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New assessment methods and the characterisation of future conditions

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Executive summary

This chapter describes the significant developments in methods and approaches for climate change impact, adaptation and vulnerability (CCIAV) assessment since the Third Assessment Report (TAR). It also introduces some of the scenarios and approaches to scenario construction that are used to characterise future conditions in the studies reported in this volume.

The growth of different approaches to assessing CCIAV has been driven by the need for improved decision analysis.
The recognition that a changing climate must be adapted to has increased the demand for policy-relevant information. The standard climate scenario-driven approach is used in a large proportion of assessments described in this report, but the use of other approaches is increasing. They include assessments of current and future adaptations to climate, adaptive capacity, social vulnerability, multiple stresses, and adaptation in the context of sustainable development. [2.2.1]

Risk management is a useful framework for decision-making and its use is expanding rapidly.
The advantages of risk-management methods include the use of formalised methods to manage uncertainty, stakeholder involvement, use of methods for evaluating policy options without being policy prescriptive, integration of different disciplinary approaches, and mainstreaming of climate change concerns into the broader decision-making context. [2.2.6]

Stakeholders bring vital inputs into CCIAV assessments about a range of risks and their management.
In particular, how a group or system can cope with current climate risks provides a solid basis for assessments of future risks. An increasing number of assessments involve, or are conducted by, stakeholders. This establishes credibility and helps to confer 'ownership' of the results, which is a prerequisite for effective risk management. [2.3.2]

The impacts of climate change can be strongly modified by non-climate factors.
Many new studies have applied socio-economic, land-use and technology scenarios at a regional scale derived from the global scenarios developed in the IPCC Special Report on Emissions Scenarios (SRES). Large differences in regional population, income and technological development implied under alternative SRES storylines can produce sharp contrasts in exposure to climate change and in adaptive capacity and vulnerability. Therefore, it is best not to rely on a single characterisation of future conditions. [2.4.6.4, 2.4.6.5]

Scenario information is increasingly being developed at a finer geographical resolution for use in CCIAV studies.
A range of downscaling methods have been applied to the SRES storylines, producing new regional scenarios of socio-economic conditions, land use and land cover, atmospheric composition, climate and sea level. Regionalisation methods are increasingly being used to develop high spatial-resolution climate scenarios based on coupled atmosphere-ocean general circulation model (AOGCM) projections. [2.4.6.1 to 2.4.6.5]

Characterisations of the future used in CCIAV studies are evolving to include mitigation scenarios, large-scale singularities, and probabilistic futures.
CCIAV studies assuming mitigated or stabilised futures are beginning to assess the benefits (through impacts ameliorated or avoided) of climate policy decisions. Characterisations of large-scale singularities have been used to assess their potentially severe biophysical and socio-economic consequences. Probabilistic characterisations of future socio-economic and climate conditions are increasingly becoming available, and probabilities of exceeding predefined thresholds of impact have been more widely estimated. [2.4.6.8, 2.4.7, 2.4.8]

2.1 Introduction

Assessments of climate change impacts, adaptation and vulnerability (CCIAV) are undertaken to inform decision-making in an environment of uncertainty. The demand for such assessments has grown significantly since the release of the IPCC Third Assessment Report (TAR), motivating researchers to expand the ranges of approaches and methods in use, and of the characterisations of future conditions (scenarios and allied products) required by those methods. This chapter describes these developments as well as illustrating the main approaches used to characterise future conditions in the studies reported in this volume.

In previous years, IPCC Working Group II[1] has devoted a Special Report and two chapters to assessment methods (IPCC, 1994; Carter et al., 1996; Ahmad et al., 2001). Moreover, the TAR also presented two chapters on the topic of scenarios (Carter et al., 2001; Mearns et al., 2001), which built on earlier descriptions of climate scenario development (IPCC-TGCIA, 1999). These contributions provide detailed descriptions of assessment methods and scenarios, which are not repeated in the current assessment.

In this chapter, an approach is defined as the overall scope and direction of an assessment and can accommodate a variety of different methods. A method is a systematic process of analysis. We identify five approaches to CCIAV in this chapter. Four are conventional research approaches: impact assessment, adaptation assessment, vulnerability assessment, and integrated assessment. The fifth approach, risk management, has emerged as CCIAV studies have begun to be taken up in mainstream policy-making.

Section 2.2 describes developments in the major approaches to CCIAV assessment, followed in Section 2.3 by discussion of a range of new and improved methods that have been applied since the TAR. The critical issue of data needs for assessment is

[1] Hereafter, IPCC Working Groups I, II, and III are referred to as WG I, WG II, and WG III, respectively.

treated at the end of this section. Most CCIAV approaches have a scenario component, so recent advances in methods of characterising future conditions are treated in Section 2.4. Since many recent studies evaluated in this volume use scenarios based on the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović et al., 2000) and derivative studies, boxed examples are presented to illustrate some of these. Finally, in Section 2.5, we summarise the key new findings in the chapter and recommend future research directions required to address major scientific, technical and information deficiencies.

2.2 New developments in approaches

2.2.1 Frameworks for CCIAV assessment

Although the following approaches and methods were all described in the TAR (Ahmad et al., 2001), their range of application in assessments has since been significantly expanded. Factors that distinguish a particular approach include the purpose of an assessment, its focus, the methods available, and how uncertainty is managed. A major aim of CCIAV assessment approaches is to manage, rather than overcome, uncertainty (Schneider and Kuntz-Duriseti, 2002), and each approach has its strengths and weaknesses in that regard. Another important trend has been the move from research-driven agendas to assessments tailored towards decision-making, where decision-makers and stakeholders either participate in or drive the assessment (Wilby et al., 2004a; UNDP, 2005).

The standard approach to assessment has been the climate scenario-driven 'impact approach', developed from the seven-step assessment framework of IPCC (1994).[2] This approach, which dominated the CCIAV literature described in previous IPCC reports, aims to evaluate the likely impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation to reduce any resulting vulnerability to climate risks. A large number of assessments in this report also follow that structure.

The other approaches discussed are adaptation- and vulnerability-based approaches, integrated assessment, and risk management. All are well represented in conventional environmental research, but they are increasingly being incorporated into mainstream approaches to decision-making, requiring a wider range of methods to fulfil objectives such as (SBI, 2001; COP, 2005):

- assessing current vulnerabilities and experience in adaptation,
- stakeholder involvement in dealing with extreme events,
- capacity-building needs for future vulnerability and adaptation assessments,
- potential adaptation measures,
- prioritisation and costing of adaptation measures,
- interrelationships between vulnerability and adaptation assessments,
- national development priorities and actions to integrate adaptation options into existing or future sustainable development plans.

The adaptation-based approach focuses on risk management by examining the adaptive capacity and adaptation measures required to improve the resilience or robustness of a system exposed to climate change (Smit and Wandel, 2006). In contrast, the vulnerability-based approach focuses on the risks themselves by concentrating on the propensity to be harmed, then seeking to maximise potential benefits and minimise or reverse potential losses (Adger, 2006). However, these approaches are interrelated, especially with regard to adaptive capacity (O'Brien et al., 2006). Integrated approaches include integrated assessment modelling and other procedures for investigating CCIAV across disciplines, sectors and scales, and representing key interactions and feedbacks (e.g., Toth et al., 2003a, b). Risk-management approaches focus directly on decision-making and offer a useful framework for considering the different research approaches and methods described in this chapter as well as confronting, head on, the treatment of uncertainty, which is pervasive in CCIAV assessment. Risk-management and integrated assessment approaches can also be linked directly to mitigation analysis (Nakićenović et al., 2007) and to the joint assessment of adaptation and mitigation (see Chapter 18).

Two common terms used to describe assessment types are 'top-down' and 'bottom-up', which can variously describe the approach to scale, to subject matter (e.g., from stress to impact to response; from physical to socio-economic disciplines) and to policy (e.g., national versus local); sometimes mixing two or more of these (Dessai et al., 2004; see also Table 2.1). The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale (see Section 2.4.6) with a sequence of analytical steps that begin with the climate system and move through biophysical impacts towards socio-economic assessment. Bottom-up approaches are those that commence at the local scale by addressing socio-economic responses to climate, which tend to be location-specific (Dessai and Hulme, 2004). Adaptation assessment and vulnerability assessment are usually categorised as bottom-up approaches. However, assessments have become increasingly complex, often combining elements of top-down and bottom-up approaches (e.g., Dessai et al., 2005a) and decision-making will utilise both (Kates and Wilbanks, 2003; McKenzie Hedger et al., 2006). The United Nations Development Programme's Adaptation Policy Framework (UNDP APF: see UNDP, 2005) has also identified a policy-based approach, which assesses current policy and plans for their effectiveness under climate change within a risk-management framework.

2.2.2 Advances in impact assessment

Application of the standard IPCC impact approach has expanded significantly since the TAR. The importance of providing a socio-economic and technological context for characterising future climate conditions has been emphasised,

[2] The seven steps are: 1. Define problem, 2. Select method, 3. Test method/sensitivity, 4. Select scenarios, 5. Assess biophysical/socio-economic impacts, 6. Assess autonomous adjustments, 7. Evaluate adaptation strategies.

Table 2.1. *Some characteristics of different approaches to CCIAV assessment. Note that vulnerability and adaptation-based approaches are highly complementary.*

	Approach			
	Impact	**Vulnerability**	**Adaptation**	**Integrated**
Scientific objectives	Impacts and risks under future climate	Processes affecting vulnerability to climate change	Processes affecting adaptation and adaptive capacity	Interactions and feedbacks between multiple drivers and impacts
Practical aims	Actions to reduce risks	Actions to reduce vulnerability	Actions to improve adaptation	Global policy options and costs
Research methods	Standard approach to CCIAV Drivers-pressure-state-impact-response (DPSIR) methods Hazard-driven risk assessment	Vulnerability indicators and profiles Past and present climate risks Livelihood analysis Agent-based methods Narrative methods Risk perception including critical thresholds Development/sustainability policy performance Relationship of adaptive capacity to sustainable development		Integrated assessment modelling Cross-sectoral interactions Integration of climate with other drivers Stakeholder discussions Linking models across types and scales Combining assessment approaches/methods
Spatial domains	Top-down Global → Local	Bottom-up Local → Regional (macro-economic approaches are top-down)		Linking scales Commonly global/regional Often grid-based
Scenario types	Exploratory scenarios of climate and other factors (e.g., SRES) Normative scenarios (e.g., stabilisation)	Socio-economic conditions Scenarios or inverse methods	Baseline adaptation Adaptation analogues from history, other locations, other activities	Exploratory scenarios: exogenous and often endogenous (including feedbacks) Normative pathways
Motivation	Research-driven	Research-/stakeholder-driven	Stakeholder-/research-driven	Research-/stakeholder-driven

and scenarios assuming no climate policy to restrict greenhouse gas (GHG) emissions have been contrasted with those assuming GHG stabilisation (e.g., Parry et al., 2001; see also Sections 2.4.6.4 and 2.4.6.8). The use of probabilities in impact assessments, presented as proof-of-concept examples in the TAR (Mearns et al., 2001), is now more firmly established (see examples in Section 2.4.8). Some other notable advances in impact assessment include: a reassessment of bioclimatic niche-based modelling, meta-analyses summarising a range of assessments, and new dynamic methods of analysing economic damages. Nevertheless, the climate-sensitive resources of many regions and sectors, especially in developing countries, have not yet been subject to detailed impact assessments.

Recent observational evidence of climatic warming, along with the availability of digital species distribution maps and greatly extended computer power has emboldened a new generation of bioclimatic niche-based modellers to predict changes in species distribution and prevalence under a warming climate using correlative methods (e.g., Bakkenes et al., 2002; Thomas et al., 2004; see also Chapter 4, Section 4.4.11). However, the application of alternative statistical techniques to the same data sets has also exposed significant variations in model performance that have recently been the subject of intensive debate (Pearson and Dawson, 2003; Thuiller et al., 2004; Luoto et al., 2005; Araújo and Rahbek, 2006) and should promote a more cautious application of these models for projecting future biodiversity.

A global-scale, meta-analysis of a range of studies for different sectors was conducted by Hitz and Smith (2004) to evaluate the aggregate impacts at different levels of global mean temperature. For some sectors and regions, such as agriculture and the coastal zone, sufficient information was available to summarise aggregated sectoral impacts as a function of global warming. For other sectors, such as marine biodiversity and energy, limited information allowed only broad conclusions of low confidence.

Dynamic methods are superseding statistical methods in some economic assessments. Recent studies account, for example, for the role of world markets in influencing climate change impacts on global agriculture (Fischer et al., 2002), the effect on damage from sea-level rise when assuming optimal adaptation measures (Neumann et al., 2000; Nicholls and Tol, 2006), the added costs for adapting to high temperatures due to uncertainties in projected climate (Hallegatte et al., 2007), and increasing long-term costs of natural disasters when explicitly accounting for altered extreme event distributions (Hallegatte et al., 2006). The role of economic dynamics has also been emphasised (Fankhauser and Tol, 2005; Hallegatte, 2005; Hallegatte et al., 2006). Some new studies suggest damage overestimations by previous assessments, while others suggest underestimations, leading to the conclusion that uncertainty is likely to be larger than suggested by the range of previous estimates.

2.2.3 Advances in adaptation assessment

Significant advances in adaptation assessment have occurred, shifting its emphasis from a research-driven activity to one where stakeholders participate in order to improve decision-making. The key advance is the incorporation of adaptation to past and present climate. This has the advantage of anchoring the assessment in what is already known, and can be used to explore adaptation to climate variability and extremes, especially

if scenarios of future variability are uncertain or unavailable (Mirza, 2003b; UNDP, 2005). As such, adaptation assessment has accommodated a wide range of methods used in mainstream policy and planning. Chapter 17 of this volume discusses adaptation practices, the processes and determinants of adaptive capacity, and limits to adaptation, highlighting the difficulty of establishing a general methodology for adaptation assessment due to the great diversity of analytical methods employed. These include the following approaches and methods.

- The scenario-based approach (e.g., IPCC, 1994; see also Section 2.2.1), where most impact assessments consider future adaptation as an output.
- Normative policy frameworks, exploring which adaptations are socially and environmentally beneficial, and applying diverse methods, such as vulnerability analysis, scenarios, cost-benefit analysis, multi-criteria analysis and technology risk assessments (UNDP, 2005).
- Indicators, employing models of specific hypothesised components of adaptive capacity (e.g., Moss et al., 2001; Yohe and Tol, 2002; Brooks et al., 2005; Haddad, 2005).
- Economic modelling, anthropological and sociological methods for identifying learning in individuals and organisations (Patt and Gwata, 2002; Tompkins, 2005; Berkhout et al., 2006).
- Scenarios and technology assessments, for exploring what kinds of adaptation are likely in the future (Dessai and Hulme, 2004; Dessai et al., 2005a; Klein et al., 2005).
- Risk assessments combining current risks to climate variability and extremes with projected future changes, utilising cost-benefit analysis to assess adaptation (e.g., ADB, 2005).

Guidance regarding methods and tools to use in prioritising adaptation options include the Compendium of Decision Tools (UNFCCC, 2004), the Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies (Feenstra et al., 1998), and Costing the Impacts of Climate Change (Metroeconomica, 2004). A range of different methods can also be used with stakeholders (see Section 2.3.2).

The financing of adaptation has received minimal attention. Bouwer and Vellinga (2005) suggest applying more structured decision-making to future disaster management and adaptation to climate change, sharing the risk between private and public sources. Quiggin and Horowitz (2003) argue that the economic costs will be dominated by the costs of adaptation, which depend on the rate of climate change, especially the occurrence of climate extremes, and that many existing analyses overlook these costs (see also Section 2.2.2).

2.2.4 Advances in vulnerability assessment

Since the TAR, the IPCC definition of vulnerability[3] has been challenged, both to account for an expanded remit by including social vulnerability (O'Brien et al., 2004a) and to reconcile it with risk assessment (Downing and Patwardhan, 2005). Different states of vulnerability under climate risks include: vulnerability to current climate, vulnerability to climate change in the absence of adaptation and mitigation measures, and residual vulnerability, where adaptive and mitigative capacities have been exhausted (e.g., Jones et al., 2007). A key vulnerability has the potential for significant adverse affects on both natural and human systems, as outlined in the United Nations Framework Convention on Climate Change (UNFCCC), thus contributing to dangerous anthropogenic interference with the climate system (see Chapter 19). Füssel and Klein (2006) review and summarise these developments.

Vulnerability is highly dependent on context and scale, and care should be taken to clearly describe its derivation and meaning (Downing and Patwardhan, 2005) and to address the uncertainties inherent in vulnerability assessments (Patt et al., 2005). Frameworks should also be able to integrate the social and biophysical dimensions of vulnerability to climate change (Klein and Nicholls, 1999; Polsky et al., 2003; Turner et al., 2003a). Formal methods for vulnerability assessment have also been proposed (Ionescu et al., 2005; Metzger and Schröter, 2006) but are very preliminary.

The methods and frameworks for assessing vulnerability must also address the determinants of adaptive capacity (Turner et al., 2003a; Schröter et al., 2005a; O'Brien and Vogel, 2006; see also Chapter 17, Section 17.3.1) in order to examine the potential responses of a system to climate variability and change. Many studies endeavour to do this in the context of human development, by aiming to understand the underlying causes of vulnerability and to further strengthen adaptive capacities (e.g., World Bank, 2006). In some quantitative approaches, the indicators used are related to adaptive capacity, such as national economic capacity, human resources, and environmental capacities (Moss et al., 2001; see also Section 2.2.3). Other studies include indicators that can provide information related to the conditions, processes and structures that promote or constrain adaptive capacity (Eriksen et al., 2005).

Vulnerability assessment offers a framework for policy measures that focus on social aspects, including poverty reduction, diversification of livelihoods, protection of common property resources and strengthening of collective action (O'Brien et al., 2004b). Such measures enhance the ability to respond to stressors and secure livelihoods under present conditions, which can also reduce vulnerability to future climate change. Community-based interactive approaches for identifying coping potentials provide insights into the underlying causes and structures that shape vulnerability (O'Brien et al., 2004b). Other methods employed in recent regional vulnerability studies include stakeholder elicitation and survey (Eakin et al., 2006; Pulhin et al., 2006), and multi-criteria modelling (Wehbe et al., 2006).

Traditional knowledge of local communities represents an important, yet currently largely under-used resource for CCIAV assessment (Huntington and Fox, 2005). Empirical knowledge from past experience in dealing with climate-related natural

[3] The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2001b, Glossary).

disasters such as droughts and floods (Osman-Elasha et al., 2006), health crises (Wandiga et al., 2006), as well as longer-term trends in mean conditions (Huntington and Fox, 2005; McCarthy and Long Martello, 2005), can be particularly helpful in understanding the coping strategies and adaptive capacity of indigenous and other communities relying on oral traditions.

2.2.5 Advances in integrated assessment

Integrated assessment represents complex interactions across spatial and temporal scales, processes and activities. Integrated assessments can involve one or more mathematical models, but may also represent an integrated process of assessment, linking different disciplines and groups of people. Managing uncertainty in integrated assessments can utilise models ranging from simple models linking large-scale processes, through models of intermediate complexity, to the complex, physically explicit representation of Earth systems. This structure is characterised by trade-offs between realism and flexibility, where simple models are more flexible but less detailed, and complex models offer more detail and a greater range of output. No single theory describes and explains dynamic behaviour across scales in socio-economic and ecological systems (Rotmans and Rothman, 2003), nor can a single model represent all the interactions within a single entity, or provide responses to questions in a rapid turn-around time (Schellnhuber et al., 2004). Therefore, integration at different scales and across scales is required in order to comprehensively assess CCIAV. Some specific advances are outlined here; integration to assess climate policy benefits is considered in Section 2.2.6.

Cross-sectoral integration is required for purposes such as national assessments, analysis of economic and trade effects, and joint population and climate studies. National assessments can utilise nationally integrated models (e.g., Izaurralde et al., 2003; Rosenberg et al., 2003; Hurd et al., 2004), or can synthesise a number of disparate studies for policy-makers (e.g., West and Gawith, 2005). Markets and trade can have significant effects on outcomes. For example, a study assessing the global impacts of climate change on forests and forest products showed that trade can affect efforts to stabilise atmospheric carbon dioxide (CO_2) and also affected regional welfare, with adverse effects on those regions with high production costs (Perez-Garcia et al., 2002). New economic assessments of aggregated climate change damages have also been produced for multiple sectors (Tol, 2002a, b; Mendelsohn and Williams, 2004; Nordhaus, 2006). These have highlighted potentially large regional disparities in vulnerability to impacts. Using an integrated assessment general equilibrium model, Kemfert (2002) found that interactions between sectors acted to amplify the global costs of climate change, compared with single-sector analysis.

Integration yields results that cannot be produced in isolation. For example, the Millennium Ecosystem Assessment assessed the impact of a broad range of stresses on ecosystem services, of which climate change was only one (Millennium Ecosystem Assessment, 2005). Linked impact and vulnerability assessments can also benefit from a multiple stressors approach. For instance, the AIR-CLIM Project integrated climate and air pollution impacts in Europe between 1995 and 2100, concluding that that while the physical impacts were weakly coupled, the costs of air pollution and climate change were strongly coupled. The indirect effects of climate policies stimulated cost reductions in air pollution control of more than 50% (Alcamo et al., 2002). Some of the joint effects of extreme weather and air pollution events on human health are described in Chapter 8, Section 8.2.6.

Earth system models of intermediate complexity that link the atmosphere, oceans, cryosphere, land system, and biosphere are being developed to assess impacts (particularly global-scale, singular events that may be considered dangerous) within a risk and vulnerability framework (Rial et al., 2004; see also Section 2.4.7). Global climate models are also moving towards a more complete representation of the Earth system. Recent simulations integrating the atmosphere with the biosphere via a complete carbon cycle show the potential of the Amazon rainforest to suffer dieback (Cox et al., 2004), leading to a positive feedback that decreases the carbon sink and increases atmospheric CO_2 concentrations (Friedlingstein et al., 2006; Denman et al., 2007).

2.2.6 Development of risk-management frameworks

Risk management is defined as the culture, processes and structures directed towards realising potential opportunities whilst managing adverse effects (AS/NZS, 2004). Risk is generally measured as a combination of the probability of an event and its consequences (ISO/IEC, 2002; see also Figure 2.1), with several ways of combining these two factors being possible. There may be more than one event, consequences can range from positive to negative, and risk can be measured qualitatively or quantitatively.

To date, most CCIAV studies have assessed climate change without specific regard to how mitigation policy will influence those impacts. However, the certainty that some climate change will occur (and is already occurring – see Chapter 1) is driving adaptation assessment beyond the limits of what scenario-driven methods can provide. The issues to be addressed include assessing current adaptations to climate variability and extremes before assessing adaptive responses to future climate, assessing the limits of adaptation, linking adaptation to sustainable development, engaging stakeholders, and decision-making under uncertainty. Risk management has been identified as a framework that can deal with all of these issues in a manner that incorporates existing methodologies and that can also accommodate other sources of risk (Jones, 2001; Willows and Connell, 2003; UNDP, 2005) in a process known as mainstreaming.

The two major forms of climate risk management are the mitigation of climate change through the abatement of GHG emissions and GHG sequestration, and adaptation to the consequences of a changing climate (Figure 2.1). Mitigation reduces the rate and magnitude of changing climate hazards; adaptation reduces the consequences of those hazards (Jones, 2004). Mitigation also reduces the upper bounds of the range of potential climate change, while adaptation copes with the lower bounds (Yohe and Toth, 2000). Hence they are complementary

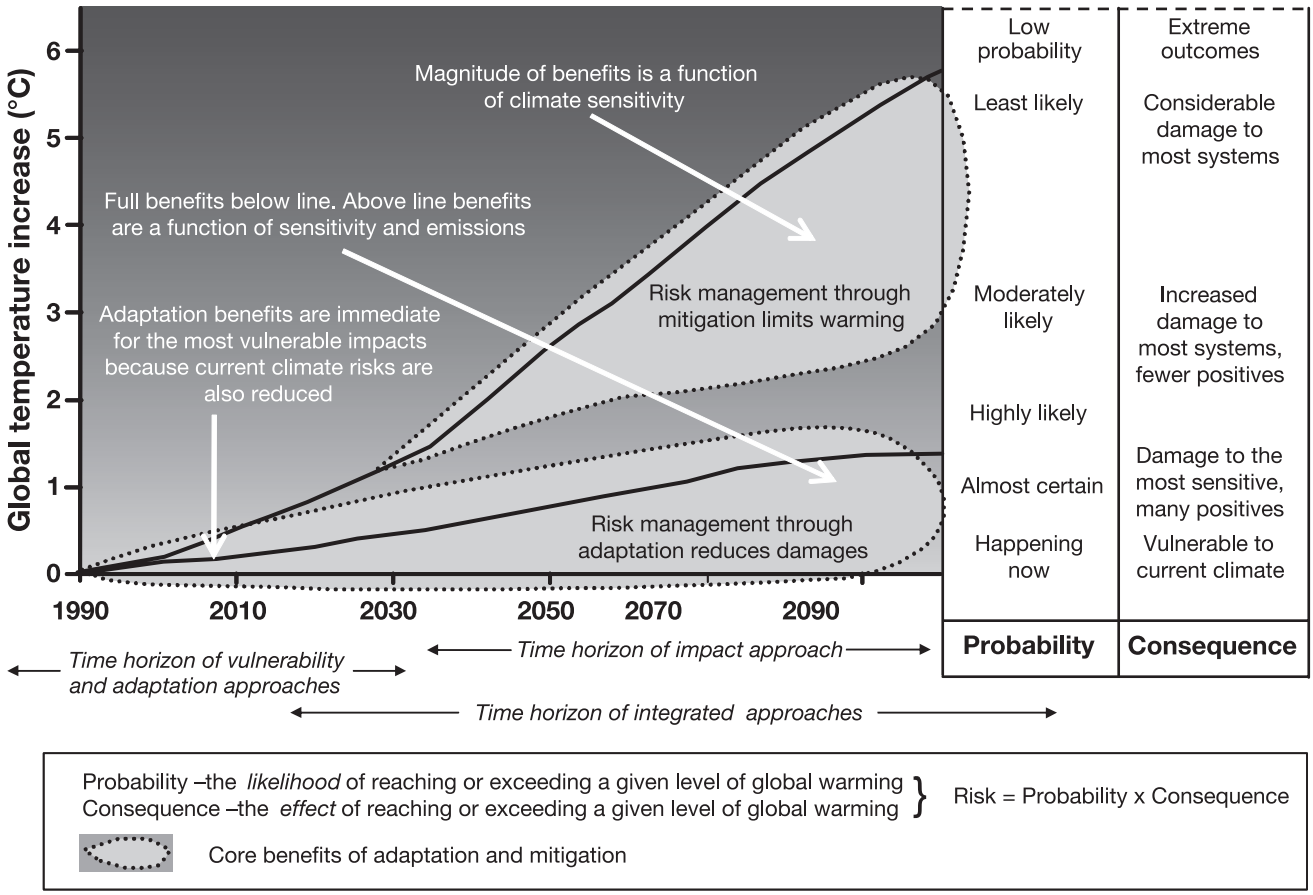


Figure 2.1. *Synthesis of risk-management approaches to global warming. The left side shows the projected range of global warming from the TAR (bold lines) with zones of maximum benefit for adaptation and mitigation depicted schematically. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level based on results from the TAR. Risk is a function of probability and consequence. The primary time horizons of approaches to CCIAV assessment are also shown (modified from Jones, 2004).*

processes, but the benefits will accumulate over different time-scales and, in many cases, they can be assessed and implemented separately (Klein et al., 2005). These complementarities and differences are discussed in Section 18.4 of this volume, while integrated assessment methods utilising a risk-management approach are summarised by Nakićenović et al. (2007).

Some of the standard elements within the risk-management process that can be adapted to assess CCIAV are as follows.

- A scoping exercise, where the context of the assessment is established. This identifies the overall approach to be used.
- Risk identification, where what is at risk, who is at risk, the main climate and non-climate stresses contributing to the risk, and levels of acceptable risk are identified. This step also identifies the scenarios required for further assessment.
- Risk analysis, where the consequences and their likelihood are analysed. This is the most developed area, with a range of methods used in mainstream risk assessment and CCIAV assessment being available.
- Risk evaluation, where adaptation and/or mitigation measures are prioritised.
- Risk treatment, where selected adaptation and/or mitigation measures are applied, with follow-up monitoring and review.

Two overarching activities are communication and consultation with stakeholders, and monitoring and review. These activities co-ordinate the management of uncertainty and ensure that clarity and transparency surround the assumptions and concepts being used. Other essential components of risk management include investment in obtaining improved information and building capacity for decision-making (adaptive governance: see Dietz et al., 2003).

Rather than being research-driven, risk management is oriented towards decision-making; e.g., on policy, planning, and management options. Several frameworks have been developed for managing risk, which use a variety of approaches as outlined in Table 2.1. The UNDP Adaptation Policy Framework (UNDP, 2005) describes risk-assessment methods that follow both the standard impact and human development approaches focusing on vulnerability and adaptation (also see Füssel and Klein, 2006). National frameworks constructed to deliver national adaptation strategies include those of the UK (Willows and Connell, 2003) and Australia (Australian Greenhouse Office, 2006). The World Bank is pursuing methods for hazard and risk management that focus on financing adaptation to climate change (van Aalst, 2006) and mainstreaming climate change into natural-hazard risk management (Burton and van Aalst, 2004; Mathur et al., 2004; Bettencourt et al., 2006).

Therefore, risk management is an approach that is being pursued for the management of climate change risks at a range

of scales; from the global (mitigation to achieve 'safe' levels of GHG emissions and concentrations, thus avoiding dangerous anthropogenic interference), to the local (adaptation at the scale of impact), to mainstreaming risk with a multitude of other activities.

2.2.7 Managing uncertainties and confidence levels

CCIAV assessments aim to understand and manage as much of the full range of uncertainty, extending from emissions through to vulnerability (Ahmad et al., 2001), as is practicable, in order to improve the decision-making process. At the same time, a primary aim of scientific investigations is to reduce uncertainty through improved knowledge. However, such investigations do not necessarily reduce the uncertainty range as used by CCIAV assessments. A phenomenon or process is usually described qualitatively before it can be quantified with any confidence; some, such as aspects of socio-economic futures, may never be well quantified (Morgan and Henrion, 1990). Often a scientific advance will expand a bounded range of uncertainty as a new process is quantified and incorporated into the chain of consequences contributing to that range. Examples include an expanded range of future global warming due to positive CO_2 feedbacks, from the response of vegetation to climate change (see Section 2.2.5; WG I SPM), and a widened range of future impacts that can be incurred by incorporating development futures in integrated impact assessments, particularly if adaptation is included (see Section 2.4.6.4). In such cases, although uncertainty appears to be expanding, this is largely because the underlying process is becoming better understood.

The variety of different approaches developed and applied since the TAR all have their strengths and weaknesses. The impact assessment approach is particularly susceptible to ballooning uncertainties because of the limits of prediction (e.g., Jones 2001). Probabilistic methods and the use of thresholds are two ways in which these uncertainties are being managed (Jones and Mearns, 2005; see also Section 2.4.8). Another way to manage uncertainties is through participatory approaches, resulting in learning-by-observation and learning-by-doing, a particular strength of vulnerability and adaptation approaches (e.g., Tompkins and Adger, 2005; UNDP, 2005). Stakeholder participation establishes credibility and stakeholders are more likely to 'own' the results, increasing the likelihood of successful adaptation (McKenzie Hedger et al., 2006).

2.3 Development in methods

2.3.1 Thresholds and criteria for risk

The risks of climate change for a given exposure unit can be defined by criteria that link climate impacts to potential outcomes. This allows a risk to be analysed and management options to be evaluated, prioritised, and implemented. Criteria are usually specified using thresholds that denote some limit of tolerable risk. A threshold marks the point where stress on an exposed system or activity, if exceeded, results in a non-linear response in that system or activity. Two types of thresholds are used in assessing change (Kenny et al., 2000; Jones 2001; see also Chapter 19, Section 19.1.2.5):

1. a non-linear change in state, where a system shifts from one identifiable set of conditions to another (systemic threshold);
2. a level of change in condition, measured on a linear scale, regarded as 'unacceptable' and inviting some form of response (impact threshold).

Thresholds used to assess risk are commonly value-laden, or normative. A systemic threshold can often be objectively measured; for example, a range of estimates of global mean warming is reported in Meehl et al. (2007) defining the point at which irreversible melting of the Greenland Ice Sheet would commence. If a policy aim were to avoid its loss, selecting from the given range a critical level of warming that is not to be exceeded would require a value judgement. In the case of an impact threshold, the response is the non-linear aspect; for example, a management threshold (Kenny et al., 2000). Exceeding a management threshold will result in a change of legal, regulatory, economic, or cultural behaviour. Hence, both cases introduce critical thresholds (IPCC, 1994; Parry et al., 1996; Pittock and Jones, 2000), where criticality exceeds, in risk-assessment terms, the level of tolerable risk. Critical thresholds are used to define the coping range (see Section 2.3.3).

Thresholds derived with stakeholders avoid the pitfall of researchers ascribing their own values to an assessment (Kenny et al., 2000; Pittock and Jones, 2000; Conde and Lonsdale, 2005). Stakeholders thus become responsible for the management of the uncertainties associated with that threshold through ownership of the assessment process and its outcomes (Jones, 2001). The probability of threshold exceedance is being used in risk analyses (Jones, 2001, 2004) on local and global scales. For example, probabilities of critical thresholds for coral bleaching and mortality for sites in the Great Barrier Reef as a function of global warming show that catastrophic bleaching will occur biennially with a warming of about 2°C (Jones, 2004). Further examples are given in Section 2.4.8. At a global scale, the risk of exceeding critical thresholds has been estimated within a Bayesian framework, by expressing global warming and sea-level rise as cumulative distribution functions that are much more likely to be exceeded at lower levels than higher levels (Jones, 2004; Mastrandrea and Schneider, 2004; Yohe, 2004). However, although this may be achieved for key global vulnerabilities, there is often no straightforward way to integrate local critical thresholds into a 'mass' damage function of many different metrics across a wide range of potential impacts (Jacoby, 2004).

2.3.2 Stakeholder involvement

Stakeholder involvement is crucial to risk, adaptation, and vulnerability assessments because it is the stakeholders who will be most affected and thus may need to adapt (Burton et al., 2002; Renn, 2004; UNDP, 2005). Stakeholders are characterised as individuals or groups who have anything of value (both monetary and non-monetary) that may be affected by climate change or by the actions taken to manage anticipated climate

risks. They might be policy-makers, scientists, communities, and/or managers in the sectors and regions most at risk both now and in the future (Rowe and Frewer, 2000; Conde and Lonsdale, 2005).

Individual and institutional knowledge and expertise comprise the principal resources for adapting to the impacts of climate change. Adaptive capacity is developed if people have time to strengthen networks, knowledge, and resources, and the willingness to find solutions (Cohen, 1997; Cebon et al., 1999; Ivey et al., 2004). Kasperson (2006) argues that the success of stakeholder involvement lies not only in informing interested and affected people, but also in empowering them to act on the enlarged knowledge. Through an ongoing process of negotiation and modification, stakeholders can assess the viability of adaptive measures by integrating scientific information into their own social, economic, cultural, and environmental context (van Asselt and Rotmans, 2002; see also Chapter 18, Section 18.5). However, stakeholder involvement may occur in a context where political differences, inequalities, or conflicts may be raised; researchers must accept that it is not their role to solve those conflicts, unless they want to be part of them (Conde and Lonsdale, 2005). Approaches to stakeholder engagement vary from passive interactions, where the stakeholders only provide information, to a level where the stakeholders themselves initiate and design the process (Figure 2.2).

Current adaptation practices for climate risks are being developed by communities, governments, Non-Governmental Organisations (NGOs), and other organised stakeholders to increase their adaptive capacity (Ford and Smit, 2004; Thomalla et al., 2005; Conde et al., 2006). Indigenous knowledge studies are a valuable source of information for CCIAV assessments, especially where formally collected and recorded data are sparse (Huntington and Fox, 2005). Stakeholders have a part to play in scenario development (Lorenzoni et al., 2000; Bärlund and Carter, 2002) and participatory modelling (e.g., Welp, 2001; van Asselt and Rijkens-Klomp, 2002).

Stakeholders are also central in assessing future needs for developing policies and measures to adapt (Nadarajah and Rankin, 2005). These needs have been recognised in regional and national approaches to assessing climate impacts and adaptation, including the UK Climate Impacts Programme (UKCIP) (West and Gawith, 2005), the US National Assessment (National Assessment Synthesis Team 2000; Parson et al., 2003), the Arctic Climate Impact Assessment (ACIA, 2005), the Finnish National Climate Change Adaptation Strategy (Marttila et al., 2005) and the related FINADAPT research consortium (Kankaanpää et al., 2005), and the Mackenzie Basin Impact Study (Cohen, 1997).

2.3.3 Defining coping ranges

The coping range of climate (Hewitt and Burton, 1971) is described in the TAR as the capacity of systems to accommodate variations in climatic conditions (Smith et al., 2001), and thus serves as a suitable template for understanding the relationship between changing climate hazards and society. The concept of the coping range has since been expanded to incorporate concepts of current and future adaptation, planning and policy horizons, and likelihood (Yohe and Tol, 2002; Willows and Connell, 2003; UNDP, 2005). It can therefore serve as a conceptual model (Morgan et al., 2001) which can be used to integrate analytical techniques with a broader understanding of climate-society relationships (Jones and Mearns, 2005).

The coping range is used to link the understanding of current adaptation to climate with adaptation needs under climate change. It is a useful mental model to use with stakeholders –

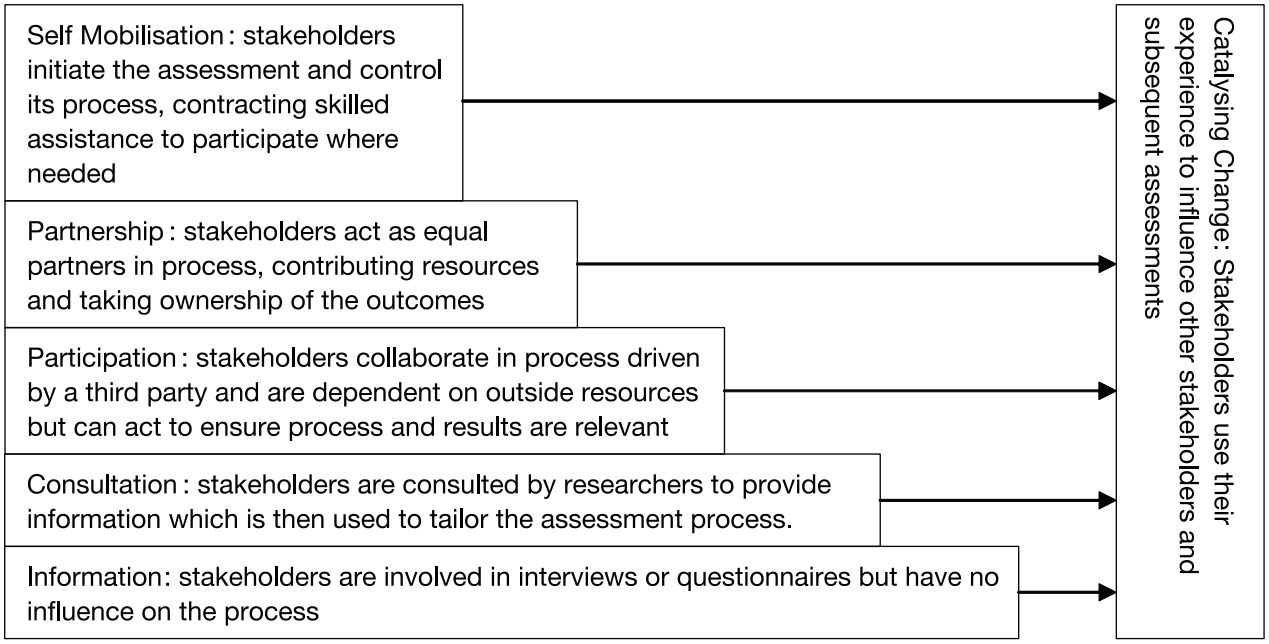


Figure 2.2. *Ladder of stakeholder participation (based on Pretty et al., 1995; Conde and Lonsdale, 2005).*

who often have an intuitive understanding of which risks can be coped with and which cannot – that can subsequently be developed into a quantitative model (Jones and Boer, 2005). It can be depicted as one or more climatic or climate-related variables upon which socio-economic responses are mapped (Figure 2.3). The core of the coping range contains beneficial outcomes. Towards one or both edges of the coping range, outcomes become negative but tolerable. Beyond the coping range, the damages or losses are no longer tolerable and denote a vulnerable state, the limits of tolerance describing a critical threshold (left side of Figure 2.3). A coping range is usually specific to an activity, group, and/or sector, although society-wide coping ranges have been proposed (Yohe and Tol, 2002).

Risk is assessed by calculating how often the coping range is exceeded under given conditions. Climate change may increase the risk of threshold exceedance but adaptation can ameliorate the adverse effects by widening the coping range (right side of Figure 2.3). For example, Jones (2001) constructed critical thresholds for the Macquarie River catchment in Australia for irrigation allocation and environmental flows. The probability of exceeding these thresholds was a function of both natural climate variability and climate change. Yohe and Tol (2002) explored hypothetical upper and lower critical thresholds for the River Nile using current and historical streamflow data. The upper threshold denoted serious flooding, and the lower threshold the minimum flow required to supply water demand. Historical frequency of exceedance served as a baseline from which to measure changing risks using a range of climate scenarios.

2.3.4 Communicating uncertainty and risk

Communicating risk and uncertainty is a vital part of helping people respond to climate change. However, people often rely on intuitive decision-making processes, or heuristics, in solving complicated problems of judgement and decision-making (Tversky and Kahneman, 1974). In many cases, these heuristics are surprisingly successful in leading to successful decisions under information and time constraints (Gigerenzer, 2000; Muramatsu and Hanich, 2005). In other cases, heuristics can lead to predictable inconsistencies or errors of judgement (Slovic et al., 2004). For example, people consistently overestimate the likelihood of low-probability events (Kahneman and Tversky, 1979; Kammen et al., 1994), resulting in choices that may increase their exposure to harm (Thaler and Johnson, 1990). These deficiencies in human judgement in the face of uncertainty are discussed at length in the TAR (Ahmad et al., 2001).

Participatory approaches establish a dialogue between stakeholders and experts, where the experts can explain the uncertainties and the ways they are likely to be misinterpreted, the stakeholders can explain their decision-making criteria, and the two parties can work together to design a risk-management strategy (Fischoff, 1996; Jacobs, 2002; NRC, 2002). Because stakeholders are often the decision-makers themselves (Kelly and Adger, 2000), the communication of impact, adaptation, and vulnerability assessment has become more important (Jacobs, 2002; Dempsey and Fisher, 2005; Füssel and Klein, 2006). Adaptation decisions also depend on changes occurring outside the climate change arena (Turner et al., 2003b).

If the factors that give rise to the uncertainties are described (Willows and Connell, 2003), stakeholders may view that information as more credible because they can make their own judgements about its quality and accuracy (Funtowicz and Ravetz, 1990). People will remember and use uncertainty assessments when they can mentally link the uncertainty and events in the world with which they are familiar; assessments of climate change uncertainty are more memorable, and hence more influential, when they fit into people's pre-existing mental maps of experience of climate variability, or when sufficient detail is provided to help people to form new mental models (Hansen, 2004). This can be aided by the development of visual tools that can communicate impacts, adaptation, and vulnerability to stakeholders while representing uncertainty in an appropriate manner (e.g., Discovery Software, 2003; Aggarwal et al., 2006).

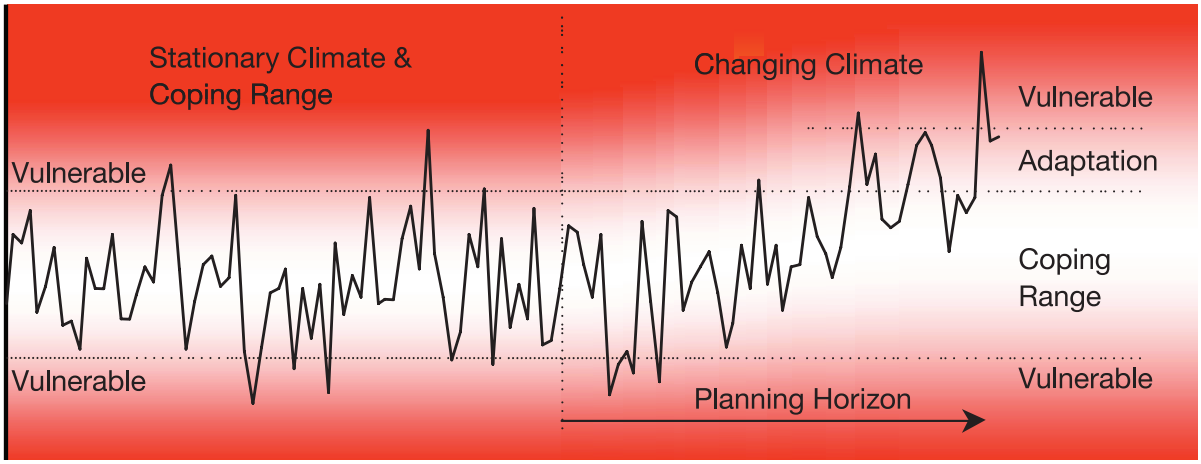


Figure 2.3. *Idealised version of a coping range showing the relationship between climate change and threshold exceedance, and how adaptation can establish a new critical threshold, reducing vulnerability to climate change (modified from Jones and Mearns, 2005).*

2.3.5 Data needs for assessment

Although considerable advances have been made in the development of methods and tools for CCIAV assessment (see previous sections), their application has been constrained by limited availability and access to good-quality data (e.g., Briassoulis, 2001; UNFCCC, 2005; see also Chapter 3, Section 3.8; Chapter 6, Section 6.6; Chapter 7, Section 7.8; Chapter 8, Section, 8.8; Chapter 9, Section 9.5; Chapter 10, Section 10.8; Chapter 12, Section 12.8; Chapter 13, Section 13.5; Chapter 15, Section 15.4; Chapter 16, Section 16.7).

In their initial national communications to the UNFCCC, a large number of non-Annex I countries reported on the lack of appropriate institutions and infrastructure to conduct systematic data collection, and poor co-ordination within and/or between different government departments and agencies (UNFCCC, 2005). Significant gaps exist in the geographical coverage and management of existing global and regional Earth-observing systems and in the efforts to retrieve the available historical data. These are especially acute in developing-country regions such as Africa, where lack of funds for modern equipment and infrastructure, inadequate training of staff, high maintenance costs, and issues related to political instability and conflict are major constraints (IRI, 2006). As a result, in some regions, observation systems have been in decline (e.g., GCOS, 2003; see also Chapter 16, Section 16.7).

Major deficiencies in data provision for socio-economic and human systems indicators have been reported as a key barrier to a better understanding of nature-society dynamics in both developed and developing countries (Wilbanks et al., 2003; but see Nordhaus, 2006). Recognising the importance of data and information for policy decisions and risk management under a changing climate, new programmes and initiatives have been put in place to improve the provision of data across disciplines and scales. Prominent among these, the Global Earth Observation System of Systems (GEOSS) plan (Group on Earth Observations, 2005) was launched in 2006, with a mission to help all 61 involved countries produce and manage Earth observational data. The Centre for International Earth Science Information Network (CIESIN) provides a wide range of environmental and socio-economic data products.[4] In addition, the IPCC Data Distribution Centre (DDC), overseen by the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), hosts various sets of outputs from coupled Atmosphere-Ocean General Circulation Models (AOGCMs), along with environmental and socio-economic data for CCIAV assessments (Parry, 2002). New sources of data from remote sensing are also becoming available (e.g., Justice et al., 2002), which could fill the gaps where no ground-based data are available but which require resourcing to obtain access. New and updated observational data sets and their deficiencies are also detailed in the WG I report for climate (Trenberth et al., 2007) and sea level (Bindoff et al., 2007).

Efforts are also being made to record human-environment interactions in moderated online databases. For instance, the DesInventar database[5] records climatic disasters of the recent past in Latin America, documenting not only the adverse climatic events themselves, but also the consequences of these events and the parties affected. Information on local coping strategies applied by different communities and sectors is being recorded by the UNFCCC.[6]

Many assessments are now obtaining data through stakeholder elicitation and survey methods. For example, in many traditional societies a large number of social interactions may not be recorded by bureaucratic processes, but knowledge of how societies adapt to climate change, perceive risk, and measure their vulnerability is held by community members (e.g., Cohen, 1997; ACIA, 2005; see also Section 2.3.2). Even in data-rich situations, it is likely that some additional data from stakeholders will be required. However, this also requires adequate resourcing.

2.4 Characterising the future

2.4.1 Why and how do we characterise future conditions?

Evaluations of future climate change impacts, adaptation, and vulnerability require assumptions, whether explicit or implicit, about how future socio-economic and biophysical conditions will develop. The literature on methods of characterising the future has grown in tandem with the literature on CCIAV, but these methods have not been defined consistently across different research communities. Box 2.1 presents a consistent typology of characterisations that expands on the definitions presented in the TAR (Carter et al., 2001), for the purpose of clarifying the use of this terminology in this chapter. Although they may overlap, different types of characterisations of the future can be usefully distinguished in terms of their plausibility and ascription of likelihood, on the one hand, and the comprehensiveness of their representation, on the other (see Box 2.1 for definitions). Since the TAR, comprehensiveness has increased and ascriptions of likelihood have become more common. The following sections make use of the typology in Box 2.1 to address notable advances in methods of characterising the future.

2.4.2 Artificial experiments

The most significant advance in artificial experiments since the TAR is the development of a new set of commitment runs by AOGCMs. These are climate change projections that assume that the radiative forcing at a particular point in time (often the current forcing) is held constant into the future (Meehl et al., 2007). The projections demonstrate the time-lags in the climate response to changes in radiative forcing (due to the delayed penetration of heat into the oceans), and of sea level to warming. Recent experiments estimate a global mean warming commitment

[4] http://www.ciesin.org/index.html
[5] http://www.desinventar.org/desinventar.html
[6] http://maindb.unfccc.int/public/adaptation

Box 2.1. Definitions of future characterisations

Figure 2.4 illustrates the relationships among the categories of future characterisations most commonly used in CCIAV studies. Because definitions vary across different fields, we present a single consistent typology for use in this chapter. Categories are distinguished according to comprehensiveness and plausibility.

Comprehensiveness indicates the degree to which a characterisation of the future captures the various aspects of the socio-economic/biophysical system it aims to represent. Secondarily, it indicates the detail with which any single element is characterised.

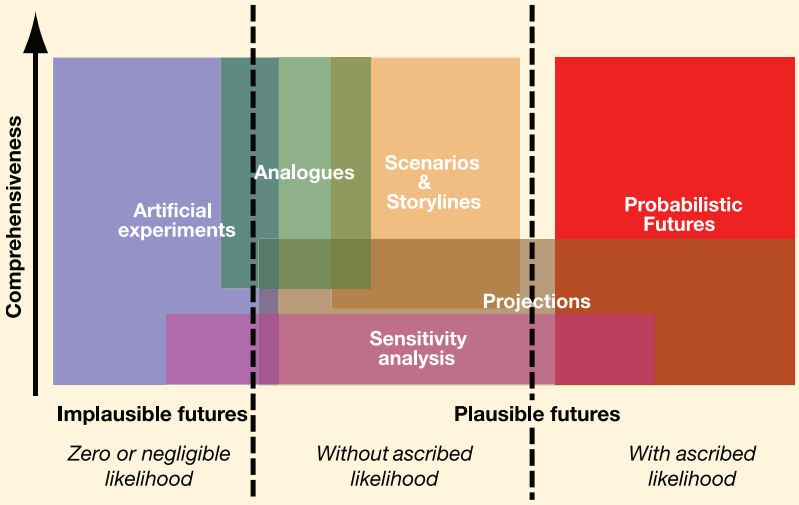


Figure 2.4. *Characterisations of the future.*

Plausibility is a subjective measure of whether a characterisation of the future is possible. Implausible futures are assumed to have zero or negligible likelihood. Plausible futures can be further distinguished by whether a specific likelihood is ascribed or not.

Artificial experiment. A characterisation of the future constructed without regard to plausibility (and hence often implausible) that follows a coherent logic in order to study a process or communicate an insight. Artificial experiments range in comprehensiveness from simple thought experiments to detailed integrated modelling studies.

Sensitivity analysis. Sensitivity analyses employ characterisations that involve arbitrary or graduated adjustments of one or several variables relative to a reference case. These adjustments may be plausible (e.g., changes are of a realistic magnitude) or implausible (e.g., interactions between the adjusted variables are ignored), but the main aim is to explore model sensitivity to inputs, and possibly uncertainty in outputs.

Analogues. Analogues are based on recorded conditions that are considered to adequately represent future conditions in a study region.These records can be of past conditions (temporal analogues) or from another region (spatial analogues). Their selection is guided by information from sources such as AOGCMs; they are used to generate detailed scenarios which could not be realistically obtained by other means. Analogues are plausible in that they reflect a real situation, but may be implausible because no two places or periods of time are identical in all respects.

Scenarios. A scenario is a coherent, internally consistent, and plausible description of a possible future state of the world (IPCC, 1994; Nakićenović et al., 2000; Raskin et al., 2005). Scenarios are not predictions or forecasts (which indicate outcomes considered most likely), but are alternative images without ascribed likelihoods of how the future might unfold. They may be qualitative, quantitative, or both. An overarching logic often relates several components of a scenario, for example a storyline and/or projections of particular elements of a system. Exploratory (or descriptive) scenarios describe the future according to known processes of change, or as extrapolations of past trends (Carter et al., 2001). Normative (or prescriptive) scenarios describe a pre-specified future, either optimistic, pessimistic, or neutral (Alcamo, 2001), and a set of actions that might be required to achieve (or avoid) it. Such scenarios are often developed using an inverse modelling approach, by defining constraints and then diagnosing plausible combinations of the underlying conditions that satisfy those constraints (see Nakićenović et al., 2007).

Storylines. Storylines are qualitative, internally consistent narratives of how the future may evolve. They describe the principal trends in socio-political-economic drivers of change and the relationships between these drivers. Storylines may be stand-alone, but more often underpin quantitative projections of future change that, together with the storyline, constitute a scenario.

Projection. A projection is generally regarded as any description of the future and the pathway leading to it. However, here we define a projection as a model-derived estimate of future conditions related to one element of an integrated system (e.g., an emission, a climate, or an economic growth projection). Projections are generally less comprehensive than scenarios, even if the projected element is influenced by other elements. In addition, projections may be probabilistic, while scenarios do not ascribe likelihoods.

Probabilistic futures. Futures with ascribed likelihoods are probabilistic. The degree to which the future is characterised in probabilistic terms can vary widely. For example, conditional probabilistic futures are subject to specific and stated assumptions about how underlying assumptions are to be represented. Assigned probabilities may also be imprecise or qualitative.

associated with radiative forcing in 2000 of about 0.6°C by 2100 (Meehl et al., 2007). Sea-level rise due to thermal expansion of the oceans responds much more slowly, on a time-scale of millennia; committed sea-level rise is estimated at between 0.3 and 0.8 m above present levels by 2300, assuming concentrations stabilised at A1B levels in 2100 (Meehl et al., 2007). However, these commitment runs are unrealistic because the instantaneous stabilisation of radiative forcing is implausible, implying an unrealistic change in emission rates (see Nakićenović et al., 2007). They are therefore only suitable for setting a lower bound on impacts seen as inevitable (Parry et al., 1998).

2.4.3 Sensitivity analysis

Sensitivity analysis (see Box 2.1) is commonly applied in many model-based CCIAV studies to investigate the behaviour of a system, assuming arbitrary, often regularly spaced, adjustments in important driving variables. It has become a standard technique in assessing sensitivity to climatic variations, enabling the construction of impact response surfaces over multi-variate climate space (e.g., van Minnen et al., 2000; Miller et al., 2003). Response surfaces are increasingly constructed in combination with probabilistic representations of future climate to assess risk of impact (see Section 2.4.8). Sensitivity analysis sampling uncertainties in emissions, natural climate variability, climate change projections, and climate impacts has been used to evaluate the robustness of proposed adaptation measures for water resource management by Dessai (2005). Sensitivity analysis has also been used as a device for studying land-use change, by applying arbitrary adjustments to areas, such as +10% forest, −10% cropland, where these area changes are either spatially explicit (Shackley and Deanwood, 2003) or not (Ott and Uhlenbrook, 2004; van Beek and van Asch, 2004; Vaze et al., 2004).

2.4.4 Analogues

Temporal and spatial analogues are applied in a range of CCIAV studies. The most common of recently reported temporal analogues are historical extreme weather events. These types of event may recur more frequently under anthropogenic climate change, requiring some form of adaptation measure. The suitability of a given climate condition for use as an analogue requires specialist judgement of its utility (i.e., how well it represents the key weather variables affecting vulnerability) and its meteorological plausibility (i.e., how well it replicates anticipated future climate conditions). Examples of extreme events judged likely or very likely by the end of the century (see Table 2.2) that might serve as analogues include the European 2003 heatwave (see Chapter 12, Section 12.6.1) and flooding events related to intense summer precipitation in Bangladesh (Mirza, 2003a) and Norway (Næss et al., 2005). Other extreme events suggested as potential analogues, but about which the likelihood of future changes is poorly known (Christensen et al., 2007a), include El Niño-Southern Oscillation (ENSO)-related events (Glantz, 2001; Heslop-Thomas et al., 2006) and intense precipitation and flooding events in central Europe (Kundzewicz et al., 2005). Note also that the suitability of such analogue events should normally be considered along with information on accompanying changes in mean climate, which may ease or exacerbate vulnerability to extreme events.

Spatial analogues have also been applied in CCIAV analysis. For example, model-simulated climates for 2071 to 2100 have been analysed for selected European cities (Hallegatte et al., 2007). Model grid boxes in Europe showing the closest match between their present-day mean temperatures and seasonal precipitation and those projected for the cities in the future were identified as spatial analogues. These 'displaced' cities were then used as a heuristic device for analysing economic impacts and adaptation needs under a changing climate. A related approach is to seek projected climates (e.g., using climate model simulations) that have no present-day climatic analogues on Earth ('novel' climates) or regions where present-day climates are no longer to be found in the future ('disappearing' climates: see Ohlemüller et al., 2006; Williams et al., 2007). Results from such studies have been linked to risks to ecological systems and biodiversity.

2.4.5 Storylines

Storylines for CCIAV studies (see Box 2.1) are increasingly adopting a multi-sectoral and multi-stressor approach (Holman et al., 2005a, b) over multiple scales (Alcamo et al., 2005; Lebel et al., 2005; Kok et al., 2006a; Westhoek et al., 2006b) and are utilising stakeholder elicitation (Kok et al., 2006b). As they have become more comprehensive, the increased complexity and richness of the information they contain has aided the interpretation of adaptive capacity and vulnerability (Metzger et al., 2006). Storyline development is also subjective, so more comprehensive storylines can have alternative, but equally plausible, interpretations (Rounsevell et al., 2006). The concept of a 'region', for example, may be interpreted within a storyline in different ways – as world regions, nation states, or sub-national administrative units. This may have profound implications for how storylines are characterised at a local scale, limiting their reproducibility and credibility (Abildtrup et al., 2006). The alternative is to link a locally sourced storyline, regarded as credible at that scale, to a global scenario.

Storylines can be an endpoint in their own right (e.g., Rotmans et al., 2000), but often provide the basis for quantitative scenarios. In the storyline and simulation (SAS) approach (Alcamo, 2001), quantification is undertaken with models for which the input parameters are estimated through interpretation of the qualitative storylines. Parameter estimation is often subjective, using expert judgement, although more objective methods, such as pairwise comparison, have been used to improve internal consistency (Abildtrup et al., 2006). Analogues and stakeholder elicitation have also been used to estimate model parameters (e.g., Rotmans et al., 2000; Berger and Bolte, 2004; Kok et al., 2006a). Moreover, participatory approaches are important in reconciling long-term scenarios with the short-term, policy-driven requirements of stakeholders (Velázquez et al., 2001; Shackley and Deanwood, 2003; Lebel et al., 2005).

2.4.6 Scenarios

Advances in scenario development since the TAR address issues of consistency and comparability between global drivers

of change, and regional scenarios required for CCIAV assessment (for reviews, see Berkhout et al., 2002; Carter et al., 2004; Parson et al., 2006). Numerous methods of downscaling from global to sub-global scale are emerging, some relying on the narrative storylines underpinning the global scenarios.

At the time of the TAR, most CCIAV studies utilised climate scenarios (many based on the IS92 emissions scenarios), but very few applied contemporaneous scenarios of socio-economic, land-use, or other environmental changes. Those that did used a range of sources to develop them. The IPCC Special Report on Emissions Scenarios (SRES: see Nakićenović et al., 2000) presented the opportunity to construct a range of mutually consistent climate and non-climatic scenarios. Originally developed to provide scenarios of future GHG emissions, the SRES scenarios are also accompanied by storylines of social, economic, and technological development that can be used in CCIAV studies (Box 2.2).

There has been an increasing uptake of the SRES scenarios since the TAR, and a substantial number of the impact studies assessed in this volume that employed future characterisations made use of them.[7] For this reason, these scenarios are highlighted in a series of boxed examples throughout Section 2.4. For some other studies, especially empirical analyses of adaptation and vulnerability, the scenarios were of limited relevance and were not adopted.

While the SRES scenarios were specifically developed to address climate change, several other major global scenario-building exercises have been designed to explore uncertainties and risks related to global environmental change. Recent examples include: the Millennium Ecosystem Assessment scenarios to 2100 (MA: see Alcamo et al., 2005), Global Scenarios Group scenarios to 2050 (GSG: see Raskin et al., 2002), and Global Environment Outlook scenarios to 2032 (GEO-3: see UNEP 2002). These exercises were reviewed and compared by Raskin et al. (2005) and Westhoek et al. (2006a), who observed that many applied similar assumptions to those used in the SRES scenarios, in some cases employing the same models to quantify the main drivers and indicators. All the exercises adopted the storyline and simulation (SAS) approach (introduced in Section 2.4.5). Furthermore, all contain important features that can be useful for CCIAV studies; with some exercises (e.g., MA and GEO-3) going one step further than the original SRES scenarios by not only describing possible emissions under differing socio-economic pathways but also including imaginable outcomes for climate variables and their impact on ecological and social systems. This helps to illustrate risks and possible response strategies to deal with possible impacts.

Five classes of scenarios relevant to CCIAV analysis were distinguished in the TAR: climate, socio-economic, land-use and land-cover, other environmental (mainly atmospheric composition), and sea-level scenarios (Carter et al., 2001). The following sections describe recent progress in each of these classes and in four additional categories: technology scenarios, adaptation scenarios, mitigation scenarios, and scenario integration.

Box 2.2. The SRES global storylines and scenarios

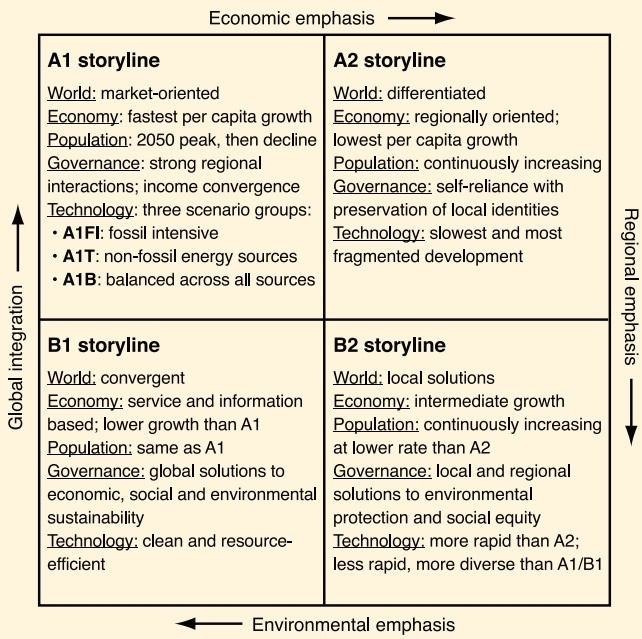


Figure 2.5. *Summary characteristics of the four SRES storylines (based on Nakićenović et al., 2000).*

SRES presented four narrative storylines, labelled A1, A2, B1, and B2, describing the relationships between the forces driving GHG and aerosol emissions and their evolution during the 21st century for large world regions and globally (Figure 2.5). Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways and result in different levels of GHG emissions. The storylines assume that no specific climate policies are implemented, and thus form a baseline against which narratives with specific mitigation and adaptation measures can be compared.

The SRES storylines formed the basis for the development of quantitative scenarios using various numerical models that were presented in the TAR. Emissions scenarios were converted to projections of atmospheric GHG and aerosol concentrations, radiative forcing of the climate, effects on regional climate, and climatic effects on global sea level (IPCC, 2001a). However, little regional detail of these projections and no CCIAV studies that made use of them were available for the TAR. Many CCIAV studies have applied SRES-based scenarios since then, and some of these are described in Boxes 2.3 to 2.7 to illustrate different scenario types.

[7] Of 17 chapters surveyed, SRES-based scenarios were used by the majority of impact studies in 5 chapters, and by a large minority in 11 chapters. The most common usage is for climate scenarios, while examples of studies employing SRES-based socio-economic, environmental, or land-use scenarios comprise a small but growing number. The remaining impact studies used either earlier IPCC scenarios (e.g., IS92) or characterisations derived from other sources.

2.4.6.1 Climate scenarios

The most recent climate projection methods and results are extensively discussed in the WG I volume (especially Christensen et al., 2007a; Meehl et al., 2007), and most of these were not available to the CCIAV studies assessed in this volume. Box 2.3 compares recent climate projections from Atmosphere-Ocean General Circulation Models (AOGCMs) with the earlier projections relied on throughout this volume. While AOGCMs are the most common source of regional climate scenarios, other methods and tools are also applied in specific CCIAV studies. Numerous regionalisation techniques[8] have been employed to obtain high-resolution, SRES-based climate scenarios, nearly always using low-resolution General Circulation Model (GCM) outputs as a starting point. Some of these methods are also used to develop scenarios of extreme weather events.

Scenarios from high-resolution models

The development and application of scenarios from high-resolution regional climate models and global atmospheric models (time-slices) since the TAR confirms that improved resolution allows a more realistic representation of the response of climate to fine-scale topographic features (e.g., lakes, mountains, coastlines). Impact models will often produce different results utilising high-resolution scenarios compared with direct GCM outputs (e.g., Arnell et al., 2003; Mearns et al., 2003; Stone et al., 2003; Leung et al., 2004; Wood et al., 2004). However, most regional model experiments still rely on only one driving AOGCM and scenarios are usually available from only one or two regional climate models (RCMs).

More elaborate and extensive modelling designs have facilitated the exploration of multiple uncertainties (across different RCMs, AOGCMs, and emissions scenarios) and how those uncertainties affect impacts. The PRUDENCE project in Europe produced multiple RCM simulations based on the ECHAM/OPYC AOGCM and HadAM3H AGCM simulations for two different emissions scenarios (Christensen et al., 2007b). Uncertainties due to the spatial scale of the scenarios and stemming from the application of different RCMs versus different GCMs (including models not used for regionalisation) were elaborated on in a range of impact studies (e.g., Ekstrom et al., 2007; Fronzek and Carter, 2007; Hingray et al., 2007; Graham et al., 2007; Olesen et al., 2007). For example, Olesen et al. (2007) found that the variation in simulated agricultural impacts was smaller across scenarios from RCMs nested in a single GCM than it was across different GCMs or across the different emissions scenarios.

The construction of higher-resolution scenarios (now often finer than 50 km), has encouraged new types of impact studies. For example, studies examining the combined impacts of increased heat stress and air pollution are now more feasible because the resolution of regional climate models is converging with that of air-quality models (e.g., Hogrefe et al., 2004). Furthermore, scenarios developed from RCMs (e.g., UKMO, 2001) are now being used in many more regions of the world, particularly the developing world (e.g., Arnell et al., 2003; Gao et al., 2003; Anyah and Semazzi, 2004; Government of India, 2004; Rupa Kumar et al., 2006). Results of these regional modelling experiments are reported in Christensen et al. (2007a).

Statistical downscaling (SD)

Much additional work has been produced since the TAR using methods of statistical downscaling (SD) for climate scenario generation (Wilby et al., 2004b; also see Christensen et al., 2007a). Various SD techniques have been used in downscaling directly to (physically-based) impacts and to a greater variety of climate variables than previously (e.g., wind speed), including extremes of variables. For example, Wang et al. (2004) and Caires and Sterl (2005) have developed extreme value models for projecting changes in wave height.

While statistical downscaling has mostly been applied for single locations, Hewitson (2003) developed empirical downscaling for point-scale precipitation at numerous sites and on a 0.1°-resolution grid over Africa. Finally, the wider availability of statistical downscaling tools is being reflected in wider application; for example, the Statistical Downscaling Model (SDSM) tool of Wilby et al. (2002), which has been used to produce scenarios for the River Thames basin (Wilby and Harris, 2006). Statistical downscaling does have some limitations; for example, it cannot take account of small-scale processes with strong time-scale dependencies (e.g., land-cover change). See Christensen et al. (2007a) for a complete discussion of the strengths and weaknesses of both statistical and dynamical downscaling.

Scenarios of extreme weather events

The improved availability of high-resolution scenarios has facilitated new studies of event-driven impacts (e.g., fire risk – Moriondo et al., 2006; low-temperature impacts on boreal forests – Jönsson et al., 2004). Projected changes in extreme weather events have been related to projected changes in local mean climate, in the hope that robust relationships could allow the prediction of extremes on the basis of changes in mean climate alone. PRUDENCE RCM outputs showed non-linear relationships between mean maximum temperature and indices of drought and heatwave (Good et al., 2006), while changes in maximum 1-day and 5-day precipitation amounts were systematically enhanced relative to changes in seasonal mean precipitation across many regions of Europe (Beniston et al., 2007). In a comprehensive review (citing over 200 papers) of the options available for developing scenarios of weather extremes for use in Integrated Assessment Models (IAMs), Goodess et al. (2003) list the advantages and disadvantages of applying direct GCM outputs, direct RCM outputs, and SD techniques. Streams of daily data are the outputs most commonly used from these sources, and these may pose computational difficulties for assessing impacts in IAMs (which

[8] Defined in the TAR as "techniques developed with the goal of enhancing the regional information provided by coupled AOGCMs and providing fine-scale climate information" (Giorgi et al., 2001).

Box 2.3. SRES-based climate scenarios assumed in this report

Not all of the impact studies reported in this assessment employed SRES-based climate scenarios. Earlier scenarios are described in previous IPCC reports (IPCC, 1992, 1996; Greco et al., 1994). The remaining discussion focuses on SRES-based climate projections, which are applied in most CCIAV studies currently undertaken.

In recent years, many simulations of the global climate response to the SRES emission scenarios have been completed with AOGCMs, also providing regional detail on projected climate. Early AOGCM runs (labelled 'pre-TAR') were reported in the TAR (Cubasch et al., 2001) and are available from the IPCC DDC. Many have been adopted in CCIAV studies reported in this volume. A new generation of AOGCMs, some incorporating improved representations of climate system processes and land surface forcing, are now utilising the SRES scenarios in addition to other emissions scenarios of relevance for impacts and policy. The new models and their projections are evaluated in WG I (Christensen et al., 2007a; Meehl et al., 2007; Randall et al., 2007) and compared with the pre-TAR results below. Projections of global mean annual temperature change for SRES and CO_2-stabilisation profiles are presented in Box 2.8.

Pre-TAR AOGCM results held at the DDC were included in a model intercomparison across the four SRES emissions scenarios (B1, B2, A2, and A1FI) of seasonal mean temperature and precipitation change for thirty-two world regions (Ruosteenoja et al., 2003).[9] The inter-model range of changes by the end of the 21st century is summarised in Figure 2.6 for the A2 scenario, expressed as rates of change per century. Recent A2 projections, reported in WG I, are also shown for the same regions for comparison.

Almost all model-simulated temperature changes, but fewer precipitation changes, were statistically significant relative to 95% confidence intervals calculated from 1,000-year unforced coupled AOGCM simulations (Ruosteenoja et al., 2003; see also Figure 2.6). Modelled surface air temperature increases in all regions and seasons, with most land areas warming more rapidly than the global average (Giorgi et al., 2001; Ruosteenoja et al., 2003). Warming is especially pronounced in high northern-latitude regions in the boreal winter and in southern Europe and parts of central and northern Asia in the boreal summer. Warming is less than the global average in southern parts of Asia and South America, Southern Ocean areas (containing many small islands) and the North Atlantic (Figure 2.6a).

For precipitation, both positive and negative changes are projected, but a regional precipitation increase is more common than a decrease. All models simulate higher precipitation at high latitudes in both seasons, in northern mid-latitude regions in boreal winter, and enhanced monsoon precipitation for southern and eastern Asia in boreal summer. Models also agree on precipitation declines in Central America, southern Africa and southern Europe in certain seasons (Giorgi et al., 2001; Ruosteenoja et al., 2003; see also Figure 2.6b).

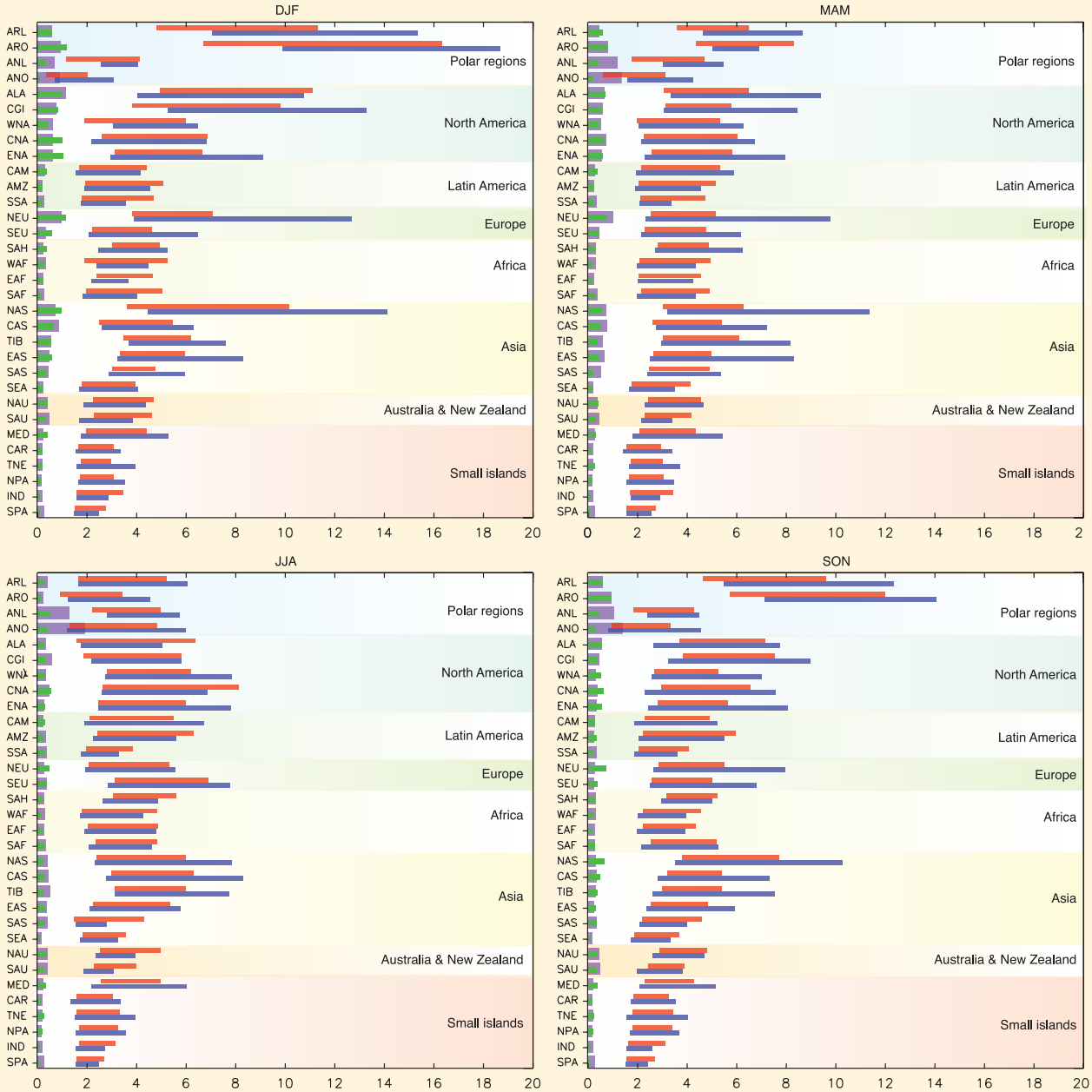
Comparing TAR projections to recent projections

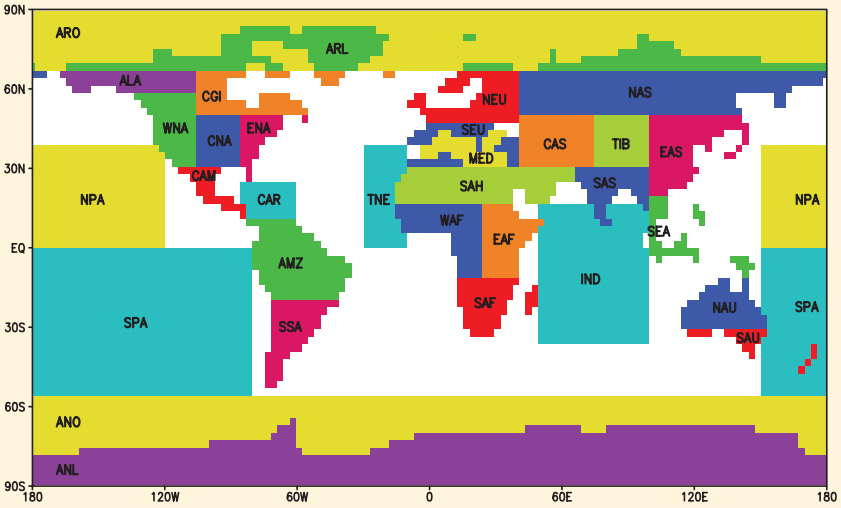
The WG I report provides an extensive intercomparison of recent regional projections from AOGCMs (Christensen et al., 2007a; Meehl et al., 2007), focusing on those assuming the SRES A1B emissions scenario, for which the greatest number of simulations (21) were available. It also contains numerous maps of projected regional climate change. In summary:

- The basic pattern of projected warming is little changed from previous assessments.
- The projected rate of warming by 2030 is insensitive to the choice of SRES scenarios.
- Averaged across the AOGCMs analysed, the global mean warming by 2090-2099 relative to 1980-1999 is projected to be 1.8, 2.8, and 3.4°C for the B1, A1B, and A2 scenarios, respectively. Local temperature responses in nearly all regions closely follow the ratio of global temperature response.
- Model-average mean local precipitation responses also roughly scale with the global mean temperature response across the emissions scenarios, though not as well as for temperature.
- The inter-model range of seasonal warming for the A2 scenario is smaller than the pre-TAR range at 2100 in most regions, despite the larger number of models (compare the red and blue bars in Figure 2.6a)
- The direction and magnitude of seasonal precipitation changes for the A2 scenario are comparable to the pre-TAR changes in most regions, while inter-model ranges are wider in some regions/seasons and narrower in others (Figure 2.6b).
- Confidence in regional projections is higher than in the TAR for most regions for temperature and for some regions for precipitation.

[9] Scatter diagrams are downloadable at: http://www.ipcc-data.org/sres/scatter_plots/scatterplots_region.html

(a) Temperature increase (°C/century)





(b) Precipitation change (%/century)

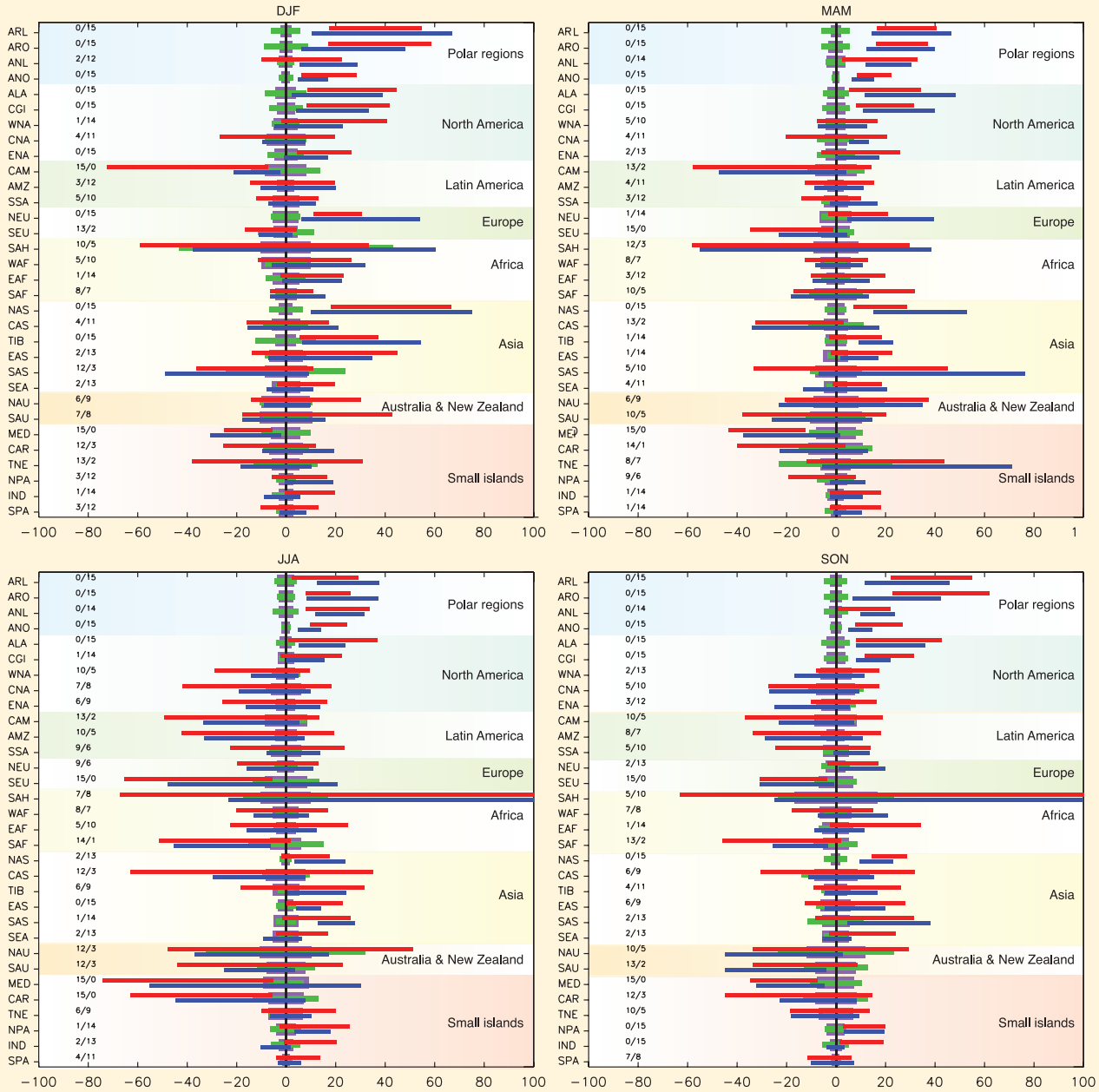


Figure 2.6. *AOGCM projections of seasonal changes in (a) mean temperature (previous page) and (b) precipitation up to the end of the 21st century for 32 world regions. For each region two ranges between minimum and maximum are shown. Red bar: range from 15 recent AOGCM simulations for the A2 emissions scenario (data analysed for Christensen et al., 2007a). Blue bar: range from 7 pre-TAR AOGCMs for the A2 emissions scenario (Ruosteenoja et al., 2003). Seasons: DJF (December–February); MAM (March–May); JJA (June–August); SON (September–November). Regional definitions, plotted on the ECHAM4 model grid (resolution 2.8 × 2.8°), are shown on the inset map (Ruosteenoja et al., 2003). Pre-TAR changes were originally computed for 1961-1990 to 2070-2099 and recent changes for 1979-1998 to 2079-2098, and are converted here to rates per century for comparison; 95% confidence limits on modelled 30-year natural variability are also shown based on millennial AOGCM control simulations with HadCM3 (mauve) and CGCM2 (green) for constant forcing (Ruosteenoja et al., 2003). Numbers on precipitation plots show the number of recent A2 runs giving negative/positive precipitation change. Percentage changes for the SAH region (Sahara) exceed 100% in JJA and SON due to low present-day precipitation.*
Key for (a) and (b):

- range of changes from seven pre-TAR AOGCMs for the A2 emissions scenario
- range of changes from 15 recent AOGCM simulations for the A2 emissions scenario
- 95% confidence limits on modelled 30-year natural variability based on HadCM3 millennial control simulation
- 95% confidence limits on modelled 30-year natural variability based on CGCM2 millennial control simulation

commonly consider only large-scale, period-averaged climate), requiring scenario analysis to be carried out offline. Interpretation of impacts then becomes problematic, requiring a method of relating the large-scale climate change represented in the IAM to the impacts of associated changes in weather extremes modelled offline. Goodess et al. suggest that a more direct, but untested, approach could be to construct conditional damage functions (cdfs), by identifying the statistical relationships between the extreme events themselves (causing damage) and large-scale predictor variables. Box 2.4 offers a global overview of observed and projected changes in extreme weather events.

2.4.6.2 Scenarios of atmospheric composition

Projections of atmospheric composition account for the concurrent effects of air pollution and climate change, which can be important for human health, agriculture and ecosystems. Scenarios of CO_2 concentration ([CO_2]) are needed in some CCIAV studies, as elevated [CO_2] can affect the acidity of the oceans (IPCC, 2007; Chapter 6, Section 6.3.2) and both the growth and water use of many terrestrial plants (Chapter 4, Section 4.4.1; Chapter 5, Section 5.4.1), with possible feedbacks on regional hydrology (Gedney et al., 2006). CO_2 is well mixed in the atmosphere, so concentrations at a single observing site will usually suffice to represent global conditions. Observed [CO_2] in

Box 2.4. SRES-based projections of climate variability and extremes

Possible changes in variability and the frequency/severity of extreme events are critical to undertaking realistic CCIAV assessments. Past trends in extreme weather and climate events, their attribution to human influence, and projected (SRES-forced) changes have been summarised globally by WG I (IPCC, 2007) and are reproduced in Table 2.2.

Table 2.2. *Recent trends, assessment of human influence on the trend, and projections for extreme weather events for which there is an observed late 20th century trend. Source: IPCC, 2007, Table SPM-2.*

Phenomenon and direction of trend	Likelihood[a] that trend occurred in late 20th century (typically post-1960)	Likelihood[a] of a human contribution to observed trend	Likelihood[a] of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely[b]	Likely[c]	Virtually certain[c]
Warmer and more frequent hot days and nights over most land areas	Very likely[d]	Likely (nights)[c]	Virtually certain[c]
Warm spells/heatwaves. Frequency increases over most land areas	Likely	More likely than not[e]	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not[e]	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in some regions since 1970	More likely than not[e]	Likely
Increased incidence of extreme high sea level (excludes tsunamis)[f]	Likely	More likely than not[e,g]	Likely[h]

Notes:

[a] The assessed likelihood, using expert judgement, of an outcome or a result: Virtually certain >99% probability of occurrence, Extremely likely >95%, Very likely >90%, Likely >66%, More likely than not >50%.

[b] Decreased frequency of cold days and nights (coldest 10%).

[c] Warming of the most extreme days and nights each year.

[d] Increased frequency of hot days and nights (hottest 10%).

[e] Magnitude of anthropogenic contributions not assessed. Attribution for these phenomena based on expert judgement rather than formal attribution studies.

[f] Extreme high sea level depends on average sea level and on regional weather systems. It is defined here as the highest 1% of hourly values of observed sea level at a station for a given reference period.

[g] Changes in observed extreme high sea level closely follow the changes in average sea level. It is very likely that anthropogenic activity contributed to a rise in average sea level.

[h] In all scenarios, the projected global average sea level at 2100 is higher than in the reference period. The effect of changes in regional weather systems on sea-level extremes has not been assessed.

2005 was about 379 ppm (Forster et al., 2007) and was projected in the TAR using the Bern-CC model to rise by 2100 to reference, low, and high estimates for the SRES marker scenarios of B1: 540 [486 to 681], A1T: 575 [506 to 735], B2: 611[544 to 769], A1B: 703 [617 to 918], A2: 836 [735 to 1080], and A1FI: 958 [824 to 1248] ppm (Appendix II in IPCC, 2001a). Values similar to these reference levels are commonly adopted in SRES-based impact studies; for example, Arnell et al. (2004) employed levels assumed in HadCM3 AOGCM climate simulations, and Schröter et al. (2005b) used levels generated by the IMAGE-2 integrated assessment model. However, recent simulations with coupled carbon cycle models indicate an enhanced rise in [CO_2] for a given emissions scenario, due to feedbacks from changing climate on the carbon cycle, suggesting that the TAR reference estimates are conservative (Meehl et al., 2007).

Elevated levels of ground-level ozone (O_3) are toxic to many plants (see Chapter 5, Box 5.2) and are strongly implicated in a range of respiratory diseases (Chapter 8, Section 8.2.6). Increased atmospheric concentrations of sulphur dioxide are detrimental to plants, and wet and dry deposition of atmospheric sulphur and nitrogen can lead to soil and surface water acidification, while nitrogen deposition can also serve as a plant fertiliser (Carter et al., 2001; see also Chapter 4, Section 4.4.1; Chapter 5, Section 5.4.3.1). Projections with global atmospheric chemistry models for the high-emissions SRES A2 scenario indicate that global mean tropospheric O_3 concentrations could increase by 20 to 25% between 2015 and 2050, and by 40 to 60% by 2100, primarily as a result of emissions of NO_x, CH_4, CO_2, and compounds from fossil fuel combustion (Meehl et al., 2007). Stricter air pollution standards, already being implemented in many regions, would reduce, and could even reverse, this projected increase (Meehl et al., 2007). Similarly, the range of recent scenarios of global sulphur and NO_x emissions that account for new abatement policies has shifted downwards compared with the SRES emissions scenarios (Smith et al., 2005; Nakićenović et al., 2007).

For the purposes of CCIAV assessment, global projections of pollution are only indicative of local conditions. Levels are highly variable in space and time, with the highest values typically occurring over industrial regions and large cities. Although projections are produced routinely for some regions in order to support air pollution policy using high-resolution atmospheric transport models (e.g., Syri et al., 2004), few models have been run assuming an altered climate, and simulations commonly assume emissions scenarios developed for air pollution policy rather than climate policy (see Alcamo et al., 2002; Nakićenović et al., 2007). Exceptions include regionally explicit global scenarios of nitrogen deposition on a 0.5° latitude × 0.5° longitude grid for studying biodiversity loss in the Millennium Ecosystem Assessment (Alcamo et al., 2005) and simulations based on SRES emissions for sulphur and nitrogen over Europe (Mayerhofer et al., 2002) and Finland (Syri et al., 2004), and for surface ozone in Finland (Laurila et al., 2004).

2.4.6.3 Sea-level scenarios

A principal impact projected under global warming is sea-level rise. Some basic techniques for developing sea-level scenarios were described in the TAR (Carter et al., 2001). Since the TAR, methodological refinements now account more effectively for regional and local factors affecting sea level and, in so doing, produce scenarios that are more relevant for planning purposes. Two main types of scenario are distinguished here: regional sea level and storm surges. A third type, characterising abrupt sea-level rise, is described in Section 2.4.7. Analogue approaches have also been reported (e.g., Arenstam Gibbons and Nicholls, 2006). More details on sea level and sea-level scenarios can be found in Bindoff et al. (2007), Meehl et

Box 2.5. SRES-based sea-level scenarios

At the global level, simple models representing the expansion of sea water and melting/sliding of land-based ice sheets and glaciers were used in the TAR to obtain estimates of globally averaged mean sea-level rise across the SRES scenarios, yielding a range of 0.09 to 0.88 m by 2100 relative to 1990 (Church et al., 2001). This range has been reassessed by WG I, yielding projections relative to 1980-1999 for the six SRES marker scenarios of B1: 0.18 to 0.38 m, A1T: 0.20 to 0.45 m, B2: 0.20 to 0.43 m, A1B: 0.21 to 0.48 m, A2: 0.23 to 0.51 m, and A1FI: 0.26 to 0.59 m (Meehl et al., 2007). Thermal expansion contributes about 60 to 70% to these estimates. Projections are smaller than given in the TAR, due mainly to improved estimates of ocean heat uptake but also to smaller assessed uncertainties in glacier and ice cap changes. However, uncertainties in carbon cycle feedbacks, ice flow processes, and recent observed ice discharge rates are not accounted for due to insufficient understanding (Meehl et al., 2007).

A number of studies have made use of the TAR sea-level scenarios. In a global study of coastal flooding and wetland loss, Nicholls (2004) used global mean sea-level rise estimates for the four SRES storylines by 2025, 2055, and 2085. These were consistent with climate scenarios used in parallel studies (see Section 2.4.6.4). Two subsidence rates were also applied to obtain relative sea level rise in countries already experiencing coastal subsidence. The United Kingdom Climate Impacts Programme adopted the TAR global mean sea-level rise estimates in national scenarios out to the 2080s. Scenarios of high water levels were also developed by combining mean sea-level changes with estimates of future storminess, using a storm surge model (Hulme et al., 2002). SRES-based sea-level scenarios accounting for global mean sea level, local land uplift, and estimates of the water balance of the Baltic Sea were estimated for the Finnish coast up to 2100 by Johansson et al. (2004), along with calculations of uncertainties and extreme high water levels.

al. (2007) and Chapter 6 of this volume. Examples of SRES-based sea-level scenarios are provided in Box 2.5.

Regional sea-level scenarios

Sea level does not change uniformly across the world under a changing climate, due to variation in ocean density and circulation changes. Moreover, long-term, non-climate-related trends, usually associated with vertical land movements, may affect relative sea level. To account for regional variations, Hulme et al. (2002) recommend applying the range of global-mean scenarios ±50% change. Alternative approaches utilise scenario generators. The Dynamic Interactive Vulnerability Assessment (DIVA) model computes relative sea-level rise scenarios using either global-mean or regional patterns of sea-level rise scenarios from CLIMBER-2, a climate model of intermediate complexity (Petoukhov et al., 2000; Ganopolski et al., 2001). CLIMsystems (2005) have developed a software tool that rapidly generates place-based future scenarios of sea-level change during the 21st century, accounting for global, regional, and local factors. Spatial patterns of sea-level rise due to thermal expansion and ocean processes from AOGCM simulations are combined with global-mean sea-level rise projections from simple climate models through the pattern-scaling technique (Santer et al., 1990). Users can specify a value for the local sea-level trends to account for local land movements.

Storm surge scenarios

In many locations, the risk of extreme sea levels is poorly characterised even under present-day climatic conditions, due to sparse tide gauge networks and relatively short records of high measurement frequency. Where such records do exist, detectable trends are highly dependent on local conditions (Woodworth and Blackman, 2004). Box 6.2 in Chapter 6 summarises several recent studies that employ extreme water level scenarios. Two methods were employed to develop these scenarios, one using a combination of stochastic sampling and dynamic modelling, the other using downscaled regional climate projections from global climate models to drive barotropic storm surge models (Lowe and Gregory, 2005).

2.4.6.4 Socio-economic scenarios

Socio-economic changes are key drivers of projected changes in future emissions and climate, and are also key determinants of most climate change impacts, potential adaptations and vulnerability (Malone and La Rovere, 2005). Furthermore, they also influence the policy options available for responding to climate change. CCIAV studies increasingly include scenarios of changing socio-economic conditions, which can substantially alter assessments of the effects of future climate change (Parry, 2004; Goklany, 2005; Hamilton et al., 2005; Schröter et al., 2005b; Alcamo et al., 2006a). Typically these assessments need information at the sub-national level, whereas many scenarios are developed at a broader scale, requiring downscaling of aggregate socio-economic scenario information.

Guidelines for the analysis of current and projected socio-economic conditions are part of the UNDP Adaptation Policy Framework (Malone and La Rovere, 2005). They advocate the use of indicators to characterise socio-economic conditions and prospects. Five categories of indicators are suggested: demographic, economic, natural resource use, governance and policy, and cultural. Most recent studies have focused on the first two of these.

The sensitivity of climate change effects to socio-economic conditions was highlighted by a series of multi-sector impact assessments (Parry et al., 1999, 2001; Parry, 2004; see Table 2.3). Two of these assessments relied on only a single representation of future socio-economic conditions (IS92a), comparing effects of mitigated versus unmitigated climate change (Arnell et al., 2002; Nicholls and Lowe, 2004). The third set considered four alternative SRES-based development pathways (see Box 2.6), finding that these assumptions are often a stronger determinant of impacts than climate change itself (Arnell, 2004; Arnell et al., 2004; Levy et al., 2004; Nicholls, 2004; Parry et al., 2004; van Lieshout et al., 2004). Furthermore, climate impacts can themselves depend on the development pathway, emphasising the limited value of impact assessments of human systems that overlook possible socio-economic changes.

The advantages of being able to link regional socio-economic futures directly to global scenarios and storylines are now being recognised. For example, the SRES scenarios have been used as a basis for developing storylines and quantitative scenarios at national (Carter et al., 2004, 2005; van Vuuren et al., 2007) and sub-national (Berkhout et al., 2002; Shackley and Deanwood, 2003; Solecki and Oliveri, 2004; Heslop-Thomas et al., 2006) scales. In contrast, most regional studies in the AIACC (Assessments of Impacts and Adaptations to Climate Change in Multiple Regions and Sectors) research programme adopted a participatory, sometimes ad hoc, approach to socio-economic scenario development, utilising current trends in key socio-economic indicators and stakeholder consultation (e.g., Heslop-Thomas et al., 2006; Pulhin et al., 2006).

Methods for downscaling quantitative socio-economic information have focused on population and gross domestic product (GDP). The downscaling of population growth has evolved beyond simple initial exercises that made the sometimes unrealistic assumption that rates of population change are uniform over an entire world region (Gaffin et al., 2004). New techniques account for differing demographic conditions and outlooks at the national level (Grübler et al., 2006; van Vuuren et al., 2007). New methods of downscaling to the sub-national level include simple rules for preferential growth in coastal areas (Nicholls, 2004), extrapolation of recent trends at the local area level (Hachadoorian et al., 2007), and algorithms leading to preferential growth in urban areas (Grübler et al., 2006; Reginster and Rounsevell, 2006).

Downscaling methods for GDP are also evolving. The first downscaled SRES GDP assumptions applied regional growth rates uniformly to all countries within the region (Gaffin et al., 2004) without accounting for country-specific differences in initial conditions and growth expectations. New methods assume various degrees of convergence across countries, depending on the scenario; a technique that avoids implausibly high growth for rich countries in developing regions (Grübler et al., 2006; van Vuuren et al., 2007). GDP scenarios have also been downscaled to the sub-national level, either by assuming constant shares of GDP in each grid cell (Gaffin et al., 2004; van Vuuren et al., 2007) or through algorithms that differentiate income across urban and rural areas (Grübler et al., 2006).

Table 2.3. *Key features of scenarios underlying three global-scale, multi-sector assessments: [a] Parry et al. (1999); [b] Arnell et al. (2002); [c] Parry (2004).*

	Impacts of unmitigated emissions [a]	Impacts of stabilisation of CO_2 concentrations [b]	Impacts of SRES emissions scenarios [c]
Emissions scenarios	IS92a (1% per increase in CO_2-equivalent concentrations per year from 1990)	Stabilisation at 750 and 550 ppm	Four SRES emissions scenarios: A1FI, A2, B1, and B2
Climate scenarios (AOGCM-based)	Derived from four ensemble HadCM2 simulations and one HadCM3 simulation forced with IS92a emissions scenarios	Derived from HadCM2 experiments assuming stabilisation at 550 and 750 ppm; comparison with IS92a	Derived from HadCM3 ensemble experiments (number of runs in brackets): A1FI (1), A2 (3), B1 (1), and B2 (2)
Socio-economic scenarios	IS92a-consistent GDP[a] and population projections	IS92a-consistent GDP[a] and population projections	SRES-based socio-economic projections

[a] GDP = Gross Domestic Product.

2.4.6.5 Land-use scenarios

Many CCIAV studies need to account for future changes in land use and land cover. This is especially important for regional studies of agriculture and water resources (Barlage et al., 2002; Klöcking et al., 2003), forestry (Bhadwal and Singh, 2002), and ecosystems (Bennett et al., 2003; Dirnbock et al., 2003; Zebisch et al., 2004; Cumming et al., 2005), but also has a large influence on regional patterns of demography and economic activity (Geurs and van Eck, 2003) and associated problems of environmental degradation (Yang et al., 2003) and pollution (Bathurst et al., 2005). Land-use and land-cover change scenarios have also been used to analyse feedbacks to the climate system (DeFries et al., 2002; Leemans et al., 2002; Maynard and Royer, 2004) and sources and sinks of GHGs (Fearnside, 2000; El-Fadel et al., 2002; Sands and Leimbach, 2003).

The TAR concluded that the use of Integrated Assessment Models (IAMs) was the most appropriate method for developing land-use change scenarios, and they continue to be the only available tool for global-scale studies. Since the TAR, however, a number of new models have emerged that provide fresh insights into regional land-use change. These regional models

Box 2.6. SRES-based socio-economic characterisations

SRES provides socio-economic information in the form of storylines and quantitative assumptions on population, gross domestic product (GDP), and rates of technological progress for four large world regions (OECD-1990, Reforming Economies, Africa + Latin America + Middle East, and Asia). Since the TAR, new information on several of the SRES driving forces has been published (see also the discussion in Nakićenović et al., 2007). For example, the range of global population size projections made by major demographic institutions has reduced by about 1–2 billion since the preparation of SRES (van Vuuren and O'Neill, 2006). Nevertheless, most of the population assumptions used in SRES still lie within the range of current projections, with the exception of some regions of the A2 scenario which now lie somewhat above it (van Vuuren and O'Neill, 2006). Researchers are now producing alternative interpretations of SRES population assumptions or new projections for use in climate change studies (Hilderink, 2004; O'Neill, 2004; Fisher et al., 2006; Grübler et al., 2006).

SRES GDP growth assumptions for the ALM region (Africa, Latin America and Middle East) are generally higher than those of more recent projections, particularly for the A1 and B1 scenarios (van Vuuren and O'Neill, 2006). The SRES GDP assumptions are generally consistent with recent projections for other regions, including fast-growing regions in Asia and, given the small share of the ALM region in global GDP, for the world as a whole.

For international comparison, economic data must be converted into a common unit; the most common choice is US$ based on market exchange rates (MER). Purchasing-power-parity (PPP) estimates, in which a correction is made for differences in price levels among countries, are considered a better alternative for comparing income levels across regions and countries. Most models and economic projections, however, use MER-based estimates, partly due to a lack of consistent PPP-based data sets. It has been suggested that the use of MER-based data results in inflated economic growth projections (Castles and Henderson, 2003). In an ongoing debate, some researchers argue that PPP is indeed a better measure and that its use will, in the context of scenarios of economic convergence, lead to lower economic growth and emissions paths for developing countries. Others argue that consistent use of either PPP- or MER-based data and projections will lead to, at most, only small changes in emissions. This debate is summarised by Nakićenović et al. (2007), who conclude that the impact on emissions of the use of alternative GDP metrics is likely to be small, but indicating alternative positions as well (van Vuuren and Alfsen, 2006). The use of these alternative measures is also likely to affect CCIAV assessments (Tol, 2006), especially where vulnerability and adaptive capacity are related to access to locally traded goods and services.

can generate very different land-use change scenarios from those generated by IAMs (Busch, 2006), often with opposing directions of change. However, the need to define outside influences on land use in regional-scale models, such as global trade, remains a challenge (e.g., Sands and Edmonds, 2005; Alcamo et al., 2006b), so IAMs have an important role to play in characterising the global boundary conditions for regional land-use change assessments (van Meijl et al., 2006).

Regional-scale land-use models often adopt a two-phase (nested scale) approach with an assessment of aggregate quantities of land use for the entire region followed by 'downscaling' procedures to create regional land-use patterns (see Box 2.7 for examples). Aggregate quantities are often based on IAMs or economic models such as General Equilibrium Models (van Meijl et al., 2006) or input-output approaches (Fischer and Sun, 2001). Methods of downscaling vary considerably and include proportional approaches to estimate regional from global scenarios (Arnell et al., 2004), regional-scale economic models (Fischer and Sun, 2001), spatial allocation procedures based on rules (Rounsevell et al., 2006), micro-simulation with cellular automata (de Nijs et al., 2004; Solecki and Oliveri, 2004), linear programming models (Holman et al., 2005a, b), and empirical-statistical techniques (de Koning et al., 1999; Verburg et al., 2002, 2006). In addressing climate change impacts on land use, Agent-Based Models (ABMs: see Alcamo et al., 2006b) aim to provide insight into the decision processes and social interactions that underpin adaptation and vulnerability assessment (Acosta-Michlik and Rounsevell, 2005).

Most land-use scenario assessments are based on gradual changes in socio-economic and climatic conditions, although responses to extreme weather events such as Hurricane Mitch in Central America have also been assessed (Kok and Winograd, 2002). Probabilistic approaches are rare, with the exception being the effects of uncertainty in alternative representations of land-use change for hydrological variables (Eckhardt et al., 2003). Not all land-use scenario exercises have addressed the effects of climate change even though they consider time-frames over which a changing climate would be important. This may reflect a perceived lack of sensitivity to climate variables (e.g., studies on urban land use: see Allen and Lu, 2003; Barredo et al., 2003, 2004; Loukopoulos and Scholz, 2004; Reginster and Rounsevell, 2006), or may be an omission from the analysis (Ahn et al., 2002; Berger and Bolte, 2004).

2.4.6.6 Technology scenarios

The importance of technology has been highlighted specifically for land-use change (Ewert et al., 2005; Rounsevell et al., 2005, 2006; Abildtrup et al., 2006) and for ecosystem service changes, such as agricultural production, water management, or climate regulation (Easterling et al., 2003; Nelson et al., 2005). Technological change is also a principal driver of GHG emissions. Since the TAR, scenarios addressing different technology pathways for climate change mitigation and adaptation have increased in number (see Nakićenović et al., 2007). Technological change can be treated as an exogenous factor to the economic system or be endogenously driven through economic and political incentives. Recent modelling exercises have represented theories on technical and institutional innovation, such as the 'Induced Innovation Theory', in scenario development (Grübler et al., 1999; Grubb et al., 2002), although more work is needed to refine these methods.

For integrated global scenario exercises, the rate and magnitude of technological development is often based on expert judgements and mental models. Storyline assumptions are then used to modify the input parameters of environmental models (e.g., for ecosystems, land use, or climate) prior to conducting model simulations (e.g., Millennium Ecosystem Assessment, 2005; Ewert et al., 2005). Such an approach is useful in demonstrating the relative sensitivity of different systems to technological change, but the role of technology remains a key uncertainty in characterisations of the future, with some arguing that only simple models should be used in constructing scenarios (Casman et al., 1999). In particular, questions such as about the rates of uptake and diffusion of new technologies deserve greater attention, especially as this affects adaptation to climate change (Easterling et al., 2003). However, only a few studies have tackled technology, suggesting an imbalance in the treatment of environmental change drivers within many CCIAV scenario studies, which future work should seek to redress.

2.4.6.7 Adaptation scenarios

Limited attention has been paid to characterising alternative pathways of future adaptation. Narrative information within scenarios can assist in characterising potential adaptive responses to climate change. For instance, the determinants of adaptive capacity and their indicators have been identified for Europe through questionnaire survey (Schröter et al., 2005b). Empirical relationships between these indicators and population and GDP from 1960 to 2000 were also established and applied to downscaled, SRES-based GDP and population projections in order to derive scenarios of adaptive capacity (see Section 2.4.6.4). The SRES storylines have also been interpreted using GDP per capita scenarios to estimate, in one study, the exposure of human populations under climate change to coastal flooding, based on future standards of coastal defences (Nicholls, 2004) and, in a second, access to safe water with respect to the incidence of diarrhoea (Hijioka et al., 2002). The rate of adaptation to climate change was analysed for the agriculture sector using alternative scenarios of innovation uptake (Easterling et al., 2003) by applying different maize yields, representing adaptation scenarios ranging from no adaptation through lagged adaptation rates and responses (following a logistic curve) to perfect (clairvoyant) adaptation (Easterling et al., 2003). This work showed the importance of implied adaptation rates at the farm scale, indicating that clairvoyant approaches to adaptation (most commonly used in CCIAV studies) are likely to overestimate the capacity of individuals to respond to climate change.

One adaptation strategy not considered by Easterling et al. (2003) was land-use change, in the form of autonomous adaptation to climate change driven by the decisions of individual land users (Berry et al., 2006). The land-use change scenarios reported previously can, therefore, be thought of as adaptation scenarios. Future studies, following consultation with key stakeholders, are more likely to include adaptation explicitly

Box 2.7. SRES-based land-use and land-cover characterisations

Future land use was estimated by most of the IAMs used to characterise the SRES storylines, but estimates for any one storyline are model-dependent, and therefore vary widely. For example, under the B2 storyline, the change in the global area of grassland between 1990 and 2050 varies between –49 and +628 million ha (Mha), with the marker scenario giving a change of +167 Mha (Nakićenović et al., 2000). The IAM used to characterise the A2 marker scenario did not include land-cover change, so changes under the A1 scenario were assumed to apply also to A2. Given the differences in socio-economic drivers between A1 and A2 that can affect land-use change, this assumption is not appropriate. Nor do the SRES land-cover scenarios include the effect of climate change on future land cover. This lack of internal consistency will especially affect the representation of agricultural land use, where changes in crop productivity play an important role (Ewert et al., 2005; Audsley et al., 2006). A proportional approach to downscaling the SRES land-cover scenarios has been applied to global ecosystem modelling (Arnell et al., 2004) by assuming uniform rates of change everywhere within an SRES macro-region. In practice, however, land-cover change is likely to be greatest where population and population growth rates are greatest. A mismatch was also found in some of the SRES storylines, and for some regions, between recent trends and projected trends for cropland and forestry (Arnell et al., 2004).

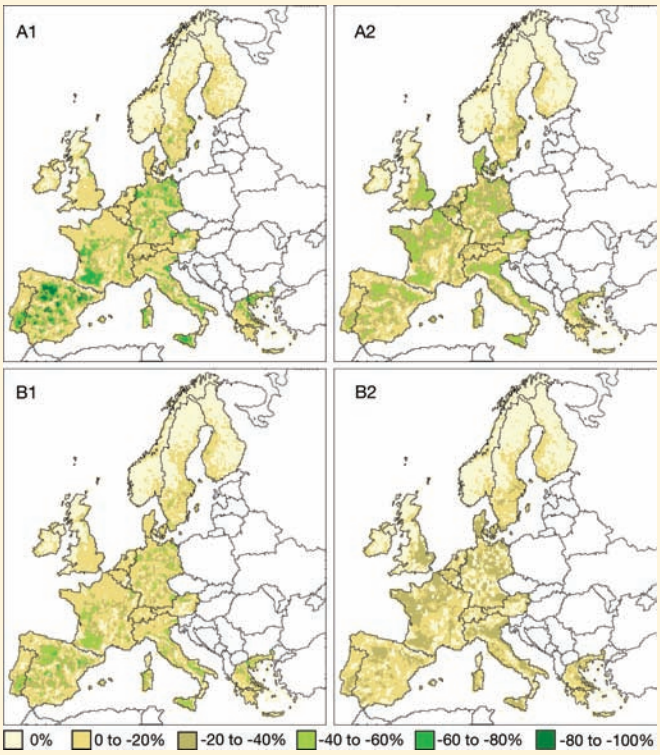


Figure 2.7. *Percentage change in cropland area (for food production) by 2080, compared with the baseline in 2000 for the four SRES storylines (A1FI, A2, B1, B2) with climate calculated by the HadCM3 AOGCM. From Schröter et al., 2005b. Reprinted with permission from AAAS.*

More sophisticated downscaling of the SRES scenarios has been undertaken at the regional scale within Europe (Kankaanpää and Carter, 2004; Ewert et al., 2005; Rounsevell et al., 2005, 2006; Abildtrup et al., 2006; Audsley et al., 2006; van Meijl et al., 2006). These analyses highlighted the potential role of non-climate change drivers in future land-use change. Indeed, climate change was shown in many examples to have a negligible effect on land use compared with socio-economic change (Schröter et al., 2005b). Technology, especially as it affects crop yield development, is an important determinant of future agricultural land use (and much more important than climate change), contributing to declines in agricultural areas of both cropland and grassland by as much as 50% by 2080 under the A1FI and A2 scenarios (Rounsevell et al., 2006). Such declines in land use did not occur within the B2 scenario, which assumes more extensive agricultural management, such as 'organic' production systems, or the widespread substitution of agricultural food and fibre production by bioenergy crops. This highlights the role of policy decisions in moderating future land-use change. However, broad-scale changes often belie large potential differences in the spatial distribution of land-use change that can occur at the sub-regional scale (Schröter et al., 2005b; see also Figure 2.7), and these spatial patterns may have greater effects on CCIAV than the overall changes in land-use quantities (Metzger et al., 2006; Reidsma et al., 2006).

as part of socio-economic scenario development, hence offering the possibility of gauging the effectiveness of adaptation options in comparison to scenarios without adaptation (Holman et al., 2005b).

2.4.6.8 Mitigation/stabilisation scenarios

Mitigation scenarios (also known as climate intervention or climate policy scenarios) are defined in the TAR (Morita et al., 2001), as scenarios that "(1) include explicit policies and/or measures, the primary goal of which is to reduce GHG emissions (e.g., carbon taxes) and/or (2) mention no climate policies and/or measures, but assume temporal changes in GHG emission sources or drivers required to achieve particular climate targets (e.g., GHG emission levels, GHG concentration levels, radiative forcing levels, temperature increase or sea level rise limits)." Stabilisation scenarios are an important subset of inverse mitigation scenarios, describing futures in which emissions reductions are undertaken so that GHG concentrations, radiative forcing, or global average temperature change do not exceed a prescribed limit.

Although a wide variety of mitigation scenarios have been developed, most focus on economic and technological aspects of emissions reductions (see Morita et al., 2001; van Vuuren et al., 2006; Nakićenović et al., 2007). The lack of detailed climate change projections derived from mitigation scenarios has hindered impact assessment. Simple climate models have been used to explore the implications for global mean temperature (see Box 2.8 and Nakićenović et al., 2007), but few AOGCM runs have been undertaken (see Meehl et al., 2007, for recent examples), with few direct applications in regional impact assessments (e.g., Parry et al., 2001). An alternative approach uses simple climate model projections of global warming under stabilisation to scale AOGCM patterns of climate change assuming unmitigated emissions, and then uses the resulting scenarios to assess regional impacts (e.g., Bakkenes et al., 2006).

The scarcity of regional socio-economic, land-use and other detail commensurate with a mitigated future has also hindered impact assessment (see discussion in Arnell et al., 2002). Alternative approaches include using SRES scenarios as surrogates for some stabilisation scenarios (Swart et al., 2002; see Table 2.4), for example to assess impacts on ecosystems (Leemans and Eickhout, 2004) and coastal regions (Nicholls and Lowe, 2004), demonstrating that socio-economic assumptions are a key determinant of vulnerability. Note that WG I reports AOGCM experiments forced by the SRES A1B and B1 emissions pathways up to 2100 followed by stabilisation of concentrations at roughly 715 and 550 ppm CO_2 (equated to 835 and 590 ppm equivalent CO_2, accounting for other GHGs: see Meehl et al., 2007).

A second approach associates impacts with particular levels or rates of climate change and may also determine the emissions and concentration paths that would avoid these outcomes.

Box 2.8. CO_2 stabilisation and global mean temperature response

Global mean annual temperature (GMAT) is the metric most commonly employed by the IPCC and adopted in the international policy arena to summarise future changes in global climate and their likely impacts (see Chapter 19, Box 19.2). Projections of global mean warming during the 21st century for the six SRES illustrative scenarios are presented by WG I (Meehl et al., 2007) and summarised in Figure 2.8. These are baseline scenarios assuming no explicit climate policy (see Box 2.2). A large number of impact studies reported by WG II have been conducted for projection periods centred on the 2020s, 2050s and 2080s[10], but only best estimates of GMAT change for these periods were available for three SRES scenarios based on AOGCMs (coloured dots in the middle panel of Figure 2.8). Best estimates (red dots) and likely ranges (red bars) for all six SRES scenarios are reported only for the period 2090-2099. Ranges are based on a hierarchy of models, observational constraints and expert judgement (Meehl et al., 2007).

A more comprehensive set of projections for these earlier time periods as well as the 2090s is presented in the lower panel of Figure 2.8. These are based on a simple climate model (SCM) and are also reported in WG I (Meehl et al., 2007, Figure 10.26). Although SCM projections for 2090-2099 contributed to the composite information used to construct the likely ranges shown in the middle panel, the projections shown in the middle and lower panels should not be compared directly as they were constructed using different approaches. The SCM projections are included to assist the reader in interpreting how the timing and range of uncertainty in projections of warming can vary according to emissions scenario. They indicate that the rate of warming in the early 21st century is affected little by different emissions scenarios (brown bars in Figure 2.8), but by mid-century the choice of emissions scenario becomes more important for the magnitude of warming (blue bars). By late century, differences between scenarios are large (e.g. red bars in middle panel; orange and red bars in lower panel), and multi-model mean warming for the lowest emissions scenario (B1) is more than 2°C lower than for the highest (A1FI).

GHG mitigation is expected to reduce GMAT change relative to baseline emissions, which in turn could avoid some adverse impacts of climate change. To indicate the projected effect of mitigation on temperature during the 21st century, and in the

[10] 30-year averaging periods for model projections held at the IPCC Data Distribution Centre.

absence of more recent, comparable estimates in the WG I report, results from the Third Assessment Report based on an earlier version of the SCM are reproduced in the upper panel of Figure 2.8 from the Third Assessment Report. These portray the GMAT response for four CO_2-stabilisation scenarios by three dates in the early (2025), mid (2055), and late (2085) 21st century. WG I does report estimates of equilibrium warming for CO_2-equivalent stabilisation (Meehl et al., 2007)[11]. Note that equilibrium temperatures would not be reached until decades or centuries after greenhouse gas stabilisation.

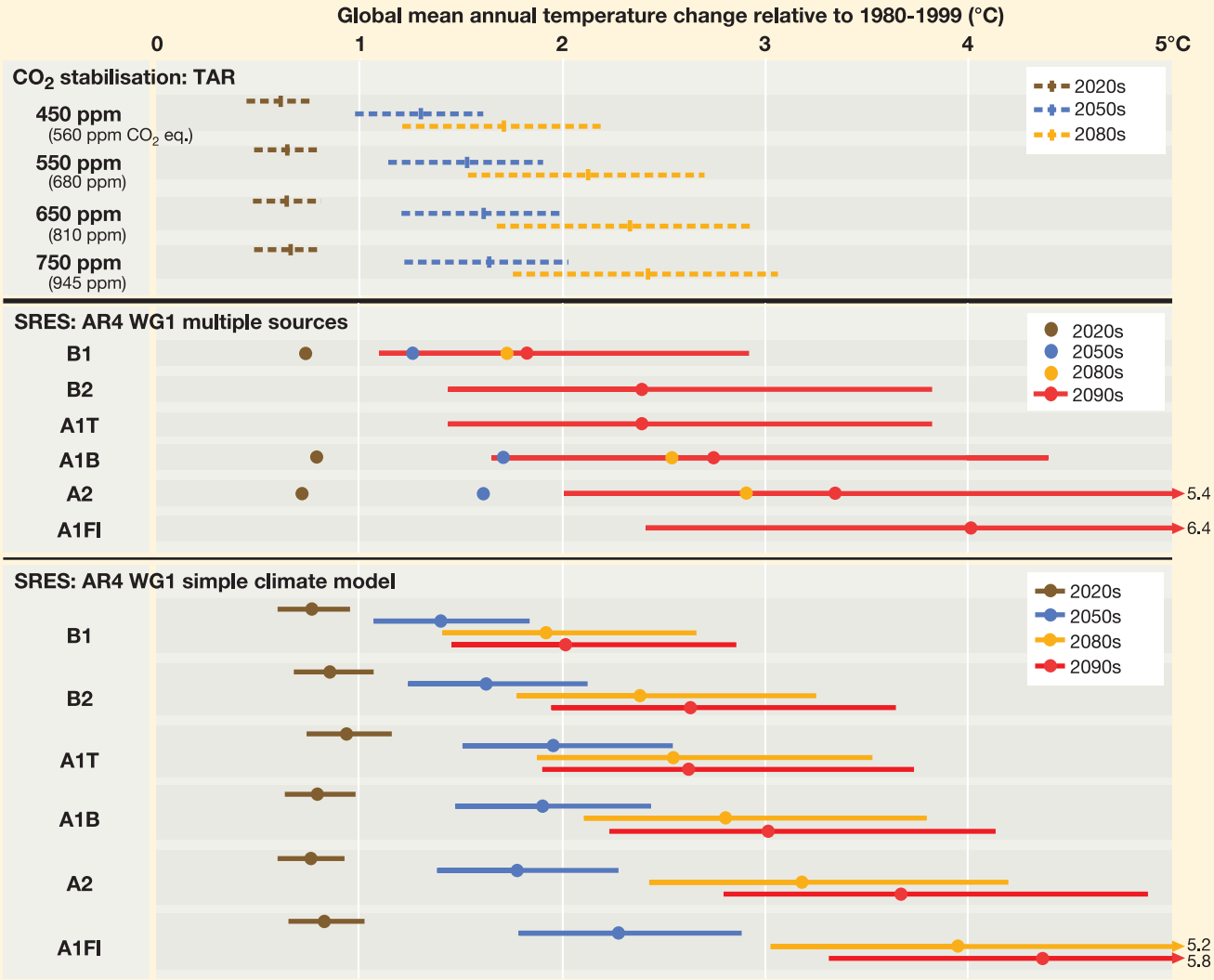


Figure 2.8. *Projected ranges of global mean annual temperature change during the 21st century for CO_2-stabilisation scenarios (upper panel, based on the TAR) and for the six illustrative SRES scenarios (middle and lower panels, based on the WG I Fourth Assessment). Different approaches have been used to obtain the estimates shown in the three panels, which are not therefore directly comparable.* ***Upper panel.*** *Projections for four CO_2-stabilisation profiles using a simple climate model (SCM) tuned to seven AOGCMs (IPCC, 2001c, Figure SPM-6; IPCC, 2001a, Figure 9.17). Broken bars indicate the projected mean (tick mark) and range of warming across the AOGCM tunings by the 2020s (brown), 2050s (blue) and 2080s (orange) relative to 1990. Time periods are based on calculations for 2025, 2055 and 2085. Approximate CO_2-equivalent values – including non-CO_2 greenhouse gases – at the time of CO_2-stabilisation (ppm) are also shown.* ***Middle panel.*** *Best estimates (red dots) and likely range (red bars) of warming by 2090-2099 relative to 1980-1999 for all six illustrative SRES scenarios and best estimates (coloured dots) for SRES B1, A1B and A2 by 2020-2029, 2050-2059 and 2080-2089 (IPCC, 2007, Figure SPM.5).* ***Lower panel.*** *Estimates based on an SCM tuned to 19 AOGCMs for 2025 (representing the 2020s), 2055 (2050s) and 2085 (2080s). Coloured dots represent the mean for the 19 model tunings and medium carbon cycle feedback settings. Coloured bars depict the range between estimates calculated assuming low carbon cycle feedbacks (mean - 1 SD) and those assuming high carbon cycle feedbacks (mean + 1 SD), approximating the range reported by Friedlingstein et al., 2006. Note that the ensemble average of the tuned versions of the SCM gives about 10% greater warming over the 21st century than the mean of the corresponding AOGCMs. (Meehl et al., 2007, Figure 10.26 and Appendix 10.A.1). To express temperature changes relative to 1850-1899, add 0.5°C.*

[11] Best estimate and likely range of equilibrium warming for seven levels of CO_2-equivalent stabilisation: 350 ppm, 1.0°C [0.6–1.4]; 450 ppm, 2.1°C [1.4–3.1]; 550 ppm, 2.9°C [1.9–4.4]; 650 ppm, 3.6°C [2.4–5.5]; 750 ppm, 4.3°C [2.8–6.4]; 1,000 ppm, 5.5°C [3.7–8.3] and 1,200 ppm, 6.3°C [4.2–9.4] (Meehl et al., 2007, Table 10.8).

Table 2.4. *The six SRES illustrative scenarios and the stabilisation scenarios (parts per million CO_2) they most resemble (based on Swart et al., 2002).*

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

Climate change and impact outcomes have been identified based on criteria for dangerous interference with the climate system (Mastrandrea and Schneider, 2004; O'Neill and Oppenheimer, 2004; Wigley, 2004; Harvey, 2007) or on meta-analysis of the literature (Hitz and Smith, 2004). A limitation of these types of analyses is that they are not based on consistent assumptions about socio-economic conditions, adaptation and sectoral interactions, and regional climate change.

A third approach constructs a single set of scenario assumptions by drawing on information from a variety of different sources. For example, one set of analyses combines climate change projections from the HadCM2 model based on the S750 and S550 CO_2-stabilisation scenarios with socio-economic information from the IS92a reference scenario in order to assess coastal flooding and loss of coastal wetlands from long-term sea level rise (Nicholls, 2004; Hall et al., 2005) and to estimate global impacts on natural vegetation, water resources, crop yield and food security, and malaria (Parry et al., 2001; Arnell et al., 2002).

2.4.6.9 Scenario integration

The widespread adoption of SRES-based scenarios in studies described in this report (see Boxes 2.2 to 2.7) acknowledges the desirability of seeking consistent scenario application across different studies and regions. For instance, SRES-based downscaled socio-economic projections were used in conjunction with SRES-derived climate scenarios in a set of global impact studies (Arnell et al., 2004; see Section 2.4.6.4). At a regional scale, multiple scenarios for the main global change drivers (socio-economic factors, atmospheric CO_2 concentration, climate factors, land use, and technology), were developed for Europe, based on interpretations of the global IPCC SRES storylines (Schröter et al., 2005b; see Box 2.7).

Nationally, scenarios of socio-economic development (Kaivo-oja et al., 2004), climate (Jylhä et al., 2004), sea level (Johansson et al., 2004), surface ozone exposure (Laurila et al., 2004), and sulphur and nitrogen deposition (Syri et al., 2004) were developed for Finland. Although the SRES driving factors were used as an integrating framework, consistency between scenario types could only be ensured by regional modelling, as simple downscaling from the global scenarios ignored important regional dependencies (e.g., between climate and air pollution and between air pressure and sea level: see Carter et al., 2004). Similar exercises have also been conducted in the east (Lorenzoni et al., 2000) and north-west (Holman et al., 2005b) of England.

Integration across scales was emphasised in the scenarios developed for the Millennium Ecosystem Assessment (MA), carried out between 2001 and 2005 to assess the consequences of ecosystem change for human well-being (Millennium Ecosystem Assessment, 2005). An SAS approach (see Section 2.4.5) was followed in developing scenarios at scales ranging from regional through national, basin, and local (Lebel et al., 2005). Many differed greatly from the set of global MA scenarios that were also constructed (Alcamo et al., 2005). This is due, in part, to different stakeholders being involved in the development of scenarios at each scale, but also reflects an absence of feedbacks from the sub-global to global scales (Lebel et al., 2005).

2.4.7 Large-scale singularities

Large-scale singularities are extreme, sometimes irreversible, changes in the Earth system such as abrupt cessation of the Atlantic Meridional Overturning Circulation (MOC) or melting of ice sheets in Greenland or West Antarctica (see Meehl et al., 2007; Randall et al., 2007; also Chapter 19, Section 19.3.5). With few exceptions, such events are not taken into account in socio-economic assessments of climate change. Shutdown of the MOC is simulated in Earth system models of intermediate complexity subject to large, rapid forcing (Meehl et al., 2007; also Chapter 19, Section 19.3.5.3). Artificial 'hosing' experiments, assuming the injection of large amounts of freshwater into the oceans at high latitudes, also have been conducted using AOGCMs (e.g., Vellinga and Wood, 2002; Wood et al., 2003) to induce an MOC shutdown. Substantial reduction of greenhouse warming occurs in the Northern Hemisphere, with a net cooling occurring mostly in the North Atlantic region (Wood et al., 2003). Such scenarios have subsequently been applied in impact studies (Higgins and Vellinga, 2004; Higgins and Schneider, 2005; also see Chapter 19, Section 19.4.2.5)

Complete deglaciation of Greenland and the West Antarctica Ice Sheet (WAIS) would raise sea level by 7 m and about 5 m, respectively (Meehl et al., 2007; also Chapter 19, Section 19.3.5.2). One recent study assumed an extreme rate of sea level rise, 5 m by 2100 (Nicholls et al., 2005), to test the limits of adaptation and decision-making (Dawson et al., 2005; Tol et al., 2006). A second study employed a scenario of rapid sea level rise of 2.2 m by 2100 by adding an ice sheet contribution to the highest TAR projection for the period, with the increase continuing unabated after 2100 (Arnell et al., 2005). Both studies describe the potential impacts of such a scenario in Europe, based on expert assessments.

2.4.8 Probabilistic futures

Since the TAR, many studies have produced probabilistic representations of future climate change and socio-economic conditions suitable for use in impact assessment. The choices faced in these studies include which components of socio-economic and climate change models to treat probabilistically and how to define the input probability density functions (pdfs) for each component. Integrated approaches derive pdfs of climate change from input pdfs for emissions and for key

parameters in models of GHG cycles, radiative forcing, and the climate system. The models then sample repeatedly from the uncertainty distributions for inputs and model parameters, in order to produce a pdf of outcomes, e.g., global temperature and precipitation change. Either simple climate models (e.g., Wigley and Raper, 2001) or climate models of intermediate complexity (Forest et al., 2002) have been applied.

Alternative methods of developing pdfs for emissions are described in Nakićenović et al. (2007), but they all require subjective judgement in the weighting of different future outcomes, which is a matter of considerable debate (Parson et al., 2006). Some argue that this should be done by experts, otherwise decision-makers will inevitably assign probabilities themselves without the benefit of established techniques to control well-known biases in subjective judgements (Schneider, 2001, 2002; Webster et al., 2002, 2003). Others argue that the climate change issue is characterised by 'deep uncertainty' – i.e., system models, parameter values, and interactions are unknown or contested – and therefore the elicited probabilities may not accurately represent the nature of the uncertainties faced (Grübler and Nakićenović, 2001; Lempert et al., 2004).

The most important uncertainties to be represented in pdfs of regional climate change, the scale of greatest relevance for impact assessments, are GHG emissions, climate sensitivity, and inter-model differences in climatic variables at the regional scale. Other important factors include downscaling techniques, and regional forcings such as aerosols and land-cover change (e.g., Dessai, 2005). A rapidly growing literature reporting pdfs of climate sensitivity is providing a significant methodological advance over the long-held IPCC estimate of 1.5°C to 4.5°C for the (non-probabilistic) range of global mean annual temperature change for a doubling of atmospheric CO_2 (see Meehl et al., 2007, for a detailed discussion). For regional change, recent methods of applying different weighting schemes to multi-model ensemble projections of climate are described in Christensen et al. (2007a). Other work has examined the full chain of uncertainties from emissions to regional climate. For example, Dessai et al. (2005b) tested the sensitivity of probabilistic regional climate changes to a range of uncertainty sources including climate sensitivity, GCM simulations, and emissions scenarios. The ENSEMBLES research project is modelling various sources of uncertainty to produce regional probabilities of climate change and its impacts for Europe (Hewitt and Griggs, 2004).

Methods to translate probabilistic climate changes for use in impact assessment (e.g., New and Hulme, 2000; Wilby and Harris, 2006; Fowler et al., 2007) include those assessing probabilities of impact threshold exceedance (e.g., Jones, 2000, 2004; Jones et al., 2007). Wilby and Harris (2006) combined information from various sources of uncertainty (emissions scenarios, GCMs, statistical downscaling, and hydrological model parameters) to estimate probabilities of low flows in the River Thames basin, finding the most important uncertainty to be the differences between the GCMs, a conclusion supported in water resources assessments in Australia (Jones and Page, 2001; Jones et al., 2005). Scholze et al. (2006) quantified risks of changes in key ecosystem processes on a global scale, by grouping scenarios according to ranges of global mean temperature change rather than considering probabilities of individual emissions scenarios. Probabilistic impact studies sampling across emissions, climate sensitivity, and regional climate change uncertainties have been conducted for wheat yield (Howden and Jones, 2004; Luo et al., 2005), coral bleaching (Jones, 2004; Wooldridge et al., 2005), water resources (Jones and Page, 2001; Jones et al., 2005), and freshwater ecology (Preston, 2006).

2.5 Key conclusions and future directions

Climate change impact, adaptation and vulnerability (CCIAV) assessment has now moved far beyond its early status as a speculative, academic endeavour. As reported elsewhere in this volume, climate change is already under way, impacts are being felt, and some adaptation is occurring. This is propelling CCIAV assessment from being an exclusively research-oriented activity towards analytical frameworks that are designed for practical decision-making. These comprise a limited set of approaches (described in Section 2.2), within which a large range of methods can be applied.

The aims of research and decision analysis differ somewhat in their treatment of uncertainty. Research aims to understand and reduce uncertainty, whereas decision analysis seeks to manage uncertainty in order to prioritise and implement actions. Therefore, while improved scientific understanding may have led to a narrowing of the range of uncertainty in some cases (e.g., increased consensus among GCM projections of regional climate change) and a widening in others (e.g., an expanded range of estimates of adaptive capacity and vulnerability obtained after accounting for alternative pathways of socio-economic and technological development), these results are largely a manifestation of advances in methods for treating uncertainty.

Decision makers are increasingly calling upon the research community to provide:

- good-quality information on what impacts are occurring now, their location and the groups or systems most affected,
- reliable estimates of the impacts to be expected under projected climate change,
- early warning of potentially alarming or irreversible impacts,
- estimation of different risks and opportunities associated with a changing climate,
- effective approaches for identifying and evaluating both existing and prospective adaptation measures and strategies,
- credible methods of costing different outcomes and response measures,
- an adequate basis to compare and prioritise alternative response measures, including both adaptation and mitigation.

To meet these demands, future research efforts need to address a set of methodological, technical and information gaps that call for certain actions.

- *Continued development of risk-management techniques*. Methods and tools should be designed both to address specific climate change problems and to introduce them into mainstream policy and planning decision-making.

- *New methods and tools appropriate for regional and local application*. An increasing focus on adaptation to climate change at local scales requires new methods, scenarios, and models to address emerging issues. New approaches are also reconciling scale issues in scenario development; for example by improving methods of interpreting and quantifying regional storylines, and through the nesting of scenarios at different scales.
- *Cross-sectoral assessments*. Limited by data and technical complexity, most CCIAV assessments have so far focused on single sectors. However, impacts of climate change on one sector will have implications, directly and/or indirectly, for others – some adverse and some beneficial. To be more policy-relevant, future analyses need to account for the interactions between different sectors, particularly at national level but also through global trade and financial flows.
- *Collection of empirical knowledge from past experience*. Experience gained in dealing with climate-related natural disasters, documented using both modern methods and traditional knowledge, can assist in understanding the coping strategies and adaptive capacity of vulnerable communities, and in defining critical thresholds of impact to be avoided.
- *Enhanced observation networks and improved access to existing data*. CCIAV studies have increasing requirements for data describing present-day environmental and socio-economic conditions. Some regions, especially in developing countries, have limited access to existing data, and urgent attention is required to arrest the decline of observation networks. Integrated monitoring systems are needed for observing human-environment interactions.
- *Consistent approaches in relation to scenarios in other assessments*. Integration of climate-related scenarios with those widely accepted and used by other international bodies is desirable (i.e., mainstreaming). The exchange of ideas and information between the research and policy communities will greatly improve scenario quality, usage, and acceptance.
- *Improved scenarios for poorly specified indicators*. CCIAV outcomes are highly sensitive to assumptions about factors such as future technology and adaptive capacity that at present are poorly understood. For instance, the theories and processes of technological innovation and its relationship with other indicators such as education, wealth, and governance require closer attention, as do studies of the processes and costs of adaptation.
- *Integrated scenarios*. There are shortcomings in how interactions between key drivers of change are represented in scenarios. Moreover, socio-economic and technological scenarios need to account for the costs and other ancillary effects of both mitigation and adaptation actions, which at present are rarely considered.
- *Provision of improved climate predictions for near-term planning horizons*. Many of the most severe impacts of climate change are manifest through extreme weather and climate events. Resource planners increasingly need reliable information, years to decades ahead, on the risks of adverse weather events at the scales of river catchments and communities.
- *Effective communication of the risks and uncertainties of climate change*. To gain trust and improve decisions, awareness-building and dialogue is necessary between those stakeholders with knowledge to share (including researchers) and with the wider public.

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