climate currently experienced in a familiar neighboring region)
- Communicating potential consequences of climate change (e.g., by specifying a future changed climate to estimate potential future shifts in natural vegetation and identifying species at risk of local extinction)
- Strategic planning (e.g., by quantifying possible future sea-level and climate changes to design effective coastal or river flood defenses)
- Guiding emissions control policy (e.g., by specifying alternative socioeconomic and technological options for achieving some prespecified GHG concentrations)
- Methodological purposes (e.g., by describing altered conditions, using a new scenario development technique, or to evaluate the performance of impact models).

Abroad distinction can be drawn between exploratory scenarios, which project anticipated futures, and normative scenarios, which project prescribed futures. In practice, however, many scenarios embrace aspects of both approaches.

3.1.3.1. Exploratory Scenarios

Exploratory (or descriptive) scenarios describe how the future might unfold, according to known processes of change or as extrapolations of past trends. They are sometimes described as BAU scenarios; often they involve no major interventions or paridigm shifts in the organization or functioning of a system but merely respect established constraints on future development (e.g., finite resources, limits on consumption). However, the term "business-as-usual" may be misleading because exploratory scenarios also can describe futures that bifurcate at some point (an example might be uptake or rejection of a new technology) or that make some assumptions about regulation and/or adaptation of a system. The simplest model is a direct extrapolation of past trends (e.g., projection of future agricultural crop productivity often is based on extrapolation of recorded increases in productivity; Mela and Suvanto, 1987; Alexandratos, 1995). Most climate scenarios considered in this report can be regarded as exploratory: They are future climates that might occur in the absence of explicit policies of GHG reduction.

3.1.3.2. Normative Scenarios

Normative (or prescriptive) scenarios describe a prespecified future, presenting "a picture of the world achievable (or avoidable) only through certain actions. The scenario itself becomes an argument for taking those actions" (Ogilvy, 1992). Normative scenarios span a wide spectrum, according to their degree of prescriptiveness. At one end of the spectrum are scenarios that are constrained in only one or a few dimensions. For example, scenarios that lead to a substantial degree of climate change sometimes are used as a reference for assessing the "worst case" as far as impacts are concerned (e.g., scenarios that explore extreme events and tails of frequency distributions).

At the other extreme of the spectrum are comprehensive, multidimensional normative scenarios that are constructed to meet the constraints of a prescribed target world. Examples are scenarios that constrain emissions within bounds ("safe emissions corridors") that avoid inducing a critical climate change, defined according to a subjectively selected impact criterion (Alcamo and Kreileman, 1996). Most of the emissions stabilization scenarios explored by the IPCC in recent assessments (IPCC, 1996a; Schimel *et al.*, 1997a) are founded on similar premises.

3.1.4. What Changes are Being Considered?

The types of scenarios examined in this chapter are depicted schematically in Figure 3-1; they include scenarios of:

- *Socioeconomic factors* (Section 3.2), which are the major underlying anthropogenic cause of environmental

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

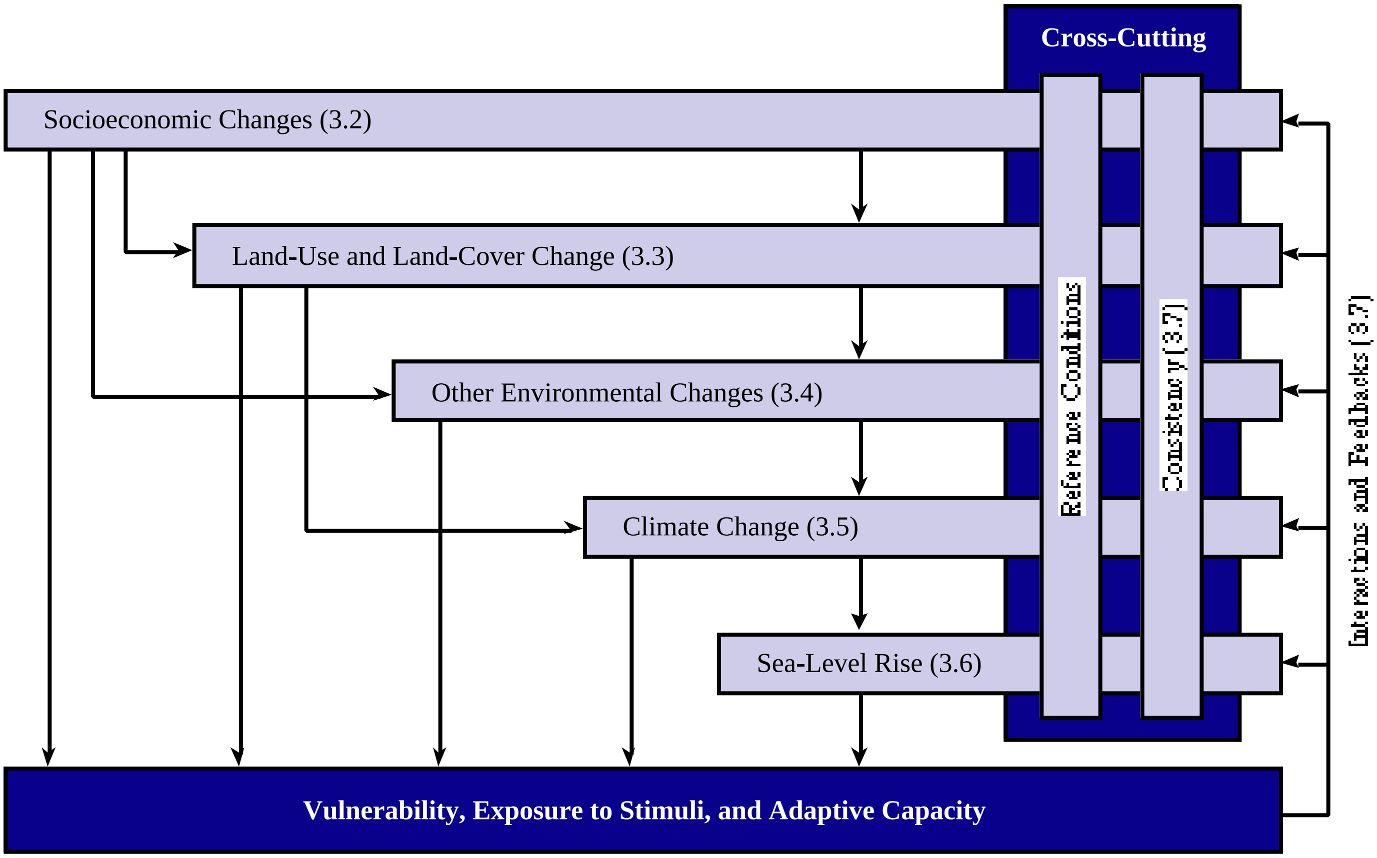

Figure 3-1: Types of scenarios required in climate impact, adaptation, and vulnerability assessment and their interactions. Numbers in parentheses refer to sections of this chapter.

change and have a direct role in conditioning the vulnerability of societies and ecosystems to climatic variations and their capacity to adapt to future changes.

- *Land use and land cover* (Section 3.3), which currently are undergoing rapid change as a result of human activities. Climate change itself may induce land-use and land-cover changes, with probable feedbacks to the climate system. Furthermore, future land cover may be influenced by efforts to sequester carbon and offset GHG emissions into the atmosphere.
- *Other environmental factors* (Section 3.4), which is a catch-all for a range of nonclimatic changes in the natural environment (e.g., CO_2 concentration, air pollution, stratospheric ozone depletion, and freshwater availability) that are projected to occur in the future and could substantially modify the vulnerability of a system or activity to impacts from climate change.
- *Climate* (Section 3.5), which is the focus of the IPCC and underpins most impact assessments reported in this volume.
- *Sea level* (Section 3.6), which generally is expected to rise relative to the land (with some regional exceptions) as a result of global warming—posing a threat to some low-lying coasts and islands.

Issues that are common to all scenarios concerning scenario consistency and the interactions and feedbacks between scenarios are treated in Section 3.7. Characterizations of future climate and related conditions during the 21st century, based on the new IPCC emissions scenarios, are introduced in Section 3.8, and the chapter closes with a brief examination of key gaps in knowledge and emerging new methods of scenario development.

3.2. Socioeconomic Scenarios

3.2.1. Purpose

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

- To characterize demographic, socioeconomic, and technological driving forces underlying anthropogenic GHG emissions that cause climate change
- To characterize the sensitivity, adaptive capacity, and vulnerability of social and economic systems in relation to climate change.

This section focuses on the second use. However, in integrated global assessments, scenarios underpinning these two applications should be consistent with one another. Many key parameters, such as population and economic growth, are common to both types of exercise. More flexibility with regard to consistency may be appropriate at local and regional scales. Regional trends may be diverse, and developments in a specific region may diverge from those at the global level.

The use of socioeconomic scenarios in assessing vulnerability to climate change is less well developed than their use in exploring GHG emissions. The IPCC *Technical Guidelines for Assessing Climate Change Impacts and Adaptations* (IPCC, 1994) recommend the use of socioeconomic scenarios, with and without climate change, to assess impacts and adaptive responses. At that time, few studies had reached that ideal. As new frameworks for characterizing vulnerability develop (Downing *et al.*, 1999), impact studies can begin to use more consistent, global scenario approaches.

Socioeconomic scenarios in impact assessment have tended to focus on quantitative characterization of key parameters and to ignore the qualitative "storyline" elements of a fully developed scenario approach. If the implications of climate change impacts and adaptation on sustainable development are to be assessed (Munasinghe, 2000), much more sophisticated descriptions of vulnerable impact units will be required, along with better understanding of institutional and economic coping capacity. Section 3.2.4 provides examples of emerging work of this kind.

Socioeconomic scenarios in general have been developed to aid decisionmaking under conditions of great complexity and uncertainty in which it is not possible to assign levels of probability to any particular state of the world at a future point in time. Therefore, it usually is not appropriate to make a statement of confidence concerning a specific socioeconomic scenario (Moss and Schneider, 2000). However, this does not mean that all scenarios are equally likely. Some, used to test sensitivities, may be at the limits of the range of plausibility. More robust statements may be possible about the level of confidence in specific quantitative indicators, such as population or GDP, associated with given scenarios.

3.2.2. Representing Baseline Conditions

The socioeconomic baseline describes the present or future state of all nonenvironmental factors that influence an exposure unit. The factors may be geographical (land use or communications), technological (pollution control, water regulation), managerial (forest rotation, fertilizer use), legislative (water-use quotas, air quality standards), economic (income levels, commodity prices), social (population, diet), or political (levels and styles of decisionmaking). The IPCC has published a set of baseline statistics for 195 countries that are representative of the early to mid-1990s (IPCC, 1998). The data were collected from a variety of sources, such as the World Bank, the United Nations Environment Programme (UNEP), and the Food and Agriculture Organization (FAO) (see Table 3-1). These are only selected, summary data; individual impact studies are likely to require information on other factors or at a much higher spatial resolution.

Climate change impact assessment requires sound understanding of current socioeconomic vulnerabilities. These vulnerabilities have implications for deliberate adaptations that "involve conscious actions to mitigate or exploit the effects of climate change" (Adger, 1999). Many of those who are exposed will be vulnerable to a range of other stresses, *irrespective* of climate change (e.g., high population growth, rapid urbanization, environmental degradation, ambient air pollution, social inequality, infrastructure degradation, and health hazards). In time, stresses associated with the development process may reinforce those generated by climate change. For instance, sea-level rise causes saltwater intrusion, which can be aggravated by diverting freshwater outflows to satisfy the needs of agriculture, energy, and human consumption.

3.2.3. Constructing Socioeconomic Scenarios

Socioeconomic scenarios can be constructed in the same variety of ways and for the same variety of purposes as global change scenarios in general. In practice, a variety of approaches may be combined in a single exercise. The UNEP country studies program has developed detailed guidance on construction and use of socioeconomic scenarios (Tol, 1998). This guidance emphasizes the importance of avoiding simple extrapolation—especially for developing countries, which may be undergoing demographic or economic transition; the role of formal modeling in filling in, but not defining, scenarios; and the role of expert judgment in blending disparate elements into coherent and plausible scenarios.

Most socioeconomic scenarios cover several different topics or domains, such as population or economic activity. Table 3-1 shows the range of issues covered in recent scenario or scenario-based exercises.

3.2.3.1. Basic Drivers

Population and economic activity are characterized in quantitative terms in most scenario exercises. The degree of disaggregation according to world region, country, or sector varies from one study to another. Coverage of other socioeconomic domains also can vary markedly among different activities.

3.2.3.2. Underlying Socioeconomic Drivers

Some scenarios incorporate explicit assumptions about underlying socioeconomic drivers of change such as social values and governance institutions. These scenarios usually are generated through synthetic or expert judgment-led approaches, expressed in qualitative terms. Social values can affect the willingness of societies to preserve ecosystems or protect biodiversity. Institutional and governance factors affect the capacity of a society to organize and direct the resources needed to reduce climate vulnerability (Adger, 1999). Qualitative factors such as institutional effectiveness and social values are key determinants of the effectiveness of coping strategies for adapting to climate change (see Chapter 18). They

Table 3-1*: Dimensions and attributes of socioeconomic scenarios reported in some recent climate change impact and adaptation assessments.*

Scenarios	**IPCC Base**[a]	**SRES**[b]	**Pakistan**[c]	**UKCIP**[d]	**ACACIA**[e]	**USNACC**[f]
Time frame/horizon	*Early 1990s*	*1990-2100*	*2020/2050*	*2020s/2050s*	*2020s/2050s/2080s*	*2050/2100*
Focus	*Impacts*	*Emissions*	*Impacts*	*Impacts*	*Impacts*	*Both*
Scenario attributes[g]						
– Economic growth	✔	✔	✔	✔	✔	✔
– Population	✔	✔	✔	✔		✔
– Land use	✔	✔	✔	✔		✔
– Energy	✔	✔	✔	✔		
– Agriculture/ food production	✔		✔	✔		
– Technological change		✔		✔	✔	✔
– Water	✔			✔		
– Level of governance		✔		✔	✔	
– Social values		✔		✔	✔	
– Contextual data						✔
– Institutional change						✔
– Biodiversity	✔			✔		
– Coastal zone management				✔		
– Settlement patterns				✔		
– Political organization					✔	
– Social policy		✔			✔	
– Environmental policy		✔			✔	
– Regional development		✔			✔	
– Literacy			✔			
– Health care			✔			

[a] IPCC Baseline Statistics (IPCC, 1998).
[b] IPCC Special Report on Emissions Scenarios (Nakicenovic *et al*., 2000).
[c] UNEPPakistan Country Study (Government of Pakistan, 1998).
[d] United Kingdom Climate Impacts Programme (Berkhout *et al*., 1999).
[e] A Concerted Action Towards A Comprehensive Climate Impacts and Adaptations Assessment for the European Union (Parry, 2000).
[f] U.S. National Assessment of the Potential Consequences of Climate Variability and Change national-scenarios; additional scenarios were developed for individual regions and sectors (<http://www.nacc.usgcrp.gov/>).
[g] Categories, some of which overlap, used by authors of the scenarios.

determine adaptive capacity and hence the vulnerability of socioeconomic systems. They are critical in any assessment of the implications of climate change for development, equity, and sustainability (Munasinghe, 2000).

3.2.3.3. Technological Change

Technology critically affects the capacity to adapt to climate change; it confers opportunities and risks. For example, genetic modification of crops and other developments in agricultural technology could enhance that sector's ability to adapt to different climatic conditions. However, excessive reliance on one particular strain of plant might increase vulnerability.

Technological change must be characterized in quantitative and qualitative terms. It may be very difficult to identify specific features of a technology that could affect vulnerability to climate change. Expert judgments are needed about the direction in which change takes place, public acceptability of different options, and the rate of adoption in the marketplace. Quantitative assumptions will be needed about the rate of improvement of a technology, including its cost, overall efficiency in using resources to meet the need for a given service, and possible impacts at various scales.

3.2.3.4. Time Horizons

The appropriate time horizon for socioeconomic scenarios depends on the use to which they are put. Climate modelers often use scenarios that look forward 100 years or more. Socioeconomic scenarios with similar time horizons may be needed to drive models of climate change, climate impacts, and land-use change. However, policymakers also may wish to use socioeconomic scenarios as decision tools in framing current policies for climate change adaptation. In this context, time horizons on the order of 20 years may be more appropriate, reflecting the immediate needs of decisionmakers.

Short-term socioeconomic scenarios can still be very uncertain. "Surprises" such as economic slumps or booms, wars, or famines frequently occur in social and economic systems. Over the course of 50–100 years, even the most basic scenario drivers, such as population and aggregate economic activity, are highly uncertain, and their future development can be projected with any credibility only by using alternative scenarios. Moreover, technologies will have been replaced at least once, and those in use 100 years hence could have unimagined effects on climate sensitivity and vulnerability. Politically led developments in local, regional, and international systems of governance also will unfold along unpredictable paths.

3.2.3.5. Spatial Resolution

Global emissions scenarios form the framework for predicting climate change and variability impacts at the national level. To assess vulnerability and adaptation potential, national scenarios must account for biophysical and socioeconomic impacts. The potential for autonomous adaptations must be understood, reflecting the ability of nature and society to cope with climate change and climate variability. Many of the impacts of climate change on the coping ability of human systems are likely to be location-specific. Impact assessors therefore should make use of local/regional scenarios, where appropriate, and be wary of generalizing experiences from one location to another. Matching of regional scenarios may be difficult, however—for example, if data on population and land use are available at different levels of resolution.

3.2.3.6. Sectoral Scenarios

As illustrated in Table 3-1, scenario exercises often make specific assumptions about individual sectors. These sectors usually are chosen because they are considered particularly sensitive to climate change (e.g., water, agriculture/food) or because they are important sources or sinks for GHGs (e.g., energy, forestry). Detailed quantitative assumptions often are made about levels of future economic activity or the price of key commodities, which will influence adaptation strategies.

Formal modeling work generally is used to improve the detail, coherence, and internal consistency of socioeconomic variables that are susceptible to quantification. Expert judgment or stakeholder consultations may be used to build consensus around the characterization of more subjective and less quantifiable variables that relate to values and institutions. Stakeholder engagement also can provide a wealth of local expertise about specific impacts and vulnerabilities.

3.2.4. Use of Socioeconomic Scenarios

This section presents a set of case studies that illustrates a range of specific approaches to the construction of socioeconomic scenarios that are relevant to climate impact assessment.

3.2.4.1. IPCC Special Report on Emissions Scenarios

The IPCC's *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al.*, 2000) was prepared to improve on the earlier set of six IS92 scenarios developed in 1992 (Leggett *et al.*, 1992). The SRES describes 40 scenarios in all—based on an extensive literature assessment, six alternative modeling approaches, and an "open process" that solicited worldwide participation and feedback. The scenarios (which are described in more detail in Section 3.8) cover the main demographic, economic, technological, and land-use driving forces of future emissions. They include emissions of all relevant GHGs plus sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane volatile organic hydrocarbons (VOCs). The IPCC specified that the scenarios should not include future policies that explicitly address climate change. However, they necessarily encompass other policies that may indirectly influence GHG sources and sinks. The scenarios suggest that assumptions about technology, rather than population and economic development, may be the most important driving force of future emissions.

The SRES emissions scenarios serve several purposes. First, they provide baselines of socioeconomic, technological, and land-use change, in combination with emissions trajectories, for the assessment of mitigation policies and measures (see TAR WGIII Chapter 2). Second, they can be used to drive the assessment of climate change (see TAR WGI and Section 3.8). Third, they provide a global socioeconomic framework for regional-scale assessment of impacts and adaptation [e.g., see the United Kingdom Climate Impacts Programme (UKCIP) and European ACACIA examples, below].

3.2.4.2. UNEP Pakistan Country Study

The Pakistan Environment Ministry has produced a suite of three socioeconomic scenarios to inform national climate impact and adaptation planning (Government of Pakistan, 1998). The scenarios focus on two reference years—2020 and 2050—and include a combination of quantitative and qualitative indicators. Quantitative scenarios are presented for population, economic growth, agricultural production, energy demand, and industrial output. Variations in future rates of literacy, health care, import tariffs, forest cover, and infrastructure are expressed in qualitative terms. The 2020 scenario is the more detailed of the two; it is a composite of existing national projections and scenarios produced for "nonclimate" policymaking. The 2020–2050 scenarios were developed for the sole purpose of informing climate impact assessments and are much less detailed (Tol, 1998).

3.2.4.3. UKCIP "Nonclimate Scenarios" for Climate Impact Assessment

A set of "nonclimate scenarios" has been developed to provide a common framework for assessing climate impacts and adaptation under the stakeholder-led UKCIP (Berkhout *et al.*, 1999). The scenarios were based on a broader "Environmental Futures" exercise (UK National Foresight Programme, 1999)—which, in turn, had drawn on emerging SRES work.

Four scenarios for the 2020s and 2050s were defined by two factors affecting the capacity and willingness of society to adapt to climate change: the extent to which social values reflect environmental concern and the effectiveness of governance institutions. Development of the scenarios involved extensive consultations with stakeholders (Lorenzoni *et al.*, 2000). As a result, detailed scenario characterization was confined to the 2020s. For each scenario, key national indicators were developed. These indicators included population and GDP, as well as more specific variables relating to land-use change, patterns of agricultural activity, water demand, and investment in coastal defense. In addition, climate vulnerability was assessed qualitatively in several "impact domains," including agriculture, water, biodiversity, coastal zone management, and infrastructure and the built environment.

The framework scenarios were found to be a useful starting point for subsequent studies. However, the scenarios needed to be articulated in more detail to be useful at the regional or sectoral level. More quantification generally was required. This exercise underlined the need for scenarios to be tailored for end users, while maintaining broad consistency about key indicators such as population and GDP.

3.2.4.4. ACACIA Scenarios for Europe

ACACIA (A Concerted Action Towards A Comprehensive Climate Impacts and Adaptations Assessment for the European Union) assessed climate impacts and potential adaptation in Europe to the 2080s (Parry, 2000). ACACIA elaborated four scenarios on the basis of a combination of the UKCIP and SRES approaches (Jordan *et al.*, 2000; see also Chapter 13). This analysis concluded that certain systems will thrive under some scenarios and will be inherently more vulnerable in others, *independent of* climate change. Adaptive strategies are likely to differ across the four scenarios. In addition, the manner in which society values different parts of the human and physical environment is markedly different under the different scenarios, with clear implications for adaptation policies.

3.2.4.5. U.S. National Assessment

The approach to socioeconomic scenarios adopted by the U.S. National Assessment of Climate Impacts was determined by the nature of the assessment process, with a national synthesis linking separate analyses in nine U.S. regions and five sectors (National Assessment Synthesis Team, 1998). Recognizing that the sensitivity of particular regions or sectors may depend on highly specific socioeconomic characteristics, the assessment adopted a two-part approach to scenario development. First, to allow national aggregation, high, medium, and low scenarios were specified for variables such as population and GDP to be used by all subnational analyses (NPA Data Services, 1999). Second, teams were asked to identify a small number of additional socioeconomic variables that would have the strongest and most direct influence on their particular region or sector. They developed and documented their own assumptions for these variables, following a consistent template developed by the National Assessment Synthesis Team (NAST) (Parson, 1999). High and low values then could be assumed for each key impact variable, without having to specify what combination of demographic, market, ecosystem, and technological factors caused it to take a particular value. Teams were advised to construct a small set of high- and low-impact scenarios on the basis of different combinations of assumptions about key impact variables. Instead of an idealized approach to scenario development, which would have attempted to specify all factors consistently across different sectors and regions, the more pragmatic and pluralistic approach adopted in the U.S. National Assessment allowed regional and sectoral specificities to be reflected.

3.3. Land-Use and Land-Cover Change Scenarios

3.3.1. Purpose

The land cover of the Earth has a central role in many important biophysical and socioeconomic processes of global environmental change. Contemporary land cover is changed mostly by human use; therefore, understanding of land-use change is essential in understanding land-cover change (Turner *et al*., 1995). Land use is defined through its purpose and is characterized by management practices such as logging, ranching, and cropping. Land cover is the actual manifestation of land use (i.e., forest, grassland, cropland) (IPCC, 2000). Land-use change and land-cover change (LUC-LCC) involve several processes that are central to the estimation of climate change and its impacts (Turner *et al.*, 1995). First, LUC-LCC influences carbon fluxes and GHG emissions (Houghton, 1995; Braswell *et al*., 1997). This directly alters atmospheric composition and radiative forcing properties. Second, LUC-LCC changes land-surface characteristics and, indirectly, climatic processes (Bonan, 1997; Claussen, 1997). Third, LUC-LCC is an important factor in determining the vulnerability of ecosystems and landscapes to environmental change (Peters and Lovejoy, 1992). LCC, for example—through nitrogen addition, drainage and irrigation, and deforestation (Skole and Tucker, 1993; Vitousek *et al.*, 1997)—may alter the properties and possible responses of ecosystems. Finally, several options and strategies for mitigating GHG emissions involve land cover and changed land-use practices (IPCC, 1996b).

The central role of LUC-LCC highlights the importance of its inclusion in scenario development for assessing global change impacts. To date this has not been done satisfactorily in most assessments (Leemans *et al.*, 1996a). For instance, in earlier emission scenarios (e.g., Leggett *et al*., 1992), constant emission factors were applied to define land use-related methane (CH_4) and nitrous oxide (N_2O) emissions. Furthermore, linear extrapolations of observed deforestation rates were assumed, along with an averaged carbon content in deforested areas. The SRES scenarios (Nakicenovic *et al.*, 2000) have improved on the underlying LUC-LCC assumptions, considerably enhancing scenario consistency. Unfortunately, these SRES scenarios provide highly aggregate regional LUC-LCC information, which is difficult to use in impact assessments. A comprehensive treatment of the other roles of LUC-LCC in the climate system is still deficient. To highlight these shortcomings, this section reviews studies and approaches in which LUC-LCC information is applied to develop scenarios for both impact and mitigation assessment.

3.3.2. Methods of Scenario Development

3.3.2.1. Baseline Data

The SAR evaluated land-use and land-cover data sets and concluded that they often were of dubious quality (Leemans *et al.*, 1996a). Since the SAR, many statistical data sources have been upgraded and their internal consistency improved (e.g., FAO, 1999), although large regional differences in quality and coverage remain. In addition, the high-resolution global database, DISCover, has become available (Loveland and Belward, 1997). This database is derived from satellite data and consists of useful land-cover classes. Furthermore, attempts also have been made to develop historical land-use and land-cover databases (Ramankutty and Foley, 1999; Klein Goldewijk, 2001). These databases use proxy sources—such as historic maps, population-density estimates, and infrastructure—to approximate land-cover patterns. All of these improvements to the information base are important for initializing and validating the models used in scenario development for global change assessments.

3.3.2.2. Regional and Sector-Specific Approaches

A large variety of LUC-LCC scenarios have been constructed. Many of them focus on local and regional issues; only a few are global in scope. Most LUC-LCC scenarios, however, are developed not to assess GHG emissions, carbon fluxes, and climate change and impacts but to evaluate the environmental consequences of different agrosystems (e.g., Koruba *et al.*, 1996), agricultural policies (e.g., Moxey *et al*., 1995), and food security (e.g., Penning de Vries *et al*., 1997) or to project future agricultural production, trade, and food availability (e.g., Alexandratos, 1995; Rosegrant *et al*., 1995). Moreover, changes in land-cover patterns are poorly defined in these studies. At best they specify aggregated amounts of arable land and pastures.

One of the more comprehensive attempts to define the consequences of agricultural policies on landscapes was the "Ground for Choices" study (Van Latesteijn, 1995). This study aimed to evaluate the consequences of increasing agricultural productivity and the Common Agricultural Policy in Europe and analyzed the possibilities for sustainable management of resources. It concluded that the total amount of agricultural land and employment would continue to decline—the direction of this trend apparently little influenced by agricultural policy. Many different possibilities for improving agricultural production were identified, leaving room for development of effective measures to preserve biodiversity, for example. This study included many of the desired physical, ecological, socioeconomic, and regional characteristics required for comprehensive LUC-LCC scenario development but did not consider environmental change.

Different LUC-LCC scenario studies apply very different methods. Most of them are based on scenarios from regression or process-based models. In the global agricultural land-use study of Alexandratos (1995), such models are combined with expert judgment, whereby regional and disciplinary experts reviewed all model-based scenarios. If these scenarios were deemed inconsistent with known trends or likely developments, they were modified until a satisfactory solution emerged for all regions. This approach led to a single consensus scenario of likely agricultural trends to 2010. Such a short time horizon is appropriate for expert panels; available evidence suggests that expert reviews of longer term scenarios tend to be conservative, underestimating emerging developments (Rabbinge and van Oijen, 1997).

3.3.2.3. Integrated Assessment Models

Most scenarios applied in climate change impact assessments fail to account satisfactorily for LUC-LCC. By incorporating land-use activities and land-cover characteristics, it becomes feasible to obtain comprehensive estimates of carbon fluxes and other GHG emissions, the role of terrestrial dynamics in the climate system, and ecosystem vulnerability and mitigation potential. Currently, the only tools for delivering this are IAMs (Weyant *et al.*, 1996; Parson and Fisher-Vanden, 1997; Rotmans and Dowlatabadi, 1998; see also Section 1.4.6), but only a few successfully incorporate LUC-LCC, including Integrated Climate Assessment Model (ICAM—Brown and Rosenberg, 1999), Asian-Pacific Integrated Model (AIM—Matsuoka *et al*., 1995), Integrated Model for the Assessment of the Greenhouse Effect (IMAGE—Alcamo *et al.*, 1998b), and Tool to Assess Regional and Global Environmental and Health Targets for Sustainability (TARGETS—Rotmans and de Vries, 1997). These models simulate interactions between global change and LUC-LCC at grid resolution (IMAGE, AIM) or by regions (ICAM, TARGETS). All of these models, however, remain too coarse for detailed regional applications.

LUC-LCC components of IAMs generally are ecosystem and crop models, which are linked to economic models that specify changes in supply and demand of different land-use products for different socioeconomic trends. The objectives of each model differ, which has led to diverse approaches, each characterizing a specific application.

ICAM, for example, uses an agricultural sector model, which integrates environmental conditions, different crops, agricultural practices, and their interactions (Brown and Rosenberg, 1999). This model is implemented for a set of typical farms. Productivity improvements and management are explicitly simulated. Productivity levels are extrapolated toward larger regions to parameterize the production functions of the economic module. The model as a whole is linked to climate change scenarios by means of a simple emissions and climate module. A major advantage of ICAM is that adaptive capacity is included explicitly. Furthermore, new crops, such as biomass energy, can be added easily. Land use-related emissions do not result from the simulations. ICAM is used most effectively to assess impacts but is less well suited for the development of comprehensive spatially explicit LUC-LCC scenarios.

IMAGE uses a generic land-evaluation approach (Leemans and van den Born, 1994), which determines the distribution and productivity of different crops on a 0.5° grid. Achievable yields are a fraction of potential yields, set through scenario-dependent regional “management” factors. Changing regional demands for land-use products are reconciled with achievable yields, inducing changes in land-cover patterns. Agricultural expansion or intensification lead to deforestation or afforestation. IMAGE simulates diverse LUC-LCC patterns, which define fluxes of GHGs and some land-climate interactions. Changing crop/vegetation distributions and productivity indicate impacts. Emerging land-use activities (Leemans *et al.*, 1996a,b) and carbon sequestration activities defined in the Kyoto Protocol, which alter land-cover patterns, are included explicitly. This makes the model very suitable for LUC-LCC scenario development but less so for impact and vulnerability assessment because IMAGE does not explicitly address adaptive capacity.

3.3.3. Types of Land-Use and Land-Cover Change Scenarios

3.3.3.1. Driving Forces of Change

In early studies, the consequences of LUC often were portrayed in terms of the CO_2 emissions from tropical deforestation. Early carbon cycle models used prescribed deforestation rates and emission factors to project future emissions. During the past decade, a more comprehensive view has emerged, embracing the diversity of driving forces and regional heterogeneity (Turner *et al.*, 1995). Currently, most driving forces of available LUC-LCC scenarios are derived from population, income, and agricultural productivity assumptions. The first two factors commonly are assumed to be exogenous variables (i.e., scenario assumptions), whereas productivity levels are determined dynamically. This simplification does not yet characterize all diverse local driving forces, but it can be an effective approximation at coarser levels (Turner *et al.*, 1995).

3.3.3.2. Processes of LUC-LCC

The central role of LUC-LCC in determining climate change and its impacts has not fully been explored in the development of scenarios. Only limited aspects are considered. Most scenarios emphasize arable agriculture and neglect pastoralism, forestry, and other land uses. Only a few IAMs have begun to include more aspects of land use. Most scenarios discriminate between urban and rural population, each characterized by its specific needs and land uses. Demand for agricultural products generally is a function of income and regional preferences. With increasing wealth, there could be a shift from grain-based diets toward more affluent meat-based diets. Such shifts strongly alter land use (Leemans, 1999). Similar functional relations are assumed to determine the demand for nonfood products. Potential productivity is determined by climatic, atmospheric CO_2, and soil conditions. Losses resulting from improper management, limited water and nutrient availability, pests and diseases, and pollutants decrease potential productivity (Penning de Vries *et al.*, 1997). Most models assume constant soil conditions. In reality, many land uses lead to land degradation that alters soil conditions, affecting yields and changing land use (Barrow, 1991). Agricultural management, including measures for yield enhancement and protection, defines actual productivity. Unfortunately, management is demonstrably difficult to represent in scenarios.

Most attempts to simulate LUC-LCC patterns combine productivity calculations and demand for land-use products. In this step, large methodological difficulties emerge. To satisfy increased demand, agricultural land uses in some regions intensify (i.e., increase productivity), whereas in others they expand in area. These processes are driven by different local, regional, and global factors. Therefore, subsequent LCC patterns and their spatial and temporal dynamics cannot be determined readily. For example, deforestation is caused by timber extraction in Asia but by conversion to pasture in Latin America. Moreover, land-cover conversions rarely are permanent. Shifting cultivation is a common practice in some regions, but in many other regions agricultural land also has been abandoned in the past (Foster *et al.*, 1998) or is abandoned regularly (Skole and Tucker, 1993). These complex LUC-LCC dynamics make the development of comprehensive scenarios a challenging task.

The outcome of LUC-LCC scenarios is land-cover change. For example, the IMAGE scenarios (Alcamo *et al.*, 1998b) illustrate some of the complexities in land-cover dynamics. Deforestation continues globally until 2050, after which the global forested area increases again in all regions except Africa and Asia. Pastures expand more rapidly than arable land, with large regional differences. One of the important assumptions in these scenarios is that biomass will become an important energy source. This requires additional cultivated land.

3.3.3.3. Adaptation

Adaptation is considered in many scenarios that are used to estimate future agricultural productivity. Several studies (Rosenberg, 1993;

Rosenzweig and Parry, 1994; Brown and Rosenberg, 1999; Mendelsohn and Neumann, 1999) assume changes in crop selection and management and conclude that climate change impacts decrease when available measures are implemented. Reilly *et al.* (1996) conclude that the agricultural sector is not very vulnerable because of its adaptive capability. However, Risbey *et al.* (1999) warn that this capability is overestimated because it assumes rapid diffusion of information and technologies.

In contrast, most impact studies on natural ecosystems draw attention to the assumed fact that LCC will increase the vulnerability of natural systems (Peters and Lovejoy, 1992; Huntley *et al.*, 1997). For example, Sala *et al.* (2000) use scenarios of LUC-LCC, climate, and other factors to assess future threats to biodiversity in different biomes. They explicitly address a biome's adaptive capacity and find that the dominant factors that determine biodiversity decline will be climate change in polar biomes and land use in tropical biomes. The biodiversity of other biomes is affected by a combination of factors, each influencing vulnerability in a different way.

3.3.4. Application and Interpretation of Scenarios and their Uncertainties

LUC-LCC scenarios are all sensitive to underlying assumptions of future changes in, for example, agricultural productivity and demand. This can lead to large differences in scenario conclusions. For example, the FAO scenario (Alexandratos, 1995) demonstrates that land as a resource is not a limiting factor, whereas the IMAGE scenarios (Alcamo *et al.*, 1996) show that in Asia and Africa, land rapidly becomes limited over the same time period. In the IMAGE scenarios, relatively rapid transitions toward more affluent diets lead to rapid expansion of (extensive) grazing systems. In contrast, the FAO study does not specify the additional requirement for pastureland. The main difference in assumptions is that animal productivity becomes increasingly dependent on cereals (FAO) compared to pastures (IMAGE). This illustrates how varying important assumptions may lead to discrepancies and inconsistencies between scenario conclusions. In interpreting LUC-LCC scenarios, their scope, underlying assumptions, and limitations should be carefully and critically evaluated before resulting land-cover patterns are declared suitable for use in other studies. Abetter perspective on how to interpret LUC-LCC both as a driving force and as a means for adaptation to climate change is strongly required. One of the central questions is, "How can we better manage land and land use to reduce vulnerability to climate change and to meet our adaptation and mitigation needs?" Answering this question requires further development of comprehensive LUC-LCC scenarios.

3.4. Environmental Scenarios

3.4.1. Purpose

Observations during the 20th century have demonstrated clearly the multifaceted nature of anthropogenic environmental changes. Therefore, it is reasonable to expect that changes in climate anticipated for the future will occur in combination with other changes in the environment. Some of these changes will occur independently of climate change (e.g., groundwater depletion, acidification); others are a cause of climate change (e.g., changing atmospheric CO_2 concentration); and still others are a direct consequence of climate change (e.g., sea-level rise). All of these could have a role in modifying the impacts of future climate change. Hence, realistic scenarios of nonclimatic environmental factors are required to facilitate analysis of these combined effects and quantify them in impact assessments.

This section introduces environmental changes that are of importance at scales from subcontinental to global and describes how scenarios commonly are constructed to represent them. Requirements for environmental scenarios are highly application- and region-specific. For example, scenarios of CO_2 concentration may be important in considering future vegetation productivity under a changing climate but are unlikely to be required for assessment of human health impacts. Most of the scenarios treated here relate to atmospheric composition: CO_2, SO_2, sulfur and nitrogen deposition, tropospheric O_3, and surface UV-B radiation. Scenarios of water resources and marine pollution also are examined. Changes in the terrestrial environment are addressed in Section 3.3, and changes in sea level are addressed in Section 3.6.

3.4.2. CO_2 Scenarios

3.4.2.1. Reference Conditions

Aside from its dominant role as a greenhouse gas, atmospheric CO_2 also has an important direct effect on many organisms, stimulating photosynthetic productivity and affecting water-use efficiency in many terrestrial plants. In 1999, the concentration of CO_2 in the surface layer of the atmosphere (denoted as $[CO_2]$) was about 367 ppm (see Table 3-2), compared with a concentration of approximately 280 ppm in preindustrial times (see TAR WGI Chapter 3). CO_2 is well mixed in the atmosphere, and, although concentrations vary somewhat by region and season (related to seasonal uptake by vegetation), projections of global mean annual concentrations usually suffice for most impact applications. Reference levels of $[CO_2]$ between 300 and 360 ppm have been widely adopted in CO_2-enrichment experiments (Cure and Acock, 1986; Poorter, 1993; see Table 3-2) and in model-based impact studies. $[CO_2]$ has increased rapidly during the 20th century, and plant growth response could be significant for responsive plants, although the evidence for this from long-term observations of plants is unclear because of the confounding effects of other factors such as nitrogen deposition and soil fertility changes (Kirschbaum *et al.*, 1996).

3.4.2.2. Development and Application of $[CO_2]$ Scenarios

Projections of $[CO_2]$ are obtained in two stages: first, the rate of emissions from different sources is evaluated; second, concentrations are evaluated from projected emissions and sequestration of carbon. Because CO_2 is a major greenhouse gas, CO_2 emissions have been projected in successive IPCC scenarios (Scenarios A–D—Shine *et al*., 1990; IS92 scenarios—Leggett *et al.*, 1992; SRES scenarios—Nakicenovic *et al.*, 2000). To obtain scenarios of future [CO_2] from those of emissions, global models of the carbon cycle are required (e.g., Schimel *et al.*, 1995). Some estimates of [CO_2] for the SRES emissions scenarios are given in Table 3-2.

In recent years, there has been growing interest in emissions scenarios that lead to [CO_2] stabilization (see Section 3.8.4). Typically, levels of [CO_2] stabilized between 350 and 1000 ppm have been examined; these levels usually are achieved during the 22nd or 23rd century, except under the most stringent emissions targets (Schimel *et al.*, 1997a). Work to develop storylines for a set of stabilization scenarios is reported in Chapter 2 of WGIII. Whatever scenarios emerge, it is likely to be some time before a set of derivative CO_2-stabilization impact and adaptation assessments are completed, although a few exploratory studies already have been conducted (UK-DETR, 1999).

Experimental CO_2-enrichment studies conventionally compare responses of an organism for a control concentration representing current [CO_2] with responses for a fixed concentration assumed for the future. In early studies this was most commonly a doubling (Cure and Acock, 1986), to coincide with equilibrium climate model experiments (see Section 3.5). However, more recent transient treatment of future changes, along with the many uncertainties surrounding estimates of future [CO_2] and future climate, present an infinite number of plausible combinations of future conditions. For example, Table 3-2 illustrates the range of [CO_2] projected for 2050 and 2100 under the SRES emissions

Table 3-2*: Some illustrative estimates of reference and future levels of atmospheric constituents that typically are applied in model-based and experimental impact studies. Global values are presented, where available. European values also are shown to illustrate regional variations at the scale of many impact studies.*

Scenario	**[CO_2][a] (ppm)**	**[SO_2][b] (μg m^{-3})**	**S-Deposition[c] (meq m^{-2} a^{-1})**	**N-Deposition[c] (meq m^{-2} a^{-1})**	**Ground-Level [O_3][d] (ppb)**
Reference/Control					
– Global/hemispheric	367	0.1–10	26	32	40
– Europe	—	5–100+	12–165 (572)	11–135 (288)	28–50 (72)
– Experiments	290–360	0–10	—	—	10–25
Future					
– Experiments	490–1350	50–1000	—	—	10–200
2010/2015					
– Global/hemispheric	388–395	—	26	36	—
– Europe	—	—	7–63 (225)	5–95 (163)	—
2050/2060					
– Global/hemispheric	463–623	—	—	—	~60
– Europe	—	—	8–80 (280)	5–83 (205)	—
2100					
– Global/hemispheric	478–1099	—	—	—	>70
– Europe	—	—	6–49 (276)	4–60 (161)	—

[a] **Carbon dioxide concentration**. *Reference*: Observed 1999 value (Chapter 3, WG I TAR). *Experiments*: Typical ranges used in enrichment experiments on agricultural crops. Some controls used ambient levels; most experiments for future conditions used levels between 600 and 1000 ppm (Strain and Cure, 1985; Wheeler *et al*., 1996). *Future*: Values for 2010, 2050, and 2100 are for the range of emissions from 35 SRES scenarios, using a simple model (data from S.C.B. Raper, Chapter 9, TAR WGI); note that these ranges differ from those presented by TAR WGI (see Footnote c of Table 3-9 for an explanation).

[b] **Sulphurdioxide concentration**. *Reference*: Global values are background levels (Rovinsky and Yegerov, 1986; Ryaboshapko *et al*., 1998); European values are annual means at sites in western Europe during the early 1980s (Saunders, 1985). *Experiments*: Typical purified or ambient (control) and elevated (future) concentrations for assessing long-term SO_2 effects on plants (Kropff, 1989).

[c] **Deposition of sulphur/nitrogen compounds**. *Reference*: Global values are mean deposition over land areas in 1992, based on the STOCHEM model (Collins *et al*., 1997; Bouwman and van Vuuren, 1999); European values are based on EMEPmodel results (EMEP, 1998) and show 5th and 95th percentiles of grid box (150 km) values for 1990 emissions, assuming 10-year average meteorology (maximum in parentheses). *Future*: Global values for 2015 are from the STOCHEM model, assuming current reduction policies; European values are based on EMEPresults for 2010, assuming a "current legislation" scenario under the Convention on Long-Range Transboundary Air Pollution (UN/ECE, 1998) and, for 2050 and 2100, assuming a modification of the preliminary SRES B1marker emissions scenario (B1-SR scenario—Mayerhofer *et al*., 2000).

[d] **Ground-level ozone concentration**. *Reference*: Global/hemispheric values are model estimates for industrialized continents of the northern hemisphere, assuming 2000 emissions (Chapter 4, TAR WGI); European values are based on EMEPmodel results (Simpson *et al*., 1997) and show 5th and 95th percentiles of mean monthly grid box (150 km) ground-level values for May-July during 1992–1996 (maximum in parentheses). *Experiments*: Typical range of purified or seasonal background values (control) and daily or subdaily concentrations (future) for assessing O_3 effects on agricultural crops (Unsworth and Hogsett, 1996; Krupa and Jäger, 1996). *Future*: Model estimates for 2060 and 2100 assuming the A1FI and A2 illustrative SRES emissions scenarios (Chapter 4, TAR WGI).

scenarios, using simple models. To cover these possibilities, although doubled [CO_2] experiments are still common, alternative concentrations also are investigated (Olesen, 1999)—often in combination with a range of climatic conditions, by using devices such as temperature gradient tunnels (Wheeler *et al.*, 1996).

3.4.3. *Scenarios of Acidifying Compounds*

3.4.3.1. Reference Conditions

Sulfur dioxide and nitrogen compounds are among the major air pollutants emitted by industrial and domestic sources. SO_2 is further oxidized to sulfate, which exists in the atmosphere mainly as aerosols. The main anthropogenic components of emissions of nitrogen compounds to the atmosphere are NO_x and ammonia (NH_3). Increased atmospheric SO_2 concentrations from anthropogenic sources are known to have negative effects on tree growth and crop yield (Kropff, 1989; Semenov *et al.*, 1998) and are described below. Concentrations of nitrogen compounds are not considered because scenarios seldom are required for impact studies. However, wet and dry deposition of sulfur and nitrogen from the atmosphere onto the Earth's surface can lead to acidification, with detrimental effects on soils, surface waters, building materials, and ecosystems (Grennfelt *et al.*, 1996). Nitrogen deposition may serve simultaneously as a plant fertilizer, positively influencing carbon gain in forests (Reich *et al.*, 1990; Woodward, 1992; Petterson *et al.*, 1993). Thus, deposition scenarios also are important.

Current global background concentrations of SO_2 are monitored at stations belonging to the Background Atmospheric Pollution Monitoring Network (BAPMoN), established by the World Meteorological Organization (WMO) and UNEP, as well as in regional networks. Annual mean SO_2 concentrations ([SO_2]) over land areas are estimated to be approximately 0.1–10 mg m^{-3} (Rovinsky and Yegorov, 1986; Ryaboshapko *et al.*, 1998). However, they can be much higher locally (Table 3-2). For example, annual average values of more than 80 mg m^{-3} were measured at some sites in Czechoslovakia in the 1970s (Materna, 1981). Model results have shown that [SO_2] averaged over the vegetative season reached 35 mg m^{-3} in some regions of Europe during 1987–1993 (Semenov *et al.*, 1998, 1999). In recent years reductions of SO_2 and NO_2 emissions have been recorded in many regions, accompanied by large-scale decreases in concentrations, especially evident in remote areas (Whelpdale and Kaiser, 1997). Typical rates of regional total (dry + wet) deposition of sulfur and nitrogen compounds, based on model simulations, are shown in Table 3-2.

Reference concentrations of SO_2 adopted in impact assessments vary according to the objective of the study. For example, in some field experiments an enhanced [SO_2] treatment is compared to a control case at ambient background concentrations. The latter concentrations can vary from year to year, depending on ambient weather and air quality conditions (Kropff, 1989). Alternatively, other experiments at locations close to pollution sources have used air purification systems to attain preindustrial levels of [SO_2] in closed chambers, comparing plant responses to those under (locally high) ambient concentrations.

3.4.3.2. Development and Application of Sulfur and Nitrogen Scenarios

Several models have been developed to project atmospheric concentrations and deposition of sulfur and (in some cases) nitrogen compounds. At the regional scale these models include: for Europe, RAINS (Alcamo *et al.*, 1990; Schöpp *et al.*, 1999) and ASAM (ApSimon *et al.*, 1994), both of which use output from mechanistic models developed by the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP); for Asia, RAINS-Asia (Foell *et al.*, 1995); and for North America and Asia, ATMOS (Arndt *et al.*, 1997). There also are global models: GRANTOUR (Penner *et al.*, 1994), MOGUNTIA (Langner and Rodhe, 1991), ECHAM (Feichter *et al.*, 1996), and STOCHEM (Collins *et al.*, 1997).

There have been few studies of the joint impacts of acidifying compounds and climate change. Some of these studies are multifactorial model simulations of plant response (e.g., Semenov *et al.*, 1998). There also have been some modeling studies based on the IS92a emissions scenario (Posch *et al.*, 1996; Fischer and Rosenzweig, 1996), under which a substantial increase in annual sulfur deposition is projected to occur by 2050, with commensurate suppression of modeled GHG warming in some regions. However, this scenario is now thought to overestimate future emissions of sulfur (Grübler, 1998), as reflected in the new SRES scenarios (see Section 3.8.1). Not all of the models used in developing the SRES scenarios provide information on nitrogen emissions, but those that do can be used to produce consistent scenarios of [NO_x], [SO_2], sulfur and nitrogen deposition, and climate change for impact studies (Mayerhofer *et al.*, 2000; Stevenson *et al.*, 2000; see Table 3-2).

3.4.4. *Scenarios of Tropospheric Ozone*

3.4.4.1. Reference Conditions

Tropospheric ozone forms part of the natural shield that protects living organisms from harmful UV-B rays. In the lowest portion of the atmosphere, however, excess accumulations of ozone can be toxic for a wide range of plant species (Fuhrer, 1996; Semenov *et al.*, 1998, 1999).Ozone is produced by a chain of chemical and photochemical reactions involving, in particular, NO, NO_2, and VOCs (Finlayson-Pitts and Pitts, 1986; Derwent *et al.*, 1991; Alexandrov *et al.*, 1992; Simpson, 1992, 1995a; Peters *et al.*, 1995). These chemical precursors of ozone can be human-derived (e.g., energy production, transport) or natural (e.g., biogenic emissions, forest fires). Surface ozone concentrations are highly variable in space and time (Table 3-2); the highest values typically are over industrial regions and large cities.

Global background concentrations of ground-level ozone (annual means) are about 20–25 ppb (Semenov *et al.*, 1999). Background concentrations have increased in Europe during the 20th century from 10–15 to 30 ppb (Grennfelt, 1996). In the northern hemisphere as a whole, trends in concentrations since 1970 show large regional differences: increases in Europe and Japan, decreases in Canada, and only small changes in the United States (Lelieveld and Thompson, 1998). In an effort to reverse the upward trends still recorded in many regions, a comprehensive protocol to abate acidification, eutrophication, and ground-level ozone was signed in 1999, setting emissions ceilings for sulfur, NO_x, NH_3, and VOCs for most of the United Nations Economic Commission for Europe (UN/ECE) region.

3.4.4.2. Development and Application of Tropospheric Ozone Scenarios

Results from the first intercomparison of model-based estimates of global tropospheric ozone concentration assuming the new SRES emissions scenarios (see Section 3.8.1) are reported in TAR WGI Chapter 4. Estimates of mean ground-level O_3 concentrations during July over the industrialized continents of the northern hemisphere under the SRES A2 and A1FI scenarios are presented in Table 3-2. These scenarios produce concentrations at the high end of the SRES range, with values in excess of 70 ppb for 2100 emissions (TAR WGI Chapter 4). Local smog events could enhance these background levels substantially, posing severe problems in achieving the accepted clean-air standard of <80 ppb in most populated areas.

Regional projections of ozone concentration also are made routinely, assuming various emissions reduction scenarios (e.g., SEPA, 1993; Simpson, 1995b; Simpson *et al.*, 1995). These projections sometimes are expressed in impact terms—for example, using AOT40 (the integrated excess of O_3 concentration above a threshold of 40 ppb during the vegetative period), based on studies of decline in tree growth and crop yield (Fuhrer, 1996; Semenov *et al.*, 1999).

There are few examples of impact studies that have evaluated the joint effects of ozone and climate change. Some experiments have reported on plant response to ozone and CO_2 concentration (Barnes *et al*., 1995; Ojanperä *et al.*, 1998), and several model-based studies have been conducted (Sirotenko *et al.*, 1995; Martin, 1997; Semenov *et al.*, 1997, 1998, 1999).

3.4.5. UV-B Radiation Scenarios

3.4.5.1. Reference Conditions

Anthropogenic emissions of chlorofluorocarbons (freons) and some other substances into the atmosphere are known to deplete the stratospheric ozone layer (Albritton and Kuijpers, 1999). This layer absorbs ultraviolet solar radiation within a wavelength range of 280–320 nm (UV-B), and its depletion leads to an increase in ground-level flux of UV-B radiation (Herman *et al.*, 1996; Jackman *et al.*, 1996; McPeters *et al.*, 1996; Madronich *et al.*, 1998; McKenzie *et al.*, 1999). Enhanced UV-B suppresses the immune system and may cause skin cancer in humans and eye damage in humans and other animal species (Diffey, 1992; de Gruijl, 1997; Longstreth *et al.*, 1998). It can affect terrestrial and marine ecosystems (IASC, 1995; Zerefos and Alkiviadis, 1997; Caldwell *et al.*, 1998; Hader *et al.*, 1998; Krupa *et al.*, 1998) and biogeochemical cycles (Zepp *et al.*, 1998) and may reduce the service life of natural and synthetic polymer materials (Andrady *et al.*, 1998). It also interacts with other atmospheric constituents, including GHGs, influencing radiative forcing of the climate (see TAR WGI Chapters 4, 6, and 7).

Analyses of ozone data and depletion processes since the early 1970s have shown that the total ozone column has declined in northern hemisphere mid-latitudes by about 6% in winter/spring and 3% in summer/autumn, and in southern hemisphere mid-latitudes by about 5% on a year-round basis. Spring depletion has been greatest in the polar regions: about 50% in the Antarctic and 15% in the Arctic (Albritton and Kuijpers, 1999). These five values are estimated to have been accompanied by increases in surface UV-B radiation of 7, 4, 6, 130, and 22%, respectively, assuming other influences such as clouds to be constant. Following a linear increase during the 1980s, the 1990s springtime ozone depletion in Antarctica has continued at about the same level each year. In contrast, a series of cold, protracted winters in the Arctic have promoted large depletions of ozone levels during the 1990s (Albritton and Kuijpers, 1999).

3.4.5.2. Development and Application of UV-B Scenarios

Scenarios of the future thickness of the ozone column under given emissions of ozone-depleting gases can be determined with atmospheric chemistry models (Alexandrov *et al.*, 1992; Brasseur *et al.*, 1998), sometimes in combination with expert judgment. Processes that affect surface UV-B flux also have been investigated via models (Alexandrov *et al.*, 1992; Matthijsen *et al*., 1998). Furthermore, several simulations have been conducted with coupled atmospheric chemistry and climate models, to investigate the relationship between GHG-induced climate change and ozone depletion for different scenarios of halogenated compounds (Austin *et al.*, 1992; Shindell *et al.*, 1998). It is known that potential stratospheric cooling resulting from climate change may increase the likelihood of formation of polar stratospheric clouds, which enhance the catalytic destruction of ozone. Conversely, ozone depletion itself contributes to cooling of the upper troposphere and lower stratosphere (see TAR WGI Chapter 7).

Serious international efforts aimed at arresting anthropogenic emissions of ozone-depleting gases already have been undertaken—namely, the Vienna Convention for the Protection of the Ozone Layer (1985) and the Montreal Protocol on Substances that Deplete the Ozone Layer (1990) and its Amendments. The abundance of ozone-depleting gases in the atmosphere peaked in the late 1990s and now is expected to decline as a result of these measures (Montzka *et al.*, 1996), recovering to pre-1980 levels around 2050 (Albritton and Kuijpers, 1999). Without these measures, ozone depletion by 2050 was projected to exceed 50% in northern mid-latitudes and 70% in southern mid-latitudes—about 10 times larger than today. UV-B radiation was projected to double and quadruple in northern and southern mid-latitudes, respectively (Albritton and Kuijpers, 1999).

There have been numerous experimental artificial exposure studies of the effects of UV-B radiation on plants (Runeckles and Krupa, 1994). There also have been a few investigations of the joint effects of enhanced UV-B and other environmental changes, including climate (Unsworth and Hogsett, 1996; Gwynne-Jones *et al.*, 1997; Sullivan, 1997). A study of the impacts of UV-B on skin cancer incidence in The Netherlands and Australia to 2050, using integrated models, is reported by Martens (1998), who employed scenarios of future ozone depletion based on the IS92a emissions scenario and two scenarios assuming compliance with the London and Copenhagen Amendments to the Montreal Protocol.

3.4.6. Water Resource Scenarios

3.4.6.1. Reference Conditions

Water is a resource of fundamental importance for basic human survival, for ecosystems, and for many key economic activities, including agriculture, power generation, and various industries. The quantity and quality of water must be considered in assessing present-day and future resources. In many parts of the world, water already is a scarce resource, and this situation seems certain to worsen as demand increases and water quality deteriorates, even in the absence of climate change. Abundance of the resource at a given location can be quantified by water availability, which is a function of local supply, inflow, consumption, and population. The quality of water resources can be described by a range of indicators, including organic/fecal pollution, nutrients, heavy metals, pesticides, suspended sediments, total dissolved salts, dissolved oxygen, and pH.

Several recent global analyses of water resources have been published (Raskin *et al.*, 1997; Gleick, 1998; Shiklomanov, 1998; Alcamo *et al.*, 2000). Some estimates are shown in Table 3-3. For regional and local impact studies, reference conditions can be more difficult to specify because of large temporal variability in the levels of lakes, rivers, and groundwater and human interventions (e.g., flow regulation and impoundment, land-use changes, water abstraction, effluent return, and river diversions; Arnell *et al.*, 1996).

Industrial wastes, urban sewage discharge, application of chemicals in agriculture, atmospheric deposition of pollutants, and salinization negatively affect the quality of surface and groundwaters. Problems are especially acute in newly industrialized countries (UNEP/GEMS, 1995). Fecal pollution of freshwater basins as a result of untreated sewage seriously threatens human health in some regions. Overall, 26% of the population (more than 1 billion people) in developing countries still do not have access to safe drinking water, and 66% do not have adequate environmental sanitation facilities—contributing

***Table 3-3**: Estimates of global and regional water intensity and water withdrawals in 1995 and scenarios for 2025.*

Aggregate World Regions	Water Intensity (m^3 cap^{-1} yr^{-1})[a]					Total Water Withdrawals (km^3)				
		2025					2025			
	1995[b]	BAU[b,c]	TEC[b,d]	VAL[b,e]	CDS[f]	**1995[b]**	BAU[b,c]	TEC[b,d]	VAL[b,e]	CDS[f]
Africa	5678	2804	2859	2974	2858	167	226	228	204	240
Asia	3884	2791	2846	3014	2778	1913	2285	2050	1499	2709
Central America	6643	4429	4507	4895	4734	126	171	140	112	145
CIS[g]	17049	16777	17124	17801	14777	274	304	226	186	480
Europe	4051	3908	3922	4119	3765	375	359	256	201	415
North America	17625	14186	14186	15533	14821	533	515	323	245	668
Oceania	64632	46455	46455	51260	42914	27	27	28	20	32
South America	30084	21146	21576	23374	21176	157	208	162	128	211
World	7305	5167	5258	5563	5150	3572	4095	3413	2595	4899

[a] Calculated by using estimates of water availability from UN Comprehensive Assessment of the Freshwater Resources of the World (Shiklomanov, 1998) and population from footnoted source.
[b] World Commission on Water for the 21st Century (Alcamo *et al*., 2000).
[c] Business-as-usual scenario (domestic water intensity increases, then stabilizes with increasing incomes, some increase in water-use efficiency).
[d] Technology, Economics, and Private Sector scenario (relative to BAU: similar population and income level; domestic water-use intensity one-third lower; higher water-use efficiency in industrialized countries).
[e] Values and Lifestyles scenario (relative to BAU: lower population and higher income; domestic water-use intensity two-thirds lower; much higher water-use efficiency in all countries).
[f] Conventional Development scenario (Raskin *et al*., 1997—population slightly higher than in BAU scenario; per capita water use falls in developed world and rises in developing world).
[g] Commonwealth of Independent States.

to almost 15,000 deaths each day from water-related diseases, nearly two-thirds of which are diarrheal (WHO, 1995; Gleick, 1998; see Chapter 9).

3.4.6.2. Development and Application of Water Resource Scenarios

Water resource scenarios have been developed at different time and space scales. For example, projections to 2025 on the basis of national water resource monitoring data have been reported by Shiklomanov (1998). Model-based projections of water use and availability to 2025 at the river basin scale have been made by Alcamo *et al.* (2000), assuming a BAU scenario and two alternative, normative scenarios that focus on water conservation. Some results of these scenario exercises are shown in Table 3-3. Among the most developed scenarios of water quality are model-based scenarios of acidification of freshwaters in Europe (e.g., NIVA, 1998). More general normative scenarios describing rural and urban access to safe drinking water by 2025 and 2050 are presented by Raskin *et al.* (1998). Scenarios of water availability have been applied in several climate change impact studies. Most of these are in the water resources sector and are reported in Chapter 4. However, they are increasingly being applied in multi-sectoral and integrated assessments (e.g., Strzepek *et al*., 1995).

3.4.7. Scenarios of Marine Pollution

3.4.7.1. Reference Conditions

Marine pollution is the major large-scale environmental factor that has influenced the state of the world oceans in recent decades. Nutrients, oxygen-demanding wastes, toxic chemicals (such as heavy metals, chlorinated hydrocarbons, potential endocrine-disrupting chemicals, and environmental estrogens), pathogens, sediments (silt), petroleum hydrocarbons, and litter are among the most important contaminants leading to degradation of marine ecosystems (Izrael and Tsyban, 1989; GESAMP, 1990; Tsyban, 1997). The following ranges of concentrations of heavy metals are characteristic of open ocean waters: mercury (0.3–7 ng l^{-1}), cadmium (10–200 ng l^{-1}), and lead (5–50 ng l^{-1}); levels of chlorinated hydrocarbons are a few ng l^{-1}. Chemical contaminants and litter are found everywhere in the open ocean, from the poles to the tropics and from beaches to abyssal depths. Nonetheless, the open ocean still remains fairly clean relative to coastal zones, where water pollution and the variability of contaminant concentrations are much higher (often by one to two orders of magnitude; specific values depend on the pattern of discharge and local conditions).

3.4.7.2. Development and Application of Marine Pollution Scenarios

Data characterizing the state of the marine environment have been obtained through national as well as international monitoring programs in recent decades, and analysis of tendencies may serve as an initial basis for developing environmental scenarios. At present, expert judgment appears to be the most promising method of scenario development because modeling methods are insufficiently developed to facilitate prediction.

In qualitative terms, trends in marine pollution during the 21st century could include enhanced eutrophication in many regions, enhancement of exotic algal blooms, expanded distribution and increased concentration of estrogens, invasion of nonindigenous organisms, microbiological contamination, accumulation of pathogens in marine ecosystems and seafood, and increases of chemical toxicants (Izrael and Tsyban, 1989; Goldberg, 1995).

3.5. Climate Scenarios

3.5.1. Purpose

The purpose of this section is to provide a summary of major methodological issues in the science of climate scenario development and to relate these developments to applications of scenarios in this report. We distinguish between a climate scenario, which refers to a plausible future climate, and a climate change scenario, which implies the *difference* between some plausible future climate and the present-day climate, though the terms are used interchangeably in the scientific literature. This brief overview is distilled largely from material presented in TAR WGI Chapter 13. See that chapter, as well as TAR WGI Chapters 8, 9, and 10, for more complete coverage of this subject.

3.5.2. Methods

Methods of climate scenario development largely have been ignored in earlier IPCC assessments, although some aspects of scenario development have been alluded to (e.g., palaeoclimatic analogs in Folland *et al.*, 1990; downscaling methods in Kattenburg *et al.*, 1996). Table 3-4 provides an overview of the main methods, which also are discussed in TAR WGI Chapter 13. Thus, we present only a very brief summary of three major methods. A fourth method, expert judgement, that also has been used in developing climate scenarios (NDU, 1978; Morgan and Keith, 1995), is discussed further in Section 3.5.5.

3.5.2.1. Incremental Scenarios for Sensitivity Studies

In this approach, particular climatic (or related) elements are changed by realistic but arbitrary amounts. They are commonly applied to study the sensitivity of an exposure unit to a wide range of variations in climate and to construct impact response surfaces over multivariate climate space. Most studies have adopted incremental scenarios of constant changes throughout the year (e.g., Terjung *et al.*, 1984; Rosenzweig *et al.*, 1996), but some have introduced seasonal and spatial variations in the changes (e.g., Rosenthal *et al.*, 1995); others have examined

***Table 3-4**: The role of various types of climate scenarios and an evaluation of their advantages and disadvantages according to the five criteria described in the text. Note that in some applications, a combination of methods may be used—for example, regional modeling and a weather generator (WGI TAR Chapter 13, Table 13.1).*

Scenario Type or Tool	Description/Use	Advantages[a]	Disadvantages[a]
Incremental	• Testing system sensitivity • Identifying key climate thresholds	• Easy to design and apply (5) • Allows impact response surfaces to be created (3)	• Potential for creating unrealistic scenarios (1,2) • Not directly related to GHG forcing (1)
Analog			
Palaeoclimatic	• Characterizing warmer periods in past	• Physically plausible changed climate that really did occur in the past of a magnitude similar to that predicted for ~2100 (2)	• Variables may be poorly resolved in space and time (3,5) • Not related to GHG forcing (1)
Instrumental	• Exploring vulnerabilities and some adaptive capacities	• Physically realistic changes (2) • Can contain a rich mixture of well-resolved, internally consistent, variables (3) • Data readily available (5)	• Not necessarily related to GHG forcing (1) • Magnitude of climate change usually quite small (1) • No appropriate analogs may be available (5)
Spatial	• Extrapolating climate/ecosystem relationships • Pedagogic	• May contain a rich mixture of well-resolved variables (3)	• Not related to GHG forcing (1,4) • Often physically implausible (2) • No appropriate analogs may be available (5)
Climate Model-Based			
Direct AOGCM outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically based models (1,2) • Long integrations (1) • Data readily available (5) • Many variables (potentially) available (3)	• Spatial information poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4,5) • Large control run biases may be a concern for use in certain regions (2)
High-resolution/ stretched grid (AGCM)	• Providing high-resolution information at global/continental scales	• Provides highly resolved information (3) • Information derived from physically based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4,5) • Problems in maintaining viable parameterizations across scales (1,2) • High resolution dependent on SSTs and sea ice margins from driving model (AOGCM) (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Regional models	• Providing high spatial/temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information derived from physically based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2,4)	• Computationally expensive, thus few multiple scenarios (4,5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)

Table 3-4 (continued)

Scenario Type or Tool	Description/Use	Advantages[a]	Disadvantages[a]
Climate Model-Based (cont.)			
Statistical downscaling	• Providing point/ high spatial resolution information	• Can generate information on high-resolution grids or nonuniform regions (3) • Potential, for some techniques, to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1,2) • Demands access to daily observational surface and/or upper air data that span range of variability (5) • Not many variables produced for some techniques (3,5) • Dependent on (usually biased) inputs from driving AOGCM (2)
Climate scenario generators	• Integrated assessments • Exploring uncertainties • Pedagogic	• May allow for sequential quantification of uncertainty (4) • Provides "integrated" scenarios (1) • Multiple scenarios easy to derive (4)	• Usually rely on linear pattern-scaling methods (1) • Poor representation of temporal variability (3) • Low spatial resolution (3)
Weather Generators	• Generating baseline climate time series • Altering higher order moments of climate • Statistical downscaling	• Generates long sequences of daily or subdaily climate (2,3) • Variables usually are internally consistent (2) • Can incorporate altered frequency/intensity of ENSO events (3)	• Poor representation of low-frequency climate variability (2,4) • Limited representation of extremes (2,3,4) • Requires access to long observational weather series (5) • In absence of conditioning, assumes constant statistical characteristics (1,2)
Expert Judgment	• Exploring probability and risk • Integrating current thinking on changes in climate	• May allow for "consensus" (4) • Has potential to integrate very broad range of relevant information (1,3,4) • Uncertainties can be readily represented (4)	• Subjectivity may introduce bias (2) • Representative survey of experts may be difficult to implement (5)

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

arbitrary changes in interannual, within-month, and diurnal variability, as well as changes in the mean (e.g., Williams *et al.*, 1988; Mearns *et al.*, 1992, 1996; Semenov and Porter, 1995). Some of these studies are discussed in Chapter 5.

3.5.2.2. Analog Approaches

Temporal and spatial analogs also have been used in constructing climate scenarios. Temporal analogs make use of climatic information from the past as an analog of possible future climate (Pittock, 1993). They are of two types: palaeoclimatic analogs and instrumentally based analogs.

Palaeoclimatic analogs: Palaeoclimatic analogs are based on reconstructions of past climate from fossil evidence, such as plant or animal remains and sedimentary deposits. Two periods have received particular attention: the mid-Holocene (~5–6 ky BP[3]), when northern hemisphere temperatures are estimated to

[3] ky BP = 1,000 years before present.

have been about 1°C warmer than today, and the Last (Eemian) Interglacial (~120–130 ky BP), when temperatures were about 2°C warmer.

The major disadvantages of this method are the causal differences between past changes in climate and posited future changes (Crowley, 1990; Mitchell, 1990) and the large uncertainties about the quality of palaeoclimatic reconstructions (Covey, 1995; Kneshgi and Lapenis, 1996; Borzenkova, 1998). However, these scenarios continue to be used occasionally in impact assessments (Anisimov and Nelson, 1996; Budyko and Menzhulin, 1996) and are useful for providing insights about system vulnerability to climate change.

Instrumentally based analogs: Periods of observed regional or global-scale warmth during the historical period also have been used as an analog of a GHG-induced warmer world. Scenarios are 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 (Lough *et al.*, 1983; Rosenberg *et al.,* 1993). Major objections to the use of these analogs include the relatively minor changes in climate involved (although small changes could be adequate for examining near-term climate change) and, again, differences between the causes of historical fluctuations and those of posited larger future climate changes (Glantz, 1988; Pittock, 1989).

Spatial analogs: These are regions that today have a climate analogous to that anticipated in the study region in future. For example, Bergthórsson *et al.* (1988) used temperatures in northern Britain as a spatial analog for the potential future temperatures over Iceland. The approach is severely restricted, however, by the frequent lack of correspondence between other important features (climatic and nonclimatic) of the two regions. Nevertheless, spatial analogs are still adopted in a few studies—for example, to assess potential effects of climate change on human health (see Chapter 9).

3.5.2.3. Use of Climate Model Outputs

The most common method of developing climate scenarios for quantitative impact assessments is to use results from GCM experiments. Most estimates of impacts described in this report rely on this type of scenario. GCMs are three-dimensional mathematical models that represent physical and dynamical processes that are responsible for climate. All models are first run for a control simulation that is representative of the present-day or preindustrial times. They have been used to conduct two types of "experiment" for estimating future climate: equilibrium and transient-response experiments. In the former, the equilibrium response (new stable state) of the global climate following an instantaneous increase (e.g., doubling) of atmospheric CO_2 concentration or its radiative equivalent, including all GHGs, is evaluated (Schlesinger and Mitchell, 1987; Mitchell *et al*., 1990). Transient experiments are conducted with coupled atmosphere-ocean models (AOGCMs), which link, dynamically, detailed models of the ocean with those of the atmosphere. AOGCMs are able to simulate time lags between a given change in atmospheric composition and the response of climate (see TAR WGI Chapter 8). Most recent evaluations of impacts, as reflected in this report, are based on scenarios formed from results of transient experiments as opposed to equilibrium experiments.

3.5.3. Baseline Climatologies

3.5.3.1. Baseline Period

Any climate scenario must adopt a reference baseline period from which to calculate changes in climate. This baseline data set serves to characterize the sensitivity of the exposure unit to present-day climate and usually serves as the base on which data sets that represent climate change are constructed. Among the possible criteria for selecting the baseline period (IPCC, 1994), it should be representative of the present-day or recent average climate in the study region and of a sufficient duration to encompass a range of climatic variations, including several significant weather anomalies (e.g., severe droughts or cool seasons).

A popular climatological baseline period is a 30-year "normal" period, as defined by the WMO. The current WMO normal period is 1961–1990, which provides a standard reference for many impact studies. Note, however, that in some regions, observations during this time period may exhibit anthropogenic climate changes relative to earlier periods.

3.5.3.2. Sources and Characteristics of Data

Sources of baseline data include a wide variety of observed data, reanalysis data (a combination of observed and model-simulated data), control runs of GCM simulations, and time series generated by stochastic weather generators. Different impact assessments require different types and resolutions of baseline climatological data. These can range from globally gridded baseline data sets at a monthly time scale to single-site data at a daily or hourly time scale. The variables most often required are temperature and precipitation, but incident solar radiation, relative humidity, windspeed, and even more exotic variables sometimes may be needed.

Two important issues in the development of baseline data sets are their spatial and temporal resolution and uncertainties related to their accuracy (New, 1999) (see TAR WGI Section 13.3.2 for further details). Evaluation of the differences between baseline data sets recently has become an important step in scenario development because these differences can have an important bearing on the results obtained in an impact assessment (Arnell, 1995; Pan *et al.*, 1996).

3.5.4. Construction of Scenarios

Techniques for constructing climate scenarios (i.e., scenario information that is directly usable in impact studies) have evolved very slowly during the past 2 decades. However, in the past few years several new developments in climate modeling and scenario development have expanded the array of techniques for scenario formation. The following subsections discuss some of these issues and present some background illustrative material.

3.5.4.1. Choosing Variables of Interest

In principle, GCM-based scenarios can be constructed for a wide range of variables at time resolutions down to subdaily time steps. In practice, however, not all data are available at the desired temporal and spatial resolutions. Most scenarios are conventionally based on changes in monthly mean climate, although with greater quantities of model output now being saved operationally, daily output and information on certain types of extreme events (e.g., mid-latitude cyclone intensities) can be accessed readily. However, consideration must be given to whether model output regarding a particular phenomenon is deemed "meaningful." For example, although information on changes in the frequency and intensity of El Niño-Southern Oscillation (ENSO) events may be desirable from an impacts point of view, analyses of possible future changes in this oscillation still are very preliminary (see TAR WGI Chapter 9).

3.5.4.2. Selecting GCM Outputs

Many equilibrium and transient climate change experiments have been performed with GCMs (Kattenberg *et al.*, 1996; TAR WGI Chapter 9). Several research centers now serve as repositories of GCM information (see, e.g., Hulme *et al.*, 1995; CSIRO, 1997). The IPCC Data Distribution Centre (IPCC-DDC, 1999) complements these existing sources. Table 3-5 lists GCM

***Table 3-5**: Catalog of GCM experiments used to develop scenarios applied by impact studies referenced in this report. Columns show the acronym of the modeling center; the common model acronym found in the impacts literature; a code for the model experiment; reference number for the experiment from Chapter 8, WGI TAR; main reference sources; type of experiment (EQ = equilibrium; TRS = transient with simple ocean; TRC = transient cold start with dynamic ocean; TRW = transient warm start with dynamic ocean); increase in CO_2-equivalent concentration; effective climate sensitivity [equilibrium warming at CO_2-doubling from AOGCM experiments (see Chapter 9, WG I TAR); in some cases this differs from climate sensitivities cited elsewhere derived from atmosphere-only GCMs]; and availability from IPCC Data Distribution Centre.*

Center	Model	Expt	WG I	Reference	Type	Forcing	ΔT_{2xCO2} (°C)	DDC
CCCma	CCC	a	—	McFarlane *et al*. (1992)	EQ	2 x CO_2	3.5	—
	CGCM1	b	6	Boer *et al*. (2000)	TRW	1% a^{-1}	3.6	✔
CCSR/NIES	CCSR-98	c	5	Emori *et al*. (1999)	TRW	1% a^{-1}	3.5	✔
CSIRO	CSIRO	d	—	Watterson *et al*. (1997)	EQ	2 x CO_2	4.3	—
	CSIRO-Mk2	e	10	Gordon and O'Farrell (1997)	TRW	1% a^{-1}	3.7	✔
DKRZ	ECHAM1	f	13	Cubasch *et al*. (1992)	TRC	IPCC90A	2.6	—
	ECHAM3	g	14	Cubasch *et al*. (1996)	TRW	IPCC90A	2.2	✔
	ECHAM4	h	15	Roeckner *et al*. (1996)	TRW	IPCC90A	2.6	✔
GFDL	GFDL	i	—	Wetherald and Manabe (1986)	EQ	2 x CO_2	4.0	—
	GFDLTR	j	—	Manabe *et al*. (1991)	TRC	1% a^{-1}	4.0	—
	GFDL-R15	k	16	Haywood *et al.* (1997)	TRW	1% a^{-1}	4.2	✔
GISS	GISS	l	—	Hansen *et al*. (1983)	EQ	2 x CO_2	4.2	—
	GISSTR	m	—	Hansen *et al*. (1988)	TRS	1.5% a^{-1}	4.2	—
NCAR	NCAR	n	—	Washington and Meehl (1984)	EQ	2 x CO_2	4.0	—
	NCAR1	o	28	Washington and Meehl (1996)	TRW	1% a^{-1}	4.6	✔
OSU	OSU	p	—	Schlesinger and Zhao (1989)	EQ	2 x CO_2	2.8	—
UKMO	UKMO	q	—	Wilson and Mitchell (1987)	EQ	2 x CO_2	5.2	—
	UKHI	r	—	Haarsma *et al*. (1993)	EQ	2 x CO_2	3.5	—
	UKTR	s	—	Murphy (1995)	TRC	1% a^{-1}	2.7	—
	HadCM2	t	22	Mitchell and Johns (1997)	TRW	1% a^{-1}	2.5	✔
	HadCM3	u	23	Gordon *et al*. (2000)	TRW	1% a^{-1}	3.0	✔

experiments that have been used to develop scenarios for impacts studies evaluated in this report.

Four criteria for selecting GCM outputs from such a large sample of experiments are suggested by Smith and Hulme (1998):

1) *Vintage*: Recent model simulations are likely (though by no means certain) to be more reliable than those of an earlier vintage since they are based on recent knowledge and incorporate more processes and feedbacks.
2) *Resolution*: In general, increased spatial resolution of models has led to better representation of climate.
3) *Validation*: Selection of GCMs that simulate the present-day climate most faithfully is preferred, on the premise that these GCMs are more likely (though not guaranteed) to yield a reliable representation of future climate.
4) *Representativeness of results*: Alternative GCMs can display large differences in estimates of regional climate change, especially for variables such as precipitation. One option is to choose models that show a range of changes in a key variable in the study region.

3.5.4.3. Constructing Change Fields

Because climate model results generally are not sufficiently accurate (in terms of absolute values) at regional scales to be used directly (Mearns *et al.*, 1997), mean differences between the control (or current climate) run and the future climate run usually are calculated and then combined with some baseline observed climate data set (IPCC, 1994). Conventionally, differences (future climate minus control) are used for temperature variables, and ratios (future climate/control) are used for other variables such as precipitation, solar radiation, relative humidity, and windspeed. Most impact applications consider one or more fixed time horizon(s) in the future (e.g., the 2020s, the 2050s, and the 2080s have been chosen as 30-year time windows for storing change fields in the IPCC-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).

3.5.4.4. Spatial Scale of Scenarios

One of the major problems in applying GCM projections to regional impact assessments is the coarse spatial scale of the gridded estimates—on the order of hundreds of kilometers—in relation to many of the exposure units being studied (often at one or two orders of magnitude finer resolution). Concern about this issue is raised in Chapters 4 and 5. Several solutions have been adopted to obtain finer resolution information.

3.5.4.4.1. Simple methods

Conventionally, regional "detail" in climate scenarios has been incorporated by appending changes in climate from the nearest coarse-scale GCM grid box to the study area (observation point or region) (e.g., Rosenzweig and Parry, 1994) or by interpolating from GCM grid box resolution to a higher resolution grid or point location (Leemans and van den Born, 1994; Harrison and Butterfield, 1996).

Three major methods have been developed to produce higher resolution climate scenarios at the sub-GCM grid scale: regional climate modeling (Giorgi and Mearns, 1991, 1999; McGregor, 1997), statistical downscaling (von Storch *et al.*, 1993; Rummukainen, 1997; Wilby and Wigley, 1997), and variable- and high-resolution GCM experiments (Fox-Rabinovitz *et al.*, 1997). All three methods are presented in Table 3-4 and discussed in detail in TAR WGI Chapter 10, but we briefly review here the first two, since they have been most commonly applied to impact assessments. Both methods are dependent on large-scale circulation variables from GCMs. Large-scale circulation refers to the general behavior of the atmosphere at large (i.e., continental) scales.

3.5.4.4.2. Regional climate modeling

The basic strategy with regional models is to rely on the GCM to reproduce the large-scale circulation of the atmosphere and to use the regional model, run at a higher resolution, to simulate sub-GCM scale regional distributions of climate. In numerous experiments with regional models driven by control and doubled CO_2 output from GCMs for regions throughout the world, the spatial pattern of changed climate—particularly changes in precipitation—simulated by the regional model departs from the more general pattern over the same region simulated by the GCM (TAR WGI Chapter 10).

3.5.4.4.3. Statistical methods

Statistical methods are much less computationally demanding than dynamic methods; they offer an opportunity to produce ensembles of high-resolution climate scenarios (for reviews, see von Storch, 1995; Wilby and Wigley, 1997). However, these techniques rely on the (questionable) assumption that observed statistical relationships will continue to be valid under future radiative forcing—that is, they are time-invariant (Wilby, 1997).

Although regional modeling and statistical techniques have been available for at least a decade—their developers claiming use in impact assessments as one of their important applications—it is only recently that they have actually provided scenarios for impact assessments (Mearns *et al.*, 1998, 1999, 2001; Sælthun *et al.*, 1998; Hay *et al.*, 1999; Brown *et al.*, 2000; Whetton *et al.*, 2001). Mearns *et al.* (1999, 2001) demonstrate that a high-resolution scenario results in agricultural impacts that differ from those produced with a coarser resolution GCM scenario (discussed in Chapter 5). Hay *et al.* (1999) found differences in runoff calculations, based on a GCM-scenario and a statistically downscaled scenario.

3.5.4.5. Temporal Resolution (Mean versus Variability)

For the most part, climate changes calculated from climate model experiments have been mean monthly changes in relevant variables. Techniques for generating changes in variability emerged in the 1990s (Mearns *et al.*, 1992, 1996, 1997; Wilks, 1992; Semenov and Barrow, 1997). The most common technique involves manipulation of the parameters of stochastic weather generators to simulate changes in variability on daily to interannual time scales (e.g., Bates *et al.*, 1994, 1996). Several studies have found important differences in the estimated impacts of climate change when effects of variance change were included (Mearns *et al.*, 1997; Semenov and Barrow, 1997). Combined changes in mean and variability also are evident in a broad suite of statistical downscaling methods (Katz and Parlange, 1996; Wilby *et al.*, 1998). Other types of variance change still are difficult to incorporate, such as possible changes in the frequency and intensity of El Niño events (Trenberth and Hoar, 1997). However, where ENSO signals are strong, weather generators can be conditioned on ENSO phases, enabling scenarios of changed ENSO frequency to be generated stochastically (e.g., Woolhiser *et al.*, 1993). However, climate models still are not capable of clearly indicating how ENSO events might change in the future (TAR WGI Chapter 9).

3.5.4.6. Incorporation of Extremes in Scenarios

Whereas changes in both the mean and higher order statistical moments (e.g., variance) of time series of climate variables affect the frequency of extremes based on these variables (e.g., extreme high daily or monthly temperatures; drought and flood episodes), other types of extremes are based on complex atmospheric phenomena (e.g., hurricanes). Given the importance of the more complex extremes—such as hurricanes, tornadoes, and storm surges (see Table 1-1)—it would be desirable to incorporate changes in the frequency of such phenomena into scenarios. Unfortunately, very little work has been performed on how to accomplish this, and there is only limited information on how the frequency, intensity, and spatial characteristics of such phenomena might change in the future (see Section 3.8.5).

An example of an attempt to incorporate such changes into impact assessments is the study of McInnes *et al.* (2000), who developed an empirical/dynamical model that gives return period versus height for tropical cyclone-related storm surges for a location on the north Australian coast. The model can accept changes in tropical cyclone characteristics that may occur as a result of climate change, such as changes in cyclone intensity. Other methods for incorporating such changes into quantitative climate scenarios remain to be developed; further advances in this area of research can be expected over the next few years.

3.5.4.7. Surprises: Low-Probability, High-Impact Events

Several types of rapid, nonlinear response of the climate system to anthropogenic forcing, sometimes referred to as "surprises," have been suggested. These include reorganization of the thermohaline circulation, rapid deglaciation, and fast changes to the carbon cycle (e.g., Stocker and Schmittner, 1997). For instance, it has been suggested that a sudden collapse of the thermohaline circulation in the North Atlantic—an event that has not been simulated by any AOGCM (TAR WGI Chapter 9) but cannot be ruled out on theoretical grounds (TAR WGI Chapter 7)—could cause major disruptions in regional climate over northwest Europe. Such a possibility has been used to create synthetic arbitrary climate scenarios to investigate possible extreme impacts (Alcamo *et al.*, 1994; Klein Tank and Können, 1997).

3.5.5. Uncertainties of Climate Scenarios

The concept of uncertainty is implicit in the philosophy of climate scenario development, and characterization and quantification of uncertainty has become one of the most vigorous and dynamic branches of climate scenario research. Some important sources of uncertainty are detailed in TAR WGI Chapter 13, of which three major sources are:

1) Uncertainties in future GHG and aerosol emissions. The IS92 and SRES emissions scenarios described in Section 3.8 exemplify these uncertainties; each scenario implies different atmospheric compositions and hence different radiative forcing.
2) Uncertainties in global climate sensitivity,[4] mainly as a result of 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 differences in regional estimates of climate change by different GCMs for the same mean global warming.

Many early impact studies employed a climate scenario derived from a single GCM. However, it was recognized early on that different GCMs yield different regional climate responses, even when they are perturbed with identical forcing (e.g., Smith and Tirpak, 1989). Therefore, various approaches have been used to capture this range of responses in impact studies. These approaches include using all available GCM results (e.g., Santer, 1985; Yohe *et al.*, 1999); using a selected subset of GCM experiments, in some cases based on the performance of the GCMs at simulating the current climate (e.g., Robock *et al.*, 1993; Risbey and Stone, 1996; Smith *et al.*, 1996); using results from different GCMs that have been "pattern-scaled" in conjunction with simple climate models to represent different types of uncertainty (e.g., Barrow *et al.*, 2000; see also Section 3.8.3); or using the mean or median GCM response (e.g., Rotmans

[4]Climate sensitivity is the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration.

et al., 1994). The effect is to generate a range of future impacts. Much of the quantitative, scenario-based, impacts literature assessed in IPCC (1990) and IPCC (1996b) reported these kinds of analyses. More recently, impact studies have begun to consider the impacts of anthropogenic climate change alongside the effects of natural multi-decadal climate variability (Hulme *et al.*, 1999a). This creates a distribution of impact indicator values for the present day to compare with the range of future impacts under alternative climate scenarios.

There have been a few preliminary attempts to derive frequency distributions of future climate by using expert judgment (Morgan and Keith, 1995; Hulme and Carter, 1999) or by projecting the statistical fit of modeled versus observed 20th-century climate onto modeled future changes (Allen *et al.*, 2000). This information may be useful for impact assessment because it offers an opportunity to express impacts in terms of risk—for example, the risk of exceeding a given threshold impact (Jones, 2000; Pittock, 1999).

3.6. Sea-Level Rise Scenarios

3.6.1. Purpose

Sea-level rise scenarios are constructed to assess climate change impacts and adaptations in the coastal zone. Variations in sea level are measured in two ways. Eustatic sea level represents the level of the ocean independent of land movements. Relative sea level is measured relative to the local land surface (Klein and Nicholls, 1998), so it consists of two components: eustatic sea-level change and local land movements. Climate modelers largely concentrate on estimating eustatic sea-level change, whereas impact researchers focus on relative sea-level change.

3.6.2. Baseline Conditions

Based on historical tide gauge records and allowing for land movements, eustatic sea level has risen at an estimated rate of 1.0–2.0 mm yr^{-1} during the past century (TAR WGI Chapter 11). This rate of sea-level rise is consistent with recent satellite altimeter data (Nerem *et al.*, 1997), which directly measures eustatic variations in sea level. Tide gauge records are the main source of information on relative sea level; records are archived by the Permanent Service for Mean Sea Level (PSMSL) (Spencer and Woodworth, 1993). These records exhibit variations in interannual and multi-decadal variability (e.g., Delcroix, 1998; Bell *et al.*, 1999; Nerem, 1999). The land surface forming the coastline at any point may be subsiding, static, or rising. Subsidence can be caused by tectonic movements, isostatic subsidence, compaction of sediments, or extraction of groundwater, oil, and/or gas. Uplift, as a result of postglacial isostatic rebound or tectonic processes, reduces or reverses relative sea-level rise. To allow for these influences, Douglas (1997) recommends that tide gauge records be at least 50 years in length before they are used to establish long-term trends or a nonstationary baseline.

Most studies of vulnerability to sea-level rise use the mean sea level at a reference date. For instance, studies employing the IPCC Common Methodology (WCC 1993, 1994) use the level in 1990 (Nicholls, 1995; Bijlsma, 1996). For more comprehensive assessments of coastal vulnerability, however, baseline time series of sea-level variability are required. These reflect tidal variations and the influences of water temperature, wind, air pressure, surface waves, and Rossby and Kelvin waves in combination with the effects of extreme weather events. Baseline information for coastal processes also may be necessary where the coastline is accreting, eroding, or changing in form as a result of previous environmental changes. Where an earlier climate or sea-level shift can be related directly to a response in coastal or adjacent marine processes, this may serve as a historical or palaeo-analog for assessment of future changes.

3.6.3. Global Average Sea-Level Rise

The major components of average global sea-level rise scenarios are thermal expansion, glaciers and small ice caps, the Greenland and Antarctic ice sheets, and surface and groundwater storage (Warrick *et al*., 1996; TAR WGI Chapter 11). These phenomena usually are modeled separately. Using GCM output, the thermal component of sea-level rise has been estimated by Bryan (1996), Sokolov *et al.* (1998), and Jackett *et al.* (2000). Contributions from glaciers and ice sheets usually are estimated via mass-balance methods that use coupled atmosphere-ocean and atmosphere-ice relationships. Such studies include: for glaciers and the Greenland ice sheet, Gregory and Oerlemans (1998); for Greenland only, Van de Wal and Oerlemans (1997) and Smith (1998); for the Antarctic ice sheet, Smith *et al.* (1998); and for Greenland and Antarctica, Ohmura *et al.* (1996) and Thompson and Pollard (1997).

Simple models that integrate these separate components through their relationship with climate, such as the upwelling diffusion-energy balance model of Wigley and Raper (1992, 1993, 1995) used in Warrick *et al.* (1996), can be used to project a range of total sea-level rise. De Wolde *et al.* (1997) used a two-dimensional model to project a smaller range than in Warrick *et al.* (1996); the major differences were related to different model assumptions. Sokolov and Stone (1998) used a two-dimensional model to achieve a larger range. Some new estimates are presented in Section 3.8.2.

3.6.4. Regional Sea-Level Rise

Regional sea-level rise scenarios require estimates of regional sea-level rise integrated with estimates of local land movements. Currently there are too few model simulations to provide a range of regional changes in sea level, restricting most scenarios to using global mean values (de Wolde, 1999). An exception is Walsh *et al.* (1998), who produced scaled scenarios of regional sea-level rise for the Gold Coast of eastern Australia on the basis of a suite of runs from a single GCM. Because relative sea-level rise scenarios are needed for coastal impact studies, local land movements also must be estimated. This requires long-term tide gauge records with associated ground- or satellite-based geodetic leveling. Geophysical models of isostatic effects, incorporating the continuing response of the Earth to ice-loading during the last glaciation, also provide estimates of long-term regional land movements (Peltier, 1998; Zwartz *et al.*, 1999).

3.6.5. Scenarios Incorporating Variability

Most impacts on the coast and near coastal marine environments will result from extreme events affecting sea level, such as storm surges and wave set-up. The magnitude of extreme events at any particular time is influenced by tidal movements, storm severity, decadal-scale variability, and regional mean sea level. These phenomena are additive. Because it is impossible to provide projections of all of these phenomena with any confidence, many assessments of coastal impacts simply add projections of global average sea level to baseline records of short-term variability (e.g., Ali, 1996; McDonald and O'Connor, 1996; McInnes and Hubbert, 1996; Lorenzo and Teixiera, 1997). Moreover, several coastal processes also are stochastic, and locally specific scenarios may have to be constructed for these (e.g., Bray and Hooke, 1997).

3.6.6. Application of Scenarios

3.6.6.1. Simple Scenarios

Simple scenarios are based on one or several estimates of sea-level rise consistent with IPCC-projected ranges of global sea-level rise for a particular date. Usually a mid-range or upper estimate is chosen. The application of a eustatic scenario, where a relative scenario is required, discounts the impact of regional sea-level change and local land movements, although it is possible to add the latter explicitly where estimates exist (Gambolati *et al*., 1999). Assessments that use simple scenarios usually test whether a coastal region is sensitive and/or vulnerable to a plausible upper limit of climate change (e.g., Zeidler, 1996; El Raey *et al.*, 1997; Olivo, 1997).

3.6.6.2. Projected Ranges

A range of global sea-level rise can be applied, bounded by its upper and lower extremes, for a particular date (e.g., Ali, 1996; Nicholls *et al.*, 1999). This will project a likely range of impacts but without any reference to the likelihood of that range or specific changes within that range (Section 2.5). The major disadvantage of this technique is the large range of uncertainty that is produced, making it difficult for policymakers and planners to decide on a concrete response.

3.6.6.3. Risk and Integrated Assessment

Risk assessment aims to produce meaningful outcomes under conditions of high uncertainty. For sea-level rise, two approaches to risk assessment have been reported. The first approach is to construct a probability distribution for a single outcome. For example, Titus and Narayanan (1996) conclude that a sea-level rise of 10–65 cm by 2100 has an 80% probability of occurring; the 99th percentile was associated with a 104-cm rise. The second approach is to calculate the probability of exceedance above a given threshold identified as a hazard. Pittock and Jones (2000) suggest the use of critical thresholds, which link an unacceptable level of harm with a key climatic or climate-related variable. For coastal impacts, the critical threshold is then linked to a projected range of sea-level scenarios, through key climatic and marine variables, and its risk of exceedance calculated (Jones *et al.*, 1999).

IAMs attempt to represent the interaction of human activities with socioeconomic and biophysical systems on a global scale (see Section 3.3.2.3). In the TARGETS model (Rotmans and de Vries, 1997), various human activities that affect a succession of phenomena are simulated to produce scenarios of sea-level rise, which then lead to calculations of people and capital at risk in low-lying coastal regions (Hoekstra, 1997). The IMAGE 2 integrated model applies baseline scenarios of global environmental change (Alcamo *et al*., 1996) to project several global outcomes, one of which is sea-level rise. Yohe and Schlesinger (1998) used a model of global economic activity to produce emissions profiles, which they then used to calculate temperature and sea-level changes and integrated with an economic damages model for the U.S. coastline. The scenarios of sea-level rise were probabilistically weighted from a sample of 280 to calculate the 10th and 90th percentiles and the median estimate, producing several ranges similar in magnitude to that of Titus and Narayanan (1996).

3.7. Representing Interactions in Scenarios and Ensuring Consistency

3.7.1. Introduction

There is great diversity in the scenarios adopted in impact assessments. This diversity is valuable in providing alternative views of the future, although it can hamper attempts to summarize and interpret likely impacts by introducing inconsistencies within or between studies. Moreover, there are certain key dependencies in climate change science that have resulted in time lags and inconsistencies in the application of scientific results between different research areas. This has been reflected in the IPCC process (see Table 3-6). Thus, although TAR WGI reviews recent projections of future climate, these results are not yet available to the impacts community to prepare and publish their analyses, on which the TAR WGII assessment is based. Instead, most impact studies have relied on earlier, more rudimentary climate projections. Similarly, the simplified assumptions used in climate model simulations about changes in radiative forcing of the climate from changing GHG and aerosol concentrations represent only a limited subset of plausible atmospheric conditions under a range of emissions scenarios reviewed by TAR WGIII.

Table 3-6*: Approximate chronology of IPCC process in relation to GCM simulations, their adoption in impact studies, and the development of IPCC emissions scenarios. Abbreviations follow: AGCM = atmospheric GCM with simple ocean; AOGCM = coupled atmosphere-ocean GCM; GHG = greenhouse gas; IS92 = IPCC emissions scenarios published in 1992 (Leggett et al., 1992); SRES = Special Report on Emissions Scenarios (Nakicenovic et al., 2000).*

Date	IPCC Process	Working Group I GCM Simulations	Working Group II GCM-Based Scenarios used in Impact Studies	Working Group III Emissions Scenarios
1988–1990	First Assessment Report (FAR), 1990	Equilibrium high-resolution AGCM	Equilibrium low–resolution 2 x CO_2	Scenarios A-D (A = Business-as-Usual)
1991–1992	FAR Supplement, 1992	Transient AOGCM cold start GHG-only (Scenario A emissions)	Equilibrium low-resolution 2 x CO_2	IS92a-f
1993–1996	Second Assessment Report (SAR), 1996	Transient AOGCM warm-start GHG + aerosol (0.5 or 1% per year emissions)	Equilibrium low/high-resolution; transient cold-start	IS92a-f (modified)
1997–1998	Regional Impacts Special Report, 1998	Transient AOGCM ensemble/ multi-century control	Equilibrium low/high-resolution; transient cold-start/warm-start	IS92a-f (modified)
1999–2001	Third Assessment Report (TAR), 2001	Transient AOGCM CO_2-stabilization; SRES-forced	Transient warm-start; multi-century control and ensembles	SRES; stabilization

Creation of comprehensive scenarios that encompass the full complexity of global change processes and their interactions (including feedbacks and synergies) represents a formidable scientific challenge. This section addresses some components of this complexity. First it treats generally accepted biogeochemical processes; second, it addresses emerging climate-system processes; and third, it reviews rarely considered interactions between anthropogenic and natural driving forces. Finally, the importance of comprehensiveness and compatibility in scenario development is discussed.

3.7.2. Representing Processes and Interactions in Scenarios

3.7.2.1. Generally Considered Interactions

Emissions of greenhouse gases have increased their atmospheric concentrations, which alter the radiative properties of the atmosphere and can change the climate (see TAR WGI Chapters 3–8). Determination of atmospheric concentrations from emissions is not straightforward; it involves the use of models that represent biogeochemical cycles and chemical processes in the atmosphere (Harvey *et al.*, 1997; TAR WGI Chapters 3–5). Several atmosphere-ocean interactions are considered in defining the future transient response of the climate system (Sarmiento *et al.*, 1998; TAR WGI Chapter 8). For the purposes of scenario development, CO_2 occupies a special role, as a greenhouse gas (IPCC, 1996a) and by directly affecting carbon fluxes through CO_2 fertilization and enhanced water-use efficiency (see Section 3.4.2). These direct responses are well known from experimentation (Kirschbaum *et al*., 1996). Biospheric carbon storage is further strongly influenced by climate, land use, and the transient response of vegetation. All of these interactions define the final CO_2 concentrations in the atmosphere and subsequent levels of climate change (see Table 3-7).

The early simple climate models that were used in the IPCC's First and Second Assessment Reports all emphasized the importance of CO_2 fertilization but few other biogeochemical interactions (Harvey *et al.*, 1997). Inclusion of more realistic responses of the carbon cycle in climate scenarios still is an evolving research area (Walker *et al*., 1999), but most interactions now are adequately represented.

3.7.2.2. Less Considered Interactions

Interactions between land, vegetation, and the atmosphere have been studied extensively in deforestation and desertification model experiments (Charney *et al.*, 1977; Bonan *et al.*, 1992; Zhang *et al.*, 1996; Hahmann and Dickinson, 1997). Changes in surface characteristics such as snow/ice and surface albedo and surface roughness length modify energy, water, and gas fluxes and affect atmospheric dynamics. These interactions occur at various scales (Hayden, 1998), but although their importance is well appreciated (Eltahir and Gong, 1996; Manzi and Planton, 1996; Lean and Rowntree, 1997; Zeng, 1998) they still generally are ignored in scenario development.

Climate modeling studies (e.g., Henderson-Sellers *et al.*, 1995; Thompson and Pollard, 1995; Sellers *et al.*, 1996) suggest an additional warming of about 0.5°C after deforestation on top of the radiative effects of GHG, but these effects are not necessarily additive on regional scales. Betts *et al.* (1997) concur that vegetation feedbacks can be significant for climate on regional scales. More recent studies, however, tend to predict smaller changes, partly as a result of the inclusion of more interactions such as the cloud radiative feedback. Field experiments show large changes in surface hydrology and micrometeorological conditions at deforested sites (Gash *et al.*, 1996). On the other hand, observations have not provided direct evidence of changes in overall climate in the Amazon basin (Chu *et al.*, 1994) or in Sahel surface albedo (Nicholson *et al.*, 1998), but the available data series are too short to be conclusive.

Palaeoclimatic reconstructions, using empirical data and model results, provide better opportunities to study vegetation-atmosphere interactions. Climate models that incorporate dynamic vegetation responses simulate larger vegetation shifts for changed past climates than expected by the orbitally forced climate effect alone. For example, an additional 200–300 km poleward displacement of forests simulated for 6,000 ky BP in North America was triggered by changes in surface albedo (Kutzbach *et al.*, 1996; Texier *et al.*, 1997; Ganopolski *et al.*, 1998). However, these shifts are not observed in all model experiments (e.g., Broström *et al*., 1998). Other modeling results suggest that oceans also play a prominent role (Hewitt and Mitchell, 1998). Thus, vegetation-ocean-climate interaction seems to be important in defining regional climate change responses.

Most vegetation models used in scenario development are equilibrium models (i.e., for a given climate they predict a fixed vegetation distribution). The latest dynamic vegetation models attempt to include plant physiology, biogeochemistry, and land surface hydrology (e.g., Goudriaan *et al.*, 1999), and some explicitly treat vegetation structure and succession. Foley *et al.* (1998) coupled one such model to a GCM and found that the most climatically sensitive zones were the desert/grassland and forest/tundra ecotones. These zones also tend to be exposed to large disturbances and natural climate variability (Schimel *et al.*, 1997b). In another model experiment, Zeng and Neelin (1999) found that interannual and inter-decadal climate variability helps to keep the African savannah region from getting either too dry or too wet, through nonlinear vegetation-atmosphere interactions. Few of these models contain simulations of disturbances, such as fire regimes (Crutzen and Goldammer, 1993; Kasischke and Stocks, 2000), which rapidly alter vegetation patterns and influence vegetation responses. Unfortunately, hardly any of these insights are included routinely in scenario development.

3.7.2.3. Rarely Considered Interactions

Most scenarios emphasize systemic interactions within nonhuman components of the climate system. These interactions are relatively well studied. The response of society to changes in the climate system is much less well studied. Land-use and land-cover change is an exception, but its treatment in climate scenarios still is far from ideal (see Section 3.3). The difficulty of including such interactions in scenario development is that many are not precisely specified and act indirectly. For example, warmer climates would change heating and cooling requirements of buildings. Such effects frequently are listed as impacts but are not factored in as adjustments to energy use and thus emission levels. Another example is population migration, which can be treated as an impact of environmental or socioeconomic change while also serving as a scenario of demographic change affecting future regional vulnerability (Döös, 1997).

A model that accounts for such societal interactions with the climate system is TARGETS (Rotmans and de Vries, 1997), which evolved from the WORLD model of Meadows *et al.*

Table 3-7*: Illustration of importance of some different feedback processes. Values are for the year 2100, obtained from a baseline scenario implemented in the IMAGE-2 integrated assessment model (adapted from Alcamo et al., 1998a). The no-feedbacks case excludes CO_2 fertilization and accelerated ice melt and includes an intermediate adaptation level of vegetation.*

Simulation	**[CO_2] (ppm)**	**Net Ecosystem Productivity (Pg a^{-1})[a]**	**Temperature Change (°C)**	**Sea-Level Rise (cm)**	**Vegetation Shift (%)[b]**
All feedbacks	737	6.5	2.8	43	41
No CO_2 fertilization	928	0.1	3.6	52	39
Vegetation adapts immediately	724	7.0	3.1	45	40
No adaptation of vegetation	762	5.3	3.2	46	41
No land-use change	690	6.9	2.9	41	39
No feedbacks	937	0.0	3.5	29	45
No land-use change/no feedbacks	889	0.2	3.4	28	45
Range	690–937	0.0–7.0	2.8–3.6	28–52	39–45

[a] 1 Pg a^{-1} = 10^{15} grams per year.
[b] Percentage of vegetated area for which climate change induces a change of vegetation class.

(1992). TARGETS is a highly aggregated model (only two regions and few resource classes) with simple relationships between population, economic development, and resource use; between environmental conditions and population/health/wealth; and between emissions, concentrations, climate, and impacts. The model generates globally averaged emissions and climate change scenarios. The strength of the model is that different interactions—including controversial ones, such as the effects of climate change on food availability and health and their interactions with population—can be explored easily, but its use for developing scenarios for impact assessment is limited.

3.7.3. Tools Capable of Addressing Interactions

Most climate scenarios for impact assessments were developed by using outputs from AOGCMs (Hulme and Brown, 1998). Often these results are scaled toward the desired emission levels with simple climate models (Hulme *et al.*, 1995; Harvey *et al.*, 1997; see Section 3.8.3). In this simple approach, most interactions are neglected.

The only models that can be used to develop more consistent scenarios that incorporate most of the important interactions are IAMs (see Section 3.3.2.3). IAMs have been developed with different levels of complexity, from extremely simple to highly complex (Harvey *et al.*, 1997). Different interactions are included, although no single model provides a fully comprehensive treatment. The models are most commonly used for emission scenario development and mitigation policy assessment (Schimel *et al.*, 1997a; Alcamo *et al.*, 1998a; Pepper *et al.*, 1998). All simulate a causal chain (e.g., human activities, emissions, climate change, sea-level rise, and other impacts). Emissions, climate change, impact, and mitigation scenarios derived from these models have been published (Schimel *et al.*, 1997a; Leemans *et al.*, 1998; Pepper *et al.*, 1998) and collected in several databases (Alcamo *et al.*, 1995; Nakicenovic *et al.*, 2000). Unfortunately, it is not always clear which interactions are explicitly included in individual IAMs. This reduces the comparability of individual IAM-derived scenarios and thus their utility.

Depending on assumed interactions during scenario development, a wide range of estimates of climate change and its impacts is possible (see Table 3-7). However, within this range certain responses are more likely than others. To define appropriate and realistic levels of interactions, expert judgment and sensitivity experiments with models could be very valuable (van der Sluijs, 1997). Innovative, objective, and systematic approaches have to be developed to evaluate underlying scenario assumptions and to validate the scenario results. This is still an immature area of scenario development.

3.7.4. Problems of Compatibility between Scenarios

One difficulty faced by authors in attempting to summarize and synthesize the results of impact studies for previous IPCC assessments (i.e., IPCC, 1996b, 1998) has been a 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 are assumed, they might not be applied in the same way in different impact studies. Finally, some studies also are inconsistent in their methods of projecting changes in climate alongside concurrent changes in related socioeconomic and environmental conditions.

For example, GHG concentrations often are transformed into CO_2-equivalent concentrations to determine radiative forcing levels and climate change. The GCM community often presents climate change simulations as “doubled CO_2” anomalies.

Box 3-2. The Global Impact of Climate Change on Five Sectors (Parry and Livermore, 1999)

In this assessment, the prospective effects of unmitigated climate change during the 21st century are estimated at a global scale in five sectoral studies (see Table 3-8). Each study has different scenario requirements, though some are common to several studies. For example, the ecosystems study estimates potential biomass on the basis of scenarios of climate, CO_2 concentration, and nitrogen deposition, but it ignores future land-cover and land-use changes that would be expected regardless of climate change. In contrast, the study on food security examines the effects on crop productivity of the same scenarios of climate (though for fewer variables) and CO_2 concentration; it too ignores likely land-cover and land-use changes and does not consider effects of nitrogen deposition, although it adopts a range of socioeconomic and technological scenarios to evaluate the number of persons at risk from hunger.

Notably, across all of the studies the scenarios adopted are designed to be mutually consistent. For instance, the population and GDP scenarios are those adopted in constructing the IS92a emissions scenario (Leggett *et al.*, 1992). An approximation of the IS92a emissions scenario is used to force the HadCM2 and HadCM3 GCMs that were employed to construct the climate and sea-level scenarios (Hulme *et al.*, 1999b). Other scenarios are chosen to be broadly consistent with these assumptions. The scenarios are required as inputs to global impact models, and results from these are described elsewhere in this report. Finally, it also should be noted that although 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.

Depending on the scenario, however, 5–40% of the forcing is caused by non-CO_2 GHGs (30% in 1990). The doubled-CO_2 scenarios often are interpreted as CO_2 only (e.g., Cramer *et al.*, 1997); others add an explicit distinction between CO_2 and non-CO_2 gases (e.g., Downing *et al.*, 1999). In determining the impacts of direct CO_2 effects and climate change, this can easily lead to inconsistencies. Similar discrepancies exist for other types of interactions.

Finally, it is a significant challenge to integrate climate or sea-level rise scenarios, with a time horizon of decades to hundreds of years, with nonclimatic scenarios of social, economic, and technological systems that can change rapidly over a time scale of years. For instance, it is difficult to devise credible socioeconomic scenarios that extend beyond the lifetime of current infrastructure and institutions. Moreover, social/economic actors who need to be involved in the scenario development process (e.g., business, governments) often find long time horizons difficult to contemplate. Box 3-2 illustrates a recent example of an attempt to harmonize climate change, sea level, atmospheric composition, and socioeconomic scenarios in a multi-sectoral global impact assessment.

3.8. Scenarios of the 21st Century

This section summarizes recent developments that are likely to affect the construction of scenarios over the coming few years. One of these developments is construction of the new SRES emission scenarios. Some features of these scenarios and their implications for atmospheric composition, global climate, and sea level are described below. In addition, a brief review of possible regional climate changes during the 21st century is presented, followed by discussions of stabilization scenarios and changes in climate variability and extreme events—key issues in constructing scenarios for policy-relevant impact and adaptation assessments.

3.8.1. SRES Storylines and Emissions Scenarios

Development of the SRES scenarios (Nakicenovic *et al.*, 2000) is outlined in Section 3.2.4.1. The 40 scenarios, 35 of which are fully quantified, are based on four different narrative storylines and associated scenario families. Each storyline describes a different world evolving through the 21st century, and each

***Table 3-8**: Summary of scenarios adopted in an assessment of global impacts on five sectors (Parry and Livermore, 1999).*

Scenario Type (up to 2100)	Ecosystems[a]	Water Resources[b]	Food Security[c]	Coastal Flooding[d]	Malaria Risk[e]
Socioeconomic/technological					
– Population	—	✔	✔	✔	✔
– GDP	—	—	✔	✔	—
– GDP per capita	—	—	✔	✔	—
– Water use	—	✔	—	—	—
– Trade liberalization	—	—	✔	—	—
– 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) and see Chapter 5.
[b] Arnell (1999) and see Chapters 4 and 19.
[c] Parry *et al*. (1999) and see Chapters 5 and 19.
[d] Nicholls *et al*. (1999) and see Chapters 6, 7, and 19.
[e] Martens *et al*. (1999) and see Chapters 8 and 18.

may lead to quite different GHG emissions trajectories. Four of the scenarios are designated as "markers," each characterizing one of four "scenario families"; two additional scenarios illustrate alternative energy developments in one of the families. The storylines and scenario families are as follows:

- *A1:* A future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity-building, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system: fossil-intensive (A1FI), nonfossil energy sources (A1T), and a balance across all sources (A1B).
- *A2:* A differentiated world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in continuously increasing population. Economic development is primarily regionally orientated, and per capita economic growth and technological change are more fragmented and slower than other storylines.
- *B1:* A convergent world with rapid change in economic structures toward a service and information economy, reductions in material intensity, and introduction of clean technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improving equity, but without additional climate change policies.
- *B2:* Aworld in which the emphasis is on local solutions to economic, social, and environmental sustainability. This is a world with continuously increasing global population at a lower rate than in scenario A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. Although this scenario also is orientated toward environmental protection and social equity, it focuses on the local and regional levels.

Measures of global population, economic development (expressed in annual GDP), and equity (per capita income ratio) for 2050 and 2100 that are implied under the SRES scenarios are shown in Table 3-9, alongside the IS92a scenario and estimates for the present day. Attempts are underway to "downscale" aspects of these global scenarios for use in regional impact assessment (e.g., Lorenzoni *et al.*, 2000).

3.8.2. Implications of SRES Scenarios for Atmospheric Composition and Global Climate

Estimates of atmospheric composition resulting from the SRES emissions scenarios are presented in TAR WGI Chapters 3–5. Information on CO_2 and ground-level O_3 concentrations is given in Tables 3-2 and 3-9. More detailed regional estimates of pollutant concentrations and deposition of acidifying compounds based on these scenarios also are beginning to emerge (e.g., Mayerhofer *et al.*, 2000; see Section 3.4).

To interpret the possible range of global temperature and sea-level response to the SRES scenarios, estimates have been made with simple models for all 35 of the quantified SRES scenarios (Table 3-9; see also TAR WGI Chapters 9 and 11). Estimates of global warming from 1990 to 2100 give a range of 1.4–5.8°C—somewhat higher than the 0.7–3.5°C of the SAR. The main reason for this increase is that the levels of radiative forcing in the SRES scenarios are higher than in the IS92a-f scenarios, primarily because of lower sulfate aerosol emissions, especially after 2050. The temperature response also is calculated differently; rather than using the conventional idealized, equilibrium climate sensitivity range of 1.5–4.5°C (IPCC, 1996a), the simple model is tuned to the effective climate sensitivities of a sample of individual AOGCMs (see TAR WGI Chapter 9 for details). Sea-level rise between 1990 and 2100 is estimated to be 9–88 cm, which also accounts for uncertainties in ice-melt parameters (see TAR WGI Chapter 11).

3.8.3. Implications of SRES Scenarios for Regional Mean Climate

3.8.3.1. Regional Information from AOGCMs

Estimates of regional climate change to 2100 based on AOGCM experiments are described in TAR WGI Chapters 9 and 10. The results of nine AOGCMs run with the A2 and B2 SRES scenarios[5] display many similarities with previous runs that assume IS92a-type emissions, although there also are some regional differences (see below). Overall, rates of warming are expected to be greater than the global average over most land areas and most pronounced at high latitudes in winter. As warming proceeds, northern hemisphere snow cover and sea-ice extent will be reduced. Models indicate warming below the global average in the North Atlantic and circumpolar southern ocean regions, as well as in southern and southeast Asia and southern South America in June–August. Globally there will be increases in average water vapor and precipitation. Regionally, December–February precipitation is expected to increase over the northern extratropics and Antarctica and over tropical Africa. Models also agree on a decrease in precipitation over Central America and little change in southeast Asia. Precipitation in June–August is projected to increase in high northern latitudes, Antarctica, and south Asia; change little in southeast Asia; and decrease in Central America, Australia, southern Africa, and the Mediterranean region.

The main differences between the SRES-based and IS92-based runs concern greater disagreement in the SRES runs on the magnitude of warming in some tropical and southern hemisphere regions and differing intermodel agreement on the

[5] Preliminary marker emissions scenarios released in 1998 for use in climate modeling (Nakicenovic *et al.*, 2000).

magnitude of precipitation change in a few regions, possibly as a result of aerosol effects. However, there are no cases in which the SRES and IS92a results indicate precipitation changes of opposite direction (see TAR WGI Chapter 10).

3.8.3.2. Regional Climate Characterizations

Only a limited number of AOGCM results based on the SRES emissions scenarios have been released and analyzed to date (i.e., results for the A2 and B2 scenarios), and none were available for the impact studies assessed in this report. In the meantime, alternative approaches have been used to gain an impression of possible regional changes in climate across a wider range of emissions scenarios. One method uses results from existing AOGCM simulations and scales the pattern of modeled regional climate change up or down according to the range of global temperature changes estimated by simple climate models for different emissions scenarios or assumptions about climate sensitivity (Santer *et al.*, 1990; Mitchell *et al.*, 1999;

Table 3-9*: Some aspects of the SRES emissions scenarios and their implications for 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 Nakicenovic et al. (2000). Calculations in columns 6–7 are relative to 1990. ΔT is change in mean annual temperature averaged across simple climate model runs emulating results of seven AOGCMs with average climate sensitivity of 2.8°C (Chapter 9, TAR WGI). CO_2 concentrations were estimated by using the same model runs (data from S.C.B. Raper, Chapter 9, TAR WGI). Sea-level rise estimates are based on temperature changes (Chapter 11, TAR WGI). SRES-min and SRES-max are minimum and maximum estimates across all 40 SRES scenarios (35 fully quantified scenarios for CO_2, ΔT, 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). 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.*

Emissions Scenario	Global Population (billions)	Global GDP[a] (10^{12} US\$ a^{-1})	Per Capita Income Ratio[b]	CO_2 Concentration[c] (ppm)	Global ΔT (°C)	Global Sea-Level Rise (cm)
1990	5.3	21	16.1	354	0	0
2000	6.1–6.2	25–28[d]	12.3–14.2[d]	367[e]	0.2	2
2050						
– SRESA1FI	8.7	164	2.8	573	1.9	17
– SRESA1B	8.7	181	2.8	536	1.6	17
– SRESA1T	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-min	8.4	59	2.4	463	0.8	5
– SRES-max	11.3	187	8.2	623	2.6	32
2100						
– SRESA1FI	7.1	525	1.5	976	4.5	49
– SRESA1B	7.1	529	1.6	711	2.9	39
– SRESA1T	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	9
– SRES-max	15.1	550	6.3	1099	5.8	88

[a] Gross domestic product (1990 US\$ trillion yr^{-1}).
[b] Ratio of developed countries and economies in transition (Annex I) to developing countries (Non-Annex I).
[c] Modeled values are not the same as those presented by TAR WGI, Appendix II, which are based on simulations using two different carbon cycle models for the six illustrative SRES emissions scenarios. Both models produce very similar results to the model applied here for a mid-range climate sensitivity; discrepancies in the high and low estimates are attributable to differences in the modeled climate-carbon cycle feedback.
[d] Modeled range across the six illustrative SRES scenarios.
[e] Observed 1999 value (Chapter 3, WG I TAR).

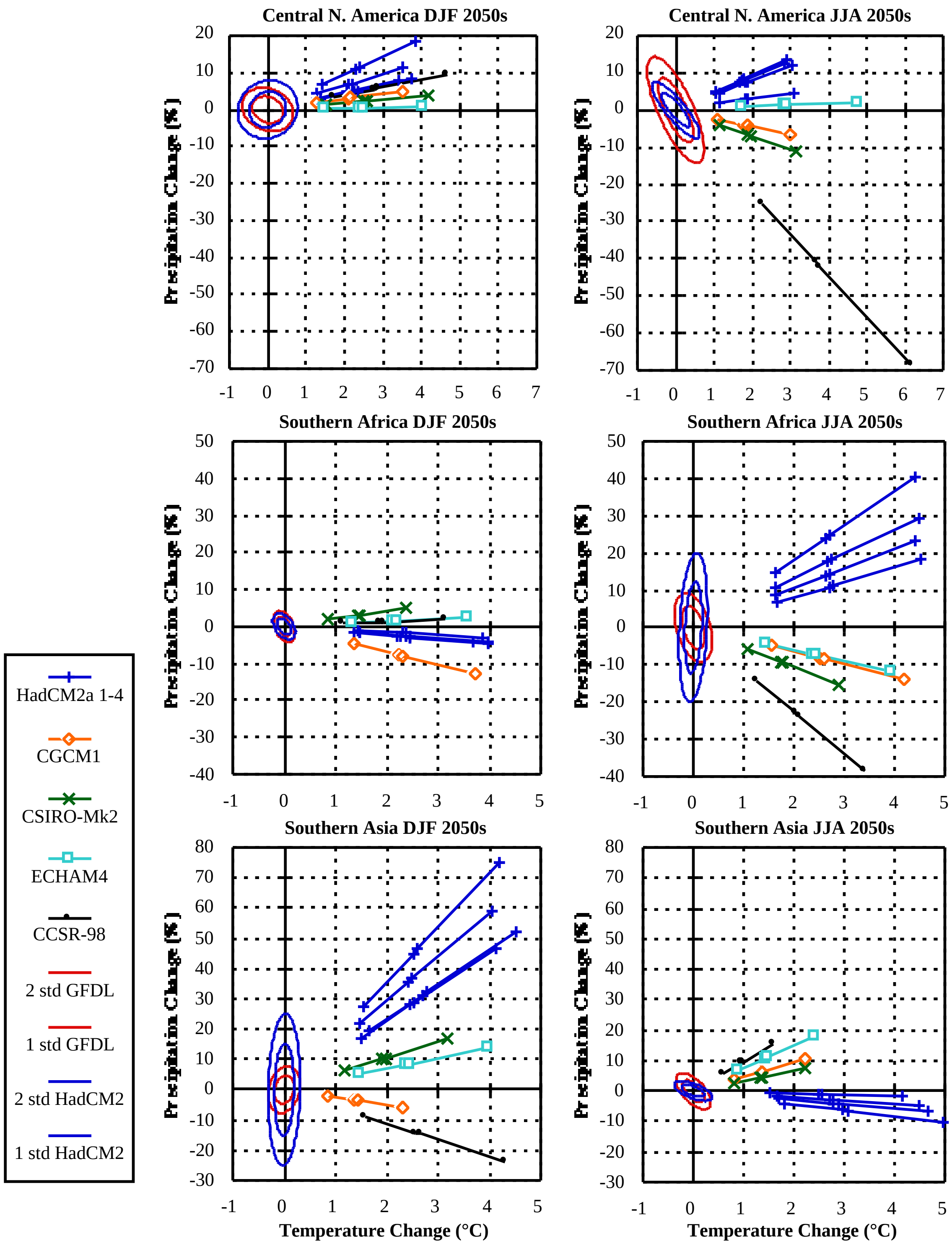

Figure 3-2: Scaled outputs of mean December-February (left) and June-August (right) temperature and precipitation change by the 2050s relative to 1961–1990 over land grid boxes representing Central North America (top), Southern Africa (middle), and Southern Asia (bottom) from eight simulations with five AOGCMs (experiments b, c, e, h, and a four-member ensemble from t; see Table 3-5). Simulations assume forcing by greenhouse gases but not aerosols, and are standardized according to the climate sensitivity of each AOGCM. Lines connect four points for each simulation, all in the same order from the origin: B1-low, B2-mid, A1-mid, A2-high. Each point represents the standardized regional changes in climate from the AOGCM, linearly scaled according to the global warming estimated with a simple climate model for one of four preliminary SRES marker emissions scenarios (B1, B2, A1, and A2) and a value of the climate sensitivity (low = 1.5°C; mid = 2.5°C, and high = 4.5°C). Also plotted are ±1 and ±2 standard deviation ellipses from the 1400-year HadCM2 and 1000-year GFDL unforced simulations, which are used to indicate natural multi-decadal variability and are orientated according to the correlation between modeled 30-year mean temperature and precipitation. Results from two other AOGCMs did not extend to the 2050s (Carter *et al*., 2000).

see also detailed discussion in TAR WGI Chapter 13). This "pattern-scaling" method has been employed by Carter *et al.* (2000), using results from simulations with seven AOGCMs, all assuming a radiative forcing approximating the IS92a emissions scenario (for GHGs but excluding aerosols) scaled across a range of global temperature changes estimated by using a simple climate model for the four preliminary marker SRES emissions scenarios.

Regional-scale summary graphs of scaled temperature and precipitation changes were constructed for 32 world regions, at subcontinental scale, chosen to represent the regions being assessed by Working Group II (Carter *et al.*, 2000). Examples of individual plots are shown in Figure 3-2. Changes are plotted alongside estimates of "natural" multi-decadal variability of temperature and precipitation, extracted from two multi-century unforced AOGCM simulations. The graphs thus provide a quick assessment of the likely uncertainty range *and* significance of each AOGCM projection; they also show the extent to which different AOGCMs agree or disagree with regard to regional response to a given magnitude of global warming. Although a preliminary comparison of these results with SRES AOGCM runs (which also include aerosol forcing) suggests broad agreement on regional temperature and precipitation changes, more rigorous comparison remains to be carried out, offering a useful test of the pattern-scaling method.

3.8.4. Stabilization Scenarios

The SRES scenarios assume no climate policy intervention, but nations already are engaged in negotiations to reduce emissions of GHGs. Targets for stabilization of GHG concentrations in the atmosphere are being investigated by scientists and policymakers. TAR WGIII Chapter 2 reviews more than 120 mitigation scenarios, most of which aim to stabilize emissions of CO_2 at some target level. Simple climate models, as well as some AOGCMs, have been used to estimate the climate and sea-level response to stabilization (see Harvey *et al.*, 1997; TAR WGI Chapters 9 and 11). Relative to most reference emissions scenarios (e.g., the SRES scenarios), stabilization scenarios reduce global warming, especially beyond 2100. However, even for the lowest stabilization targets considered (450 ppm), based on long simulations by AOGCMs, the climate system and oceans may continue to respond for many centuries after stabilization of atmospheric concentrations of GHGs. Furthermore, because of regional variations in the time lag of response, regional patterns of climate change might be quite different from the unmitigated case (Whetton *et al.*, 1998).

3.8.5. Scenarios of Changes in Climate Variability and Extreme Events

It is demonstrated throughout this report that changes in climatic variability and extremes often play a dominant role in climate change impacts. Moreover, the magnitude and frequency of extreme events can change rapidly with only relatively small changes in climatic averages (see Section 3.5.4.6). However, climate modelers have more confidence in estimates of changes in averages than in changes in variability and extremes (see TAR WGI Chapters 8–10 and 13). Thus, impact assessors need to look carefully at the extent to which changes in variability and extremes are covered implicitly by changes in averages; when this is not the case, they must incorporate possible changes in these phenomena into scenarios. Table 3-10 summarizes projected changes in several types of extreme climate events and their likelihood taken from TAR WGI Technical Summary (see Table 1-1 for a typology of extremes). Table 3-10 also provides representative examples, drawn from different sectors and regions, of impacts that would be expected with high confidence, conditional on the occurrence of a given change in climate extremes. All of this information is reported in other chapters in this report.

3.9. State of the Science and Future Needs for Scenario Development

This chapter outlines the current practice of scenario development for climate impact, vulnerability, and adaptation assessment. Methods of scenario construction and application are evolving rapidly, so it is useful to identify which aspects are well developed and which aspects still are deficient.

3.9.1. Well-Developed Features

Some features of scenario development and application are well established and tested:

- Extensive monitoring efforts and continued development of global and regional databases has improved the quality and consistency of baseline observational data required for some scenario exercises, even in some data-sparse regions.
- Many impact studies apply incremental scenarios to explore the sensitivity of an exposure unit to a range of climate futures; studies seldom rely exclusively on a single, model-based scenario.
- Estimates of long-term mean global changes are available and widely applied for a limited number of variables (e.g., population, economic development, CO_2 concentration, global mean temperature), based on projections produced by specialized international organizations or the use of simple models.
- A growing volume of information now is available to enable scientists to construct regional scenarios of many features of global change, even though uncertainties in most projections remain high. A notable example is the IPCC-DDC, which was established in 1998 to facilitate the timely distribution of a consistent set of up-to-date projections of changes in climate and related environmental and socioeconomic factors for use in climate impact and adaptation assessment. Some of the studies reported in this volume use scenarios derived from information held in the DDC (see, e.g., Table 3-5).

***Table 3-10**: Examples of impacts resulting from projected changes in extreme climate events.*

Projected Changes during the 21st Century in Extreme Climate Phenomena and their Likelihood[a]	**Representative Examples of Projected Impacts[b]** *(all high confidence of occurrence in some areas[c])*
Simple Extremes	
Higher maximum temperatures; more hot days and heat waves[d] over nearly all land areas (*Very Likely*[a])	• Increased incidence of death and serious illness in older age groups and urban poor • Increased heat stress in livestock and wildlife • Shift in tourist destinations • Increased risk of damage to a number of crops • Increased electric cooling demand and reduced energy supply reliability
Higher (increasing) minimum temperatures; fewer cold days, frost days, and cold waves[d] over nearly all land areas (*Very Likely*[a])	• Decreased cold-related human morbidity and mortality • Decreased risk of damage to a number of crops, and increased risk to others • Extended range and activity of some pest and disease vectors • Reduced heating energy demand
More intense precipitation events (*Very Likely*[a] over many areas)	• Increased flood, landslide, avalanche, and mudslide damage • Increased soil erosion • Increased flood runoff could increase recharge of some floodplain aquifers • Increased pressure on government and private flood insurance systems and disaster relief
Complex Extremes	
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (*Likely*[a])	• Decreased crop yields • Increased damage to building foundations caused by ground shrinkage • Decreased water resource quantity and quality • Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (*Likely*[a] over some areas)[e]	• Increased risks to human life, risk of infectious disease epidemics, and many other risks • Increased coastal erosion and damage to coastal buildings and infrastructure • Increased damage to coastal ecosystems such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions (*Likely*[a]) (see also under droughts and intense precipitation events)	• Decreased agricultural and rangeland productivity in drought- and flood-prone regions • Decreased hydro-power potential in drought-prone regions
Increased Asian summer monsoon precipitation variability (*Likely*[a])	• Increase in flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms (little agreement between current models)[d]	• Increased risks to human life and health • Increased property and infrastructure losses • Increased damage to coastal ecosystems

[a] Likelihood refers to judgmental estimates of confidence used by TAR WGI: *very likely* (90-99% chance); *likely* (66-90% chance). Unless otherwise stated, information on climate phenomena is taken from the Summary for Policymakers, TAR WGI.
[b] These impacts can be lessened by appropriate response measures.
[c] Based on information from chapters in this report; high confidence refers to probabilities between 67 and 95% as described in Footnote 6 of TAR WGII, Summary for Policymakers.
[d] Information from TAR WGI, Technical Summary, Section F.5.
[e] Changes in regional distribution of tropical cyclones are possible but have not been established.

3.9.2. Deficiencies in Knowledge and Future Needs

There are many shortcomings of current scenario development, but there also are promising new methods that may address these problems and require further attention. These include:

- Future socioeconomic, environmental, and land-use changes have not been represented satisfactorily in many recent impact studies and need to be integrated into the process of scenario development.
- Many impact studies fail to consider adequately uncertainties embedded in the scenarios they adopt. New techniques are emerging to explore the role of scenarios, conditional probabilities, and conditional forecasts in providing policy-relevant advice in impact assessments in an environment of high uncertainty.
- There is a mismatch between the time and space scales at which scenario information commonly is provided and the resolution at which it is required for impact assessments. Methods of obtaining higher resolution scenarios of global change from broad-scale projections are being actively developed and refined. However, in some regions of the world the coverage and availability of baseline global change data are still poor, which has hampered efforts at scenario development.
- Most global change scenarios consider long-term and broad-scale changes in mean conditions. Scenarios of changes in variability and the frequency of extreme events (climatic or nonclimatic) seldom are constructed because it is difficult to simulate such events and because they are complicated to formulate and explain. More research is required into methods of representing variability change in scenarios.
- Scenarios for impact studies lag new developments in climate modeling. There is a need to reduce this time lag to deliver up-to-date scenarios for impact assessment (e.g., constructing regional climate and sea-level scenarios by using outputs from AOGCM simulations that are based on SRES emissions scenarios).
- Few comprehensive scenarios have been developed to date for examining the consequences of stabilizing GHG concentrations at different concentrations, in line with Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).
- Climate change mitigation conventionally has been treated separately from impacts and adaptation, except in some studies that use IAMs. However, these two methods of responding to climate change are inextricably linked, and this linkage should be reflected in scenarios. Efforts to develop the SRES scenarios with well-elaborated narratives and improved appreciation of important interactions in the climate system seem likely to generate greater consistency among scenarios.
- Few scenarios directly address adaptation, but existing scenario methods could be refined to do so (e.g., by combining scenarios of climate change with decision support and similar systems being used to foster adaptation under current climate variability).
- Improved guidance material and training is required in the construction of integrated global change scenarios (see, e.g., IPCC-TGCIA, 1999; Hulme *et al*., 2000), especially concerning the development of nonclimatic scenarios.

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