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Assessing key vulnerabilities and the risk from climate change

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Executive summary

Climate change will lead to changes in geophysical, biological and socio-economic systems. An impact describes a specific change in a system caused by its exposure to climate change. Impacts may be judged to be harmful or beneficial. Vulnerability to climate change is the degree to which these systems are susceptible to, and unable to cope with, adverse impacts. The concept of risk, which combines the magnitude of the impact with the probability of its occurrence, captures uncertainty in the underlying processes of climate change, exposure, impacts and adaptation. [19.1.1]

Many of these impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them '*key*'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19.1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgements informed by the state of scientific knowledge. No single metric can adequately describe the diversity of key vulnerabilities, nor determine their ranking. [19.1.1]

This chapter identifies seven criteria from the literature that may be used to identify key vulnerabilities, and then describes some potential key vulnerabilities identified using these criteria. The criteria are [19.2]:

- magnitude of impacts,
- timing of impacts,
- persistence and reversibility of impacts,
- likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates,
- potential for adaptation,
- distributional aspects of impacts and vulnerabilities,
- importance of the system(s) at risk.

Key vulnerabilities are associated with many climate-sensitive systems, including food supply, infrastructure, health, water resources, coastal systems, ecosystems, global biogeochemical cycles, ice sheets and modes of oceanic and atmospheric circulation. [19.3]

General conclusions include the following [19.3].

- Some observed key impacts have been at least partly attributed to anthropogenic climate change. Among these are increases in human mortality, loss of glaciers, and increases in the frequency and/or intensity of extreme events.
- Global mean temperature changes of up to 2°C above 1990-2000 levels (see Box 19.2) would exacerbate current key impacts, such as those listed above (high confidence), and trigger others, such as reduced food security in many low-latitude nations (medium confidence). At the same time, some systems, such as global agricultural productivity, could benefit (low/medium confidence).
- Global mean temperature changes of 2 to 4°C above 1990-2000 levels would result in an increasing number of key impacts at all scales (high confidence), such as widespread loss of biodiversity, decreasing global agricultural productivity and commitment to widespread deglaciation of Greenland (high confidence) and West Antarctic (medium confidence) ice sheets.
- Global mean temperature changes greater than 4°C above 1990-2000 levels would lead to major increases in vulnerability (very high confidence), exceeding the adaptive capacity of many systems (very high confidence).
- Regions that are already at high risk from observed climate variability and climate change are more likely to be adversely affected in the near future by projected changes in climate and increases in the magnitude and/or frequency of already damaging extreme events.

The 'reasons for concern' identified in the Third Assessment Report (TAR) remain a viable framework in which to consider key vulnerabilities. Recent research has updated some of the findings from the TAR [19.3.7].

- There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high-mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase (very high confidence).
- There is new evidence that observed climate change is likely to have already increased the risk of certain extreme events such as heatwaves, and it is more likely than not that warming has contributed to the intensification of some tropical cyclones, with increasing levels of adverse impacts as temperatures increase (very high confidence).
- The distribution of impacts and vulnerabilities is still considered to be uneven, and low-latitude, less-developed areas are generally at greatest risk due to both higher sensitivity and lower adaptive capacity; but there is new evidence that vulnerability to climate change is also highly variable within countries, including developed countries.
- There is some evidence that initial net market benefits from climate change will peak at a lower magnitude and sooner than was assumed for the TAR, and it is likely that there will be higher damages for larger magnitudes of global mean temperature increases than was estimated in the TAR.
- The literature offers more specific guidance on possible thresholds for initiating partial or near-complete deglaciation of the Greenland and West Antarctic ice sheets.

Adaptation can significantly reduce many potentially dangerous impacts of climate change and reduce the risk of many key vulnerabilities. However, the technical, financial and institutional capacity, and the actual planning and implementation of effective adaptation, is currently quite limited in many regions. In addition, the risk-reducing potential of planned adaptation is either very limited or very costly for some key vulnerabilities, such as loss of biodiversity, melting of mountain glaciers and disintegration of major ice sheets. [19.4.1]

A general conclusion on the basis of present understanding is that for market and social systems there is considerable adaptation potential, but the economic costs are potentially large, largely unknown and unequally distributed, as is the adaptation potential itself. For biological and geophysical systems, the adaptation potential is much less than in social and market systems. There is wide agreement that it will be much more difficult for both human and natural systems to adapt to larger magnitudes of global mean temperature change than to smaller ones, and that adaptation will be more difficult and/or costly for faster warming rates than for slower rates. [19.4.1]

Several conclusions appear robust across a diverse set of studies in the integrated assessment and mitigation literature [19.4.2, 19.4.3].

- Given the uncertainties in factors such as climate sensitivity, regional climate change, vulnerability to climate change, adaptive capacity and the likelihood of bringing such capacity to bear, a risk-management framework emerges as a useful framework to address key vulnerabilities. However, the assignment of probabilities to specific key impacts is often very difficult, due to the large uncertainties involved.
- Actions to mitigate climate change and reduce greenhouse gas emissions will reduce the risk associated with most key vulnerabilities. Postponement of such actions, in contrast, generally increases risks.
- Given current atmospheric greenhouse gas concentrations (IPCC, 2007a) and the range of projections for future climate change, some key impacts (e.g., loss of species, partial deglaciation of major ice sheets) cannot be avoided with high confidence. The probability of initiating some large-scale events is very likely to continue to increase as long as greenhouse gas concentrations and temperature continue to increase.

19.1 Introduction

19.1.1 Purpose, scope and structure of the chapter

Many social, biological and geophysical systems are at risk from climate change. Since the Third Assessment Report (TAR; IPCC, 2001a), policy-makers and the scientific community have increasingly turned their attention to climate change impacts, vulnerabilities and associated risks that may be considered ‘key’ because of their magnitude, persistence and other characteristics. An impact describes a specific change in a system caused by its exposure to climate change. Impacts may be judged to be either harmful or beneficial. Vulnerability to climate change is the degree to which these systems are susceptible to, and unable to cope with, the adverse impacts. The concept of risk, which combines the magnitude of the impact with the probability of its occurrence, captures uncertainty in the underlying processes of climate change, exposure, sensitivity and adaptation.

The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with ‘dangerous anthropogenic interference’ (DAI) with the climate system, in the terminology of the United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19.1). Ultimately, the determination of DAI cannot be based on scientific arguments alone, but involves other judgements informed by the state of scientific knowledge.

The purpose of this chapter is two-fold. First, it synthesises information from Working Group I (WGI) and Chapters 3-16 of Working Group II (WGII) of the IPCC Fourth Assessment Report (AR4) within the uncertainty framework established by IPCC (Moss and Schneider, 2000; IPCC, 2007b) and the risk management approach discussed in Chapter 2, and identifies key vulnerabilities based on seven criteria (see Section 19.2). A focus on key vulnerabilities is meant to help policy-makers and stakeholders assess the level of risk and design pertinent response strategies. Given this focus, the analytic emphasis of this chapter is on people and systems that may be *adversely* affected by climate change, particularly where impacts could have serious and/or irreversible consequences. Positive impacts on a system are addressed when reported in the literature and where relevant to the assessment of key vulnerabilities. A comprehensive assessment of positive and negative climate impacts in all sectors and regions is beyond the scope of this chapter, and readers are encouraged to turn to the sectoral and regional chapters of this volume (Chapters 3-16) for this information.

Furthermore, it is acknowledged that the impacts of future climate change will occur in the context of an evolving socio-economic baseline. This chapter attempts to reflect the limited literature examining the possible positive and negative relationships between baseline scenarios and future impacts. However, the purpose of this chapter is not to compare the effects of climate change with the effects of socio-economic development, but rather to assess the additional effects of climate change on top of whatever baseline development scenario is assumed. Whether a climate change impact would be greater or smaller than welfare gains or losses associated with particular development scenarios is beyond the scope of this chapter but is dealt with in Chapter 20 and by Working Group III (WGIII).

Second, this chapter provides an assessment of literature focusing on the contributions that various mitigation and adaptation response strategies, such as stabilisation of greenhouse gas concentrations in the atmosphere, could make in avoiding or reducing the probability of occurrence of key impacts. Weighing the benefits of avoiding such climate-induced risks versus the costs of mitigation or adaptation, as well as the distribution of such costs and benefits (i.e., equity implications of such trade-offs) is also beyond the scope of this chapter, as is attempting a normative trade-off analysis among and between various groups and between human and natural systems. (The term ‘normative’ is used in this chapter to refer to a process or statement that inherently involves value judgements or beliefs.) Many more examples of such literature can be obtained in Chapters 18 and 20 of this volume and in the Working Group III (WGIII) AR4.

The remainder of Section 19.1 presents the conceptual framework, and Section 19.2 presents the specific criteria used in this chapter for the assessment of key vulnerabilities. Section 19.3 presents selected key vulnerabilities based on these criteria. Key vulnerabilities are linked to specific levels of global mean temperature increase (above 1990-2000 levels; see Box 19.2) using available estimates from the literature wherever possible. Section 19.3 provides an indicative, rather than an exhaustive, list of key vulnerabilities, representing the authors' collective judgements based on the criteria presented in Section 19.2, selected from a vast array of possible candidates suggested in the literature. Section 19.4 draws on the literature addressing the linkages between key vulnerabilities and strategies to avoid them by adaptation (Section 19.4.1) and mitigation (Section 19.4.2). Section 19.4.4 concludes this chapter by suggesting research priorities for the natural and social sciences that may provide relevant knowledge for assessing key vulnerabilities of climate change. The assessment of key vulnerabilities and review of the particular assemblage of literature needed to do so is unique to the mission of Chapter 19. Accordingly, in Sections 19.3 and 19.4, we have made judgments with regard to likelihood and confidence whereas, in some cases, other chapters in this volume and in the WGI AR4 have not.

Another important area of concern, also marked by large uncertainties, is the assessment of impacts resulting from multiple factors. In some cases, key vulnerabilities emerging from such interactions are assessed, such as the fragmentation of habitats that constrains some species, which – when combined with climate change – forces species movements across disturbed habitats. This is a multi-stressor example that is likely to multiply the impacts relative to either stressor acting alone. Other examples from the literature are also given in the text; though any attempt to be comprehensive or quantitative in such multi-stress situations is beyond the scope of the chapter.

19.1.2 Conceptual framework for the identification and assessment of key vulnerabilities

19.1.2.1 Meaning of 'key vulnerability'

Vulnerability to climate change is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (see Chapter 17; Füssel and Klein, 2006). The term 'vulnerability' may therefore refer to the vulnerable system itself, e.g., low-lying islands or coastal cities; the impact to this system, e.g., flooding of coastal cities and agricultural lands or forced migration; or the mechanism causing these impacts, e.g., disintegration of the West Antarctic ice sheet.

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them *key*. Key impacts that may be associated with key vulnerabilities are found in many social, economic, biological and geophysical systems, and various tabulations of risks, impacts and vulnerabilities have been provided in the literature (e.g., Smith et al., 2001; Corfee-Morlot and Höhne, 2003; Hare, 2003; Oppenheimer and Petsonk, 2003, 2005; ECF, 2004; Hitz and Smith, 2004; Leemans and Eickhout, 2004; Schellnhuber et al., 2006). Key vulnerabilities are associated with many climate-sensitive systems, including, for example, food supply, infrastructure, health, water resources, coastal systems,

Box 19.1. UNFCCC Article 2

The text of the UNFCCC Article 2 reads:

"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

Box 19.2. Reference for temperature levels

Levels of global mean temperature change are variously presented in the literature with respect to: pre-industrial temperatures in a specified year e.g., 1750 or 1850; the average temperature of the 1961-1990 period; or the average temperature within the 1990-2000 period. The best estimate for the increase above pre-industrial levels in the 1990-2000 period is 0.6°C, reflecting the best estimate for warming over the 20th century (Folland et al., 2001; Trenberth et al., 2007). Therefore, to illustrate this by way of a specific example, a 2°C increase above pre-industrial levels corresponds to a 1.4°C increase above 1990-2000 levels. Climate impact studies often assess changes in response to regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (see Christensen et al., 2007). Unless otherwise specified, this chapter refers to global mean temperature change above 1990-2000 levels, which reflects the most common metric used in the literature on key vulnerabilities. However, given the many conventions in the literature for baseline periods, the reader is advised to check carefully and to adjust baseline levels for consistency every time a number is given for impacts at some specified level of global mean temperature change.

ecosystems, global biogeochemical cycles, ice sheets, and modes of oceanic and atmospheric circulation (see Section 19.3).

19.1.2.2 Scientific assessment and value judgements

The assessment of key vulnerabilities involves substantial scientific uncertainties as well as value judgements. It requires consideration of the response of biophysical and socio-economic systems to changes in climatic and non-climatic conditions over time (e.g., changes in population, economy or technology), important non-climatic developments that affect adaptive capacity, the potential for effective adaptation across regions, sectors and social groupings, value judgements about the acceptability of potential risks, and potential adaptation and mitigation measures. To achieve transparency in such complex assessments, scientists and analysts need to provide a 'traceable account' of all relevant assumptions (Moss and Schneider, 2000).

Scientific analysis can inform policy processes but choices about which vulnerabilities are 'key', and preferences for policies appropriate for addressing them, necessarily involve value judgements. "Natural, technical and social sciences can provide essential information and evidence needed for decision-making on what constitutes 'dangerous anthropogenic interference with the climate system'. At the same time, such decisions are value judgments determined through socio-political processes, taking into account considerations such as development, equity and sustainability, as well as uncertainties and risk" (IPCC, 2001b).

19.1.2.3 UNFCCC Article 2

The question of which impacts might constitute DAI in terms of Article 2 has only recently attracted a high level of attention, and the literature still remains relatively sparse (see Oppenheimer and Petsonk 2005; Schellnhuber et al., 2006 for reviews). Interpreting Article 2 (ultimately the obligation of the Conference of the Parties to the UNFCCC) involves a scientific assessment of what impacts might be associated with different levels of greenhouse gas concentrations or climate change; and a normative evaluation by policy-makers of which potential impacts and associated likelihoods are significant enough to constitute, individually or in combination, DAI. This assessment is informed by the magnitude and timing of climate impacts as well as by their distribution across regions, sectors and population groups (e.g., Corfee-Morlot and Agrawala, 2004; Schneider and Mastrandrea, 2005; Yamin et al., 2005). The social, cultural and ethical dimensions of DAI have drawn increasing attention recently (Jamieson 1992, 1996; Rayner and Malone, 1998; Adger, 2001; Gupta et al., 2003; Gardiner, 2006). The references to adverse effects as significant deleterious effects in Article 1 of the UNFCCC[1] and to natural ecosystems, food production, and sustainable development in Article 2 provide guidance as to which impacts may be considered relevant to the definition of DAI (Schneider et al., 2001).

Interpreting Article 2 is necessarily a dynamic process because the assessment of what levels of greenhouse gas concentrations may be considered 'dangerous' would be modified based on changes in scientific knowledge, social values and political priorities.

19.1.2.4 Distribution and aggregation of impacts

Vulnerability to climate change differs considerably across socio-economic groups, thus raising important questions about equity. Most studies of impacts in the context of key vulnerabilities and Article 2 have focused on aggregate impacts, grouping developing countries or populations with special needs or situations. Examples include island nations faced with sea-level rise (Barnett and Adger, 2003), countries in semi-arid regions with a marginal agricultural base, indigenous populations facing regionalised threats, or least-developed countries (LDCs; Huq et al., 2003). Within developed countries, research on vulnerability has often focused on groups of people, for example those living in coastal or flood-prone regions, or socially vulnerable groups such as the elderly.

No single metric for climate impacts can provide a commonly accepted basis for climate policy decision-making (Jacoby, 2004; Schneider, 2004). Aggregation, whether by region, sector, or population group, implies value judgements about the selection, comparability and significance of vulnerabilities and cohorts (e.g., Azar and Sterner, 1996; Fankhauser et al., 1997; Azar, 1998, on regional aggregation). The choice of scale at which impacts are examined is also crucial, as considerations of fairness, justice or equity require examination of the distribution of impacts, vulnerability and adaptation potential, not only between, but also within, groupings (Jamieson, 1992; Gardiner, 2004; Yamin et al., 2005).

19.1.2.5 Critical levels and thresholds

Article 2 of the UNFCCC defines international policy efforts in terms of avoidance of a level of greenhouse gas concentrations beyond which the effects of climate change would be considered to be 'dangerous'. Discussions about 'dangerous interference with the climate system' and 'key vulnerabilities' are also often framed around thresholds or critical limits (Patwardhan et al., 2003; Izrael, 2004). Key vulnerabilities may be linked to systemic thresholds where non-linear processes cause a system to shift from one major state to another (such as a hypothetical sudden change in the Asian monsoon or disintegration of the West Antarctic ice sheet). Systemic thresholds may lead to large and widespread consequences that may be considered as 'dangerous'. Examples include climate impacts such as those arising from ice sheet disintegration leading to large sea-level rises or changes to the carbon cycle, or those affecting natural and managed ecosystems, infrastructure and tourism in the Arctic.

Smooth and gradual climate change may also lead to damages that are considered unacceptable beyond a certain point. For instance, even a gradual and smooth increase of sea-level rise would eventually reach a level that certain stakeholders would consider unacceptable. Such normative impact thresholds could

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[1] Article 1 reads, "For the purposes of this Convention: 1. 'Adverse effects of climate change' means changes in the physical environment or biota resulting from climate change which have significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or on the operation of socio-economic systems or on human health and welfare."

be defined at the global level (e.g., Toth et al., 2002, for natural ecosystems) and some have already been identified at the regional level (e.g., Jones, 2001, for irrigation in Australia).

19.2 Criteria for selecting 'key' vulnerabilities

As previously discussed, determining which impacts of climate change are potentially 'key' and what is 'dangerous' is a dynamic process involving, inter alia, combining scientific knowledge with factual and normative elements (Patwardhan et al., 2003; Dessai et al., 2004; Pittini and Rahman, 2004). Largely factual or objective criteria include the scale, magnitude, timing and persistence of the harmful impact (Parry et al., 1996; Kenny et al., 2000; Moss and Schneider, 2000; Goklany, 2002; Corfee-Morlot and Höhne, 2003; Schneider, 2004; Oppenheimer, 2005). Normative and subjective elements are embedded in assessing the uniqueness and importance of the threatened system, equity considerations regarding the distribution of impacts, the degree of risk aversion, and assumptions regarding the feasibility and effectiveness of potential adaptations (IPCC, 2001a; OECD, 2003; Pearce, 2003; Tol et al., 2004). Normative criteria are influenced by the perception of risk, which depends on the cultural and social context (e.g., Slovic, 2000; Oppenheimer and Todorov, 2006). Some aspects of confidence in the climate change–impact relationship are factual, while others are subjective (Berger and Berry, 1988). In addition, the choice of which factual criteria to employ in assessing impacts has a normative component.

This chapter identifies seven criteria from the literature that may be used to identify key vulnerabilities, and then describes some potential key vulnerabilities identified using these criteria. The criteria are listed and explained in detail below:

- magnitude of impacts,
- timing of impacts,
- persistence and reversibility of impacts,
- likelihood (estimates of uncertainty) of impacts and vulnerabilities, and confidence in those estimates,
- potential for adaptation,
- distributional aspects of impacts and vulnerabilities,
- importance of the system(s) at risk.

Magnitude

Impacts of large magnitude are more likely to be evaluated as 'key' than impacts with more limited effects. The magnitude of an impact is determined by its scale (e.g., the area or number of people affected) and its intensity (e.g., the degree of damage caused). Therefore, many studies have associated key vulnerabilities or dangerous anthropogenic interference primarily with large-scale geophysical changes in the climate system.

Various aggregate metrics are used to describe the magnitude of climate impacts. The most widely used quantitative measures for climate impacts (see Chapter 20 and WGIII AR4 Chapter 3 (Fisher et al., 2007)) are monetary units such as welfare, income or revenue losses (e.g., Nordhaus and Boyer, 2000), costs of anticipating and adapting to certain biophysical impacts such as a large sea-level rise (e.g., Nicholls et al., 2005), and estimates of people's willingness to pay to avoid (or accept as compensation for) certain climate impacts (see, e.g., Li et al., 2004). Another aggregate, non-monetary indicator is the number of people affected by certain impacts such as food and water shortages, morbidity and mortality from diseases, and forced migration (Barnett, 2003; Arnell, 2004; Parry et al., 2004; van Lieshout et al., 2004; Schär and Jendritzky, 2004; Stott et al., 2004). Climate impacts are also quantified in terms of the biophysical end-points, such as agricultural yield changes (see Chapter 5; Füssel et al., 2003; Parry et al., 2004) and species extinction numbers or rates (see Chapter 4; Thomas et al., 2004). For some impacts, qualitative rankings of magnitude are more appropriate than quantitative ones. Qualitative methods have been applied to reflect social preferences related to the potential loss of cultural or national identity, loss of cultural heritage sites, and loss of biodiversity (Schneider et al., 2000).

Timing

A harmful impact is more likely to be considered 'key' if it is expected to happen soon rather than in the distant future (Bazermann, 2005; Weber, 2005). Climate change in the 20th century has already led to numerous impacts on natural and social systems (see Chapter 1), some of which may be considered 'key'. Impacts occurring in the distant future which are caused by nearer-term events or forcings (i.e., 'commitment'), may also be considered 'key'. An often-cited example of such 'delayed irreversibility' is the disintegration of the West Antarctic ice sheet: it has been proposed that melting of ice shelves in the next 100 to 200 years may lead to gradual but irreversible deglaciation and a large sea-level rise over a much longer time-scale (see Section 19.3.5.2; Meehl et al., 2007). Debates over an 'appropriate' rate of time preference for such events (i.e., discounting) are widespread in the integrated assessment literature (WGIII AR4 Chapter 2: Halsnaes et al., 2007), and can influence the extent to which a decision-maker might label such possibilities as 'key'.

Another important aspect of timing is the rate at which impacts occur. In general, adverse impacts occurring suddenly (and surprisingly) would be perceived as more significant than the same impacts occurring gradually, as the potential for adaptation for both human and natural systems would be much more limited in the former case. Finally, very rapid change in a non-linear system can exacerbate other vulnerabilities (e.g., impacts on agriculture and nutrition can aggravate human vulnerability to disease), particularly where such rapid change curtails the ability of systems to prevent and prepare for particular kinds of impacts (Niemeyer et al., 2005).

Persistence and reversibility

A harmful impact is more likely to be considered 'key' if it is persistent or irreversible. Examples of impacts that could become key due to persistence include the emergence of near-permanent drought conditions (e.g., in semi-arid and arid regions in Africa – Nyong, 2005; see Chapter 9) and intensified cycles of extreme flooding that were previously regarded as 'one-off' events (e.g., in parts of the Indian subcontinent; see Chapter 10).

Examples of climate impacts that are irreversible, at least on time-scales of many generations, include changes in regional or global biogeochemical cycles and land cover (Denman et al., 2007; see Section 19.3.5.1), the loss of major ice sheets (Meehl et al., 2007; see Section 19.3.5.2); the shutdown of the meridional overturning circulation (Randall et al., 2007; Meehl et al., 2007; see Section 19.3.5.3), the extinction of species (Thomas et al., 2004; Lovejoy and Hannah, 2005), and the loss of unique cultures (Barnett and Adger, 2003). The latter is illustrated by Small Island Nations at risk of submergence through sea-level rise (see Chapter 16) and the necessity for the Inuit of the North American Arctic (see Chapter 15) to cope with recession of the sea ice that is central to their socio-cultural environment.

Likelihood and confidence

Likelihood of impacts and our confidence in their assessment are two properties often used to characterise uncertainty of climate change and its impacts (Moss and Schneider, 2000; IPCC, 2007b). Likelihood is the probability of an outcome having occurred or occurring in the future; confidence is the subjective assessment that any statement about an outcome will prove correct. Uncertainty may be characterised by these properties individually or in combination. For example, in expert elicitations of subjective probabilities (Nordhaus, 1994; Morgan and Keith, 1995; Arnell et al., 2005; Morgan et al., 2006), likelihood of an outcome has been framed as the central value of a probability distribution, whereas confidence is reflected primarily by its spread (the lesser the spread, the higher the confidence). An impact characterised by high likelihood is more apt to be seen as 'key' than the same impact with a lower likelihood of occurrence. Since risk is defined as consequence (impact) multiplied by its likelihood (probability), the higher the probability of occurrence of an impact the higher its risk, and the more likely it would be considered 'key'.

Potential for adaptation

To assess the potential harm caused by climate change, the ability of individuals, groups, societies and nature to adapt to or ameliorate adverse impacts must be considered (see Section 19.3.1; Chapter 17). The lower the availability and feasibility of effective adaptations, the more likely such impacts would be characterised as 'key vulnerabilities'. The potential for adaptation to ameliorate the impacts of climate change differs between and within regions and sectors (e.g., O'Brien et al., 2004). There is often considerable scope for adaptation in agriculture and in some other highly managed sectors. There is much less scope for adaptation to some impacts of sea-level rise such as land loss in low-lying river deltas, and there are no realistic options for preserving many endemic species in areas that become climatically unsuitable (see Chapter 17). Adaptation assessments need to consider not only the technical feasibility of certain adaptations but also the availability of required resources (which is often reduced in circumstances of poverty), the costs and side-effects of adaptation, the knowledge about those adaptations, their timeliness, the (dis-)incentives for adaptation actors to actually implement them, and their compatibility with individual or cultural preferences.

The adaptation literature (see Chapter 17) can be largely separated into two groups: one with a more favourable view of the potential for adaptation of social systems to climate change, and an opposite group that expresses less favourable views, stressing the limits to adaptation in dealing with large climate changes and the social, financial and technical obstacles that might inhibit the actual implementation of many adaptation options (see, e.g., the debate about the Ricardian climate change impacts methods – Mendelsohn et al., 1994; Cline, 1996; Mendelsohn and Nordhaus, 1996; Kaufmann, 1998; Hanemann, 2000; Polsky and Easterling, 2001; Polsky, 2004; Schlenker et al., 2005). This chapter reports the range of views in the literature on adaptive capacity relevant for the assessment of key vulnerabilities, and notes that these very different views contribute to the large uncertainty that accompanies assessments of many key vulnerabilities.

Distribution

The distribution of climate impacts across regions and population groups raises important equity issues (see Section 19.1.2.4 for a detailed discussion). The literature concerning distributional impacts of climate change covers an increasingly broad range of categories, and includes, among others, income (Tol et al., 2004), gender (Denton, 2002; Lambrou and Laub, 2004) and age (Bunyavanich et al., 2003), in addition to regional, national and sectoral groupings. Impacts and vulnerabilities that are highly heterogeneous or which have significant distributional consequences are likely to have higher salience, and therefore a greater chance of being considered as 'key'.

Importance of the vulnerable system

A salient, though subjective, criterion for the identification of 'key vulnerabilities' is the importance of the vulnerable system or system property. Various societies and peoples may value the significance of impacts and vulnerabilities on human and natural systems differently. For example, the transformation of an existing natural ecosystem may be regarded as important if that ecosystem is the unique habitat of many endemic species or contains endangered charismatic species. On the other hand, if the livelihoods of many people depend crucially on the functioning of a system, this system may be regarded as more important than a similar system in an isolated area (e.g., a mountain snowpack system with large downstream use of the melt water versus an equally large snowpack system with only a small population downstream using the melt water).

19.3 Identification and assessment of key vulnerabilities

This section discusses what the authors have identified as possible key vulnerabilities based on the criteria specified in the Introduction and Section 19.2, and on the literature on impacts that may be considered potentially 'dangerous' in the sense of Article 2. The key vulnerabilities identified in this section are, as noted earlier, not a comprehensive list but illustrate a range of impacts relevant for policy-makers. Section 19.3.1 introduces, in condensed tabular form, key vulnerabilities, organising them by type of system, i.e., market, social, ecological or geophysical. The following sections discuss some of the key vulnerabilities by type of system, and add discussions of extreme events and an update on the 'reasons for concern' framework from the TAR. Each sub-section is cross-referenced to the relevant sections of the Fourth Assessment Report as well as primary publications from which more detail can be obtained. As noted in Section 19.1.1, the likelihood and confidence judgements in this section reflect the assessments of the authors of this chapter.

19.3.1 Introduction to Table 19.1

Table 19.1 provides short summaries of some vulnerabilities which, in the judgment of the authors of this chapter and in the light of the WGI AR4 and chapters of the WGII AR4, may be considered 'key' according to the criteria set out above in Section 19.2. The table presents vulnerabilities grouped by the following categories, described in the following text:

- Global social systems
- Regional systems
- Global biological systems
- Geophysical systems
- Extreme events

The table attempts to describe, as quantitatively as the literature allows, how impacts vary with global mean temperature increase above 1990-2000 levels. In addition, the authors of this chapter have assigned confidence estimates to this information. Where known, the table presents information regarding the dependence of effects on rates of warming, duration of the changes, exposure to the stresses, and adaptation taking into account uncertainties

Table 19.1. *Examples of potential key vulnerabilities. This list is not ordered by priority or severity but by category of system, process or group, which is either affected by or which causes vulnerability. Information is presented where available on how impacts may change at larger increases in global mean temperature (GMT). All increases in GMT are relative to circa 1990. Entries are necessarily brief to limit the size of the table, so further details, caveats and supporting evidence should be sought in the accompanying text, cross-references, and in the primary scientific studies referenced in this and other chapters of the AR4. In many cases, climate change impacts are marginal or synergistic on top of other existing and changing stresses. Confidence symbol legend: *** very high confidence, ** high confidence, * medium confidence, • low confidence. Sources in [square brackets] are from chapters in the WGII AR4 unless otherwise indicated. Where no source is given, the entries are based on the conclusions of the Chapter 19 authors.*

Systems, processes or groups at risk [cross-references]	Prime criteria for 'key vulnerability' (based on the seven criteria listed in Section 19.2)	Relationship between temperature and risk. Temperature change by 2100 (relative to 1990-2000)					
		0°C	1°C	2°C	3°C	4°C	5°C
Global social systems							
Food supply [19.3.2.2]	Distribution, Magnitude		Productivity decreases for some cereals in low latitudes */• [5.4]				
			Productivity increases for some cereals in mid/high latitudes */• [5.4]		Cereal productivity decreases in some mid/high-latitude regions */• [5.4]		
				Global production potential increases to around 3°C * [5.4, 5.6]	Global production potential very likely to decrease above about 3°C * [5.4, 5.6]		
Infrastructure [19.3.2]	Distribution, Magnitude, Timing	Damages likely to increase exponentially, sensitive to rate of climate change, change in extreme events and adaptive capacity ** [3.5, 6.5.3, 7.5].					
Health [19.3.2]	Distribution, Magnitude, Timing, Irreversibility	Current effects are small but discernible * [1.3.7, 8.2].	Although some risks would be reduced, aggregate health impacts would increase, particularly from malnutrition, diarrhoeal diseases, infectious diseases, floods and droughts, extreme heat, and other sources of risk */**. Sensitive to status of public health system *** [8.ES, 8.3, 8.4, 8.6].				
Water resources [19.3.2]	Distribution, Magnitude, Timing	Decreased water availability and increased drought in some mid latitudes and semi-arid low latitudes ** [3.2, 3.4, 3.7].	Severity of floods, droughts, erosion, water-quality deterioration will increase with increasing climate change ***. Sea-level rise will extend areas of salinisation of groundwater, decreasing freshwater availability in coastal areas *** [3.ES]. Hundreds of millions people would face reduced water supplies ** [3.5].				
Migration and conflict	Distribution, Magnitude	Stresses such as increased drought, water shortages, and riverine and coastal flooding will affect many local and regional populations **. This will lead in some cases to relocation within or between countries, exacerbating conflicts and imposing migration pressures * [19.2].					
Aggregate market impacts and distribution	Magnitude, Distribution	Uncertain net benefits and greater likelihood of lower benefits or higher damages than in TAR •. Net market benefits in many high-latitude areas; net market losses in many low-latitude areas. * [20.6, 20.7]. Most people negatively affected •/*.			Net global negative market impacts increasing with higher temperatures * [20.6]. Most people negatively affected *.		

Systems, processes or groups at risk [cross-references]	Prime criteria for ‘key vulnerability’ (based on the seven criteria listed in Section 19.2)	Relationship between temperature and risk. Temperature change by 2100 (relative to 1990-2000) 0°C 1°C 2°C 3°C 4°C 5°C
Regional systems		
Africa [19.3.3]	Distribution, Magnitude, Timing, Low Adaptive Capacity	Tens of millions of people at risk of increased water stress; increased spread of malaria • [9.2, 9.4.1, 9.4.3]. Hundreds of millions of additional people at risk of increased water stress; increased risk of malaria in highlands; reductions in crop yields in many countries, harm to many ecosystems such as Succulent Karoo • [9.4.1, 9.4.3, 9.4.4, 9.4.5].
Asia [19.3.3]	Distribution, Magnitude, Timing, Low Adaptive Capacity	About 1 billion people would face risks from reduced agricultural production potential, reduced water supplies or increases in extremes events • [10.4].
Latin America [19.3.3]	Magnitude, Irreversibility, Distribution, and Timing, Low Adaptive Capacity	Tens of millions of people at risk of water shortages • [13.ES, 13.4.3]; many endemic species at risk from land-use and climate change • (~1°C) [13.4.1, 13.4.2]. More than a hundred million people at risk of water shortages • [13.ES, 13.4.3]; low-lying coastal areas, many of which are heavily populated, at risk from sea-level rise and more intense coastal storms • (about 2-3°C) [13.4.4]. Widespread loss of biodiversity, particularly in the Amazon • [13.4.1, 13.4.2].
Polar regions [19.3.3]	Timing, Magnitude, Irreversibility, Distribution, Low Adaptive Capacity	Climate change is already having substantial impacts on societal and ecological systems ** [15.ES]. Continued warming likely to lead to further loss of ice cover and permafrost ** [15.3]. Arctic ecosystems further threatened **, although net ecosystem productivity estimated to increase ** [15.2.2, 15.4.2]. While some economic opportunities will open up (e.g., shipping), traditional ways of life will be disrupted ** [15.4, 15.7].
Small islands [19.3.3]	Irreversibility, Magnitude, Distribution, Low Adaptive Capacity	Many islands already experiencing some negative effects ** [16.2]. Increasing coastal inundation and damage to infrastructure due to sea-level rise ** [16.4].
Indigenous, poor or isolated communities [19.3.3]	Irreversibility, Distribution, Timing, Low Adaptive Capacity	Some communities already affected ** [11.4, 14.2.3, 15.4.5]. Climate change and sea-level rise add to other stresses **. Communities in low-lying coastal and arid areas are especially threatened ** [3.4, 6.4].
Drying in Mediterranean, western North America, southern Africa, southern Australia, and north-eastern Brazil [19.3.3]	Distribution, Magnitude, Timing	Climate models generally project decreased precipitation in these regions [3.4.1, 3.5.1, 11.3.1]. Reduced runoff will exacerbate limited water supplies, decrease water quality, harm ecosystems and result in decreased crop yields ** [3.4.1, 11.4].
Inter-tropical mountain glaciers and impacts on high-mountain communities [19.3.3]	Magnitude, Timing, Persistence, Low Adaptive Capacity, Distribution	Inter-tropical glaciers are melting and causing flooding in some areas; shifts in ecosystems are likely to cause water security problems due to decreased storage */** [Box 1.1, 10.ES, 10.2, 10.4.4, 13.ES, 13.2.4, 19.3]. Accelerated reduction of inter-tropical mountain glaciers. Some of these systems will disappear in the next few decades * [Box 1.1, 9.2.1, Box 9.1, 10.ES, 10.2.4, 10.4.2, 13.ES, 13.2.4.1].
Global biological systems		
Terrestrial ecosystems and biodiversity [19.3.4]	Irreversibility, Magnitude, Low Adaptive Capacity, Persistence, Rate of Change, Confidence	Many ecosystems already affected *** [1.3]. circa 20-30% species at increasingly high risk of extinction * [4.4]. Major extinctions around the globe ** [4.4] Terrestrial biosphere tends toward a net carbon source ** [4.4]
Marine ecosystems and biodiversity [19.3.4]	Irreversibility, Magnitude, Low Adaptive Capacity, Persistence, Rate of Change, Confidence	Increased coral bleaching ** [4.4] Most corals bleached ** [4.4] Widespread coral mortality *** [4.4]

Systems, processes or groups at risk [cross-references]	Prime criteria for 'key vulnerability' (based on the seven criteria listed in Section 19.2)	Relationship between temperature and risk. Temperature change by 2100 (relative to 1990-2000)					
		0°C	1°C	2°C	3°C	4°C	5°C
Global biological systems							
Freshwater ecosystems [19.3.4]	Irreversibility, Magnitude, Persistence Low Adaptive Capacity	Some lakes already showing decreased fisheries output; pole-ward migration of aquatic species ** [1.3.4, 4.4.9].		Intensified hydrological cycles, more severe droughts and floods *** [3.4.3].		Extinction of many freshwater species **, major changes in limnology of lakes **, increased salinity of inland lakes **.	
Geophysical systems							
Biogeochemical cycles [WGII 4.4.9, 19.3.5.1; WGI 7.3.3, 7.3.4, 7.3.5, 7.4.1.2, 10.4.1, 10.4.2]	Magnitude, Persistence, Confidence, Low Adaptive Capacity, Rate of Change	Ocean acidification already occurring, increasing further as atmospheric CO$_2$ concentration increases ***; ecological changes are potentially severe * [1.3.4, 4.4.9]. Carbon cycle feedback increases projected CO$_2$ concentrations by 2100 by 20-220 ppm for SRES[2] A2, with associated additional warming of 0.1 to 1.5°C **. AR4 temperature range (1.1-6.4°C) accounts for this feedback from all scenarios and models but additional CO$_2$ and CH$_4$ releases are possible from permafrost, peat lands, wetlands, and large stores of marine hydrates at high latitudes * [4.4.6, 15.4.2]. Permafrost already melting, and above feedbacks generally increase with climate change, but eustatic sea-level rise likely to increase stability of hydrates *** [1.3.1].					
Greenland ice sheet [WGII 6.3, 19.3.5.2; WGI 6.4.3.3, 10.7.4.3]	Magnitude, Irreversibility, Low Adaptive Capacity, Confidence	Localised deglaciation (already observed, due to local warming); extent would increase with temperature increase *** [19.3.5].		Commitment to widespread ** to near-total * deglaciation, 2-7 m sea-level rise[3] over centuries to millennia * [19.3.5].		Near-total deglaciation **[19.3.5]	
West Antarctic ice sheet [WGII 6.3, 19.3.5.2; WGI 6.4.3.3, 10.7.4.4]	Magnitude, Irreversibility, Low Adaptive Capacity	Localised ice shelf loss and grounding line retreat * (already observed, due to local warming) [1.3.1, 19.3.5]		Commitment to partial deglaciation, 1.5-5 m sea-level rise over centuries to millennia •/* [19.3.5] Likelihood of near-total deglaciation increases with increases in temperature ** [19.3.5]			
Meridional overturning circulation [WGII 19.3.5.3; WGI 8.7.2.1, 10.3.4]	Magnitude, Persistence, Distribution, Timing, Low Adaptive Capacity, Confidence	Variations including regional weakening (already observed but no trend identified)		Considerable weakening **. Commitment to large-scale and persistent change including possible cooling in northern high-latitude areas near Greenland and north-west Europe • highly dependent on rate of climate change [12.6, 19.3.5].			
Extreme events							
Tropical cyclone intensity [WGII 7.5, 8.2, 11.4.5, 16.2.2, 16.4, 19.3.6; WGI Table TS-4, 3.8.3, Q3.3, 9.5.3.6, Q10.1]	Magnitude, Timing, Distribution	Increase in Category 4-5 storms*/**, with impacts exacerbated by sea-level rise		Further increase in tropical cyclone intensity */** exceeding infrastructure design criteria with large economic costs ** and many lives threatened **.			
Flooding, both large-scale and flash floods [WGII 14.4.1; WGI Table TS-4, 10.3.6.1, Q10.1]	Timing, Magnitude	Increases in flash flooding in many regions due to increased rainfall intensity** and in floods in large basins in mid and high latitudes **.		Increased flooding in many regions (e.g., North America and Europe) due to greater increase in winter rainfall exacerbated by loss of winter snow storage **. Greater risk of dam burst in glacial mountain lakes ** [10.2.4.2].			
Extreme heat [WGII 14.4.5; WGI Table TS-4, 10.3.6.2, Q10.1]	Timing, Magnitude	Increased heat stress and heat-waves, especially in continental areas ***.		Frequency of heatwaves (according to current classification) will increase rapidly, causing increased mortality, crop failure, forest die-back and fire, and damage to ecosystems ***.			
Drought [WGI Table TS-4, 10.3.6.1]	Magnitude, Timing	Drought already increasing * [1.3.2.1]. Increasing frequency and intensity of drought in mid-latitude continental areas projected ** [WGI 10.3.6.1].		Extreme drought increasing from 1% land area to 30% (SRES A2 scenario) [WGI 10.3.6.1]. Mid-latitude regions seriously affected by poleward migration of Annular Modes ** [WGI 10.3.5.5].			
Fire [WGII 1.3.6; WGI 7.3]	Timing, Magnitude	Increased fire frequency and intensity in many areas, particularly where drought increases ** [4.4, 14.2.2].		Frequency and intensity likely to be greater, especially in boreal forests and dry peat lands after melting of permafrost ** [4.4.5, 11.3, 13.4.1, 14.4.2, 14.4.4].			

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[2] SRES: Special Report on Emissions Scenarios, see Nakićenović et al., 2000.

[3] Range is based on a variety of methods including models and analysis of palaeo data [19.3.5.2]

regarding socio-economic development. However, only in a few cases does the literature address rate or duration of warming and its consequences. As entries in the table are necessarily short, reference should be made to the relevant chapters and to the accompanying text in this chapter for more detailed information and cross-referencing, including additional caveats where applicable.

19.3.2 Global social systems

The term 'social systems' is used here in a broad sense to describe human systems, and includes both market systems and social systems. Market systems typically involve the provision and sale of goods and services in formal or informal markets. Valuation of non-market impacts (e.g., losses of human life, species lost, distributional inequity, etc.) involves a series of normative judgements that limit the degree of consensus and confidence commanded by different studies (see Section 19.1.2). The importance of non-market impacts and equity weighting is suggested by Stern (2007) but, in the absence of likelihood and confidence assessments, it is difficult to apply to any risk-management framework calculations.

We first discuss impacts on major market systems, followed by a discussion of impacts on major aspects of social systems. Such impacts are often considered to be important in the context of sustainable development.

19.3.2.1 Agriculture

Ensuring that food production is not threatened is an explicit criterion of UNFCCC Article 2. In general, low-latitude areas are most at risk of having decreased crop yields. In contrast, mid- and high-latitude areas could generally, although not in all locations, see increases in crop yields for temperature increases of up to 1-3°C (see Chapter 5 Section 5.4.2). Taken together, there is low to medium confidence that global agricultural production could increase up to approximately 3°C of warming. For temperature increases beyond 1-3°C, yields of many crops in temperate regions are projected to decline (•/*[4]). As a result, beyond 3°C warming, global production would decline because of climate change (•/*) and the decline would continue as GMT increases (•/*). Most studies on global agriculture have not yet incorporated a number of critical factors, including changes in extreme events or the spread of pests and diseases. In addition, they have not considered the development of specific practices or technologies to aid adaptation.

19.3.2.2 Other market sectors

Other market systems will also be affected by climate change. These include the livestock, forestry and fisheries industries, which are very likely to be directly affected as climate affects the quality and extent of rangeland for animals, soils and other growing conditions for trees, and freshwater and marine ecosystems for fish. Other sectors are also sensitive to climate change. These include energy, construction, insurance, tourism and recreation. The aggregate effects of climate change on many of these sectors has received little attention in the literature and remains highly uncertain. Some sectors are likely to see shifts in expenditure; with some contracting and some expanding. Yet, for some sectors, such as insurance, the impacts of climate change are likely to result in increased damage payments and premiums (see Chapter 7).

Other sectors, such as tourism and recreation, are likely to see some substantial shifts (e.g., reduction in ski season, loss of some ski areas, shifts in location of tourist destinations because of changes in climate and extreme events; e.g., Hamilton et al., 2005; see also Chapter 7 Section 7.4.2 and Chapter 14 Section 14.4.7). Global net energy demand is very likely to change (Tol, 2002b). Demand for air-conditioning is highly likely to increase, whereas demand for heating is highly likely to decrease. The literature is not clear on what temperature is associated with minimum global energy demand, so it is uncertain whether warming will initially increase or decrease net global demand for energy relative to some projected baseline. However, as temperatures rise, net global demand for energy will eventually rise as well (Hitz and Smith, 2004).

19.3.2.3 Aggregate market impacts

The total economic impacts from climate change are highly uncertain. Depending upon the assumptions used (e.g., climate sensitivity, discount rate and regional aggregation) total economic impacts are typically estimated to be in the range of a few percent of gross world product for a few degrees of warming (see Chapter 20). Some estimates suggest that gross world product could increase up to about 1-3°C warming, largely because of estimated direct CO_2 effects on agriculture, but such estimates carry only low confidence. Even the direction of gross world product change with this level of warming is highly uncertain. Above the 1-3°C level of warming, available studies indicate that gross world product could decrease (•). For example, Tol (2002a) estimates net positive global market impacts at 1°C when weighting by economic output, but finds much smaller positive impacts when equity-weighted. Nordhaus (2006) uses a geographically based method and finds more negative economic impacts than previous studies, although still in the range of a few percent of gross world product.

Studies of aggregate market impacts tend to rely on scenarios of average changes in climate and focus on direct economic effects alone. Potential damages from increased severity of extreme climate events are often not included. The damages from an increase in extreme events could substantially increase market damages, especially at larger magnitudes of climate change (*). Also, recent studies draw attention to indirect effects of climate change on the economy (e.g., on capital accumulation and investment, on savings rate); although there is debate about methods, the studies agree that such effects could be significant and warrant further attention (see Section 19.3.7; Fankhauser and Tol, 2005; Kemfert, 2006; Roson and Tol, 2006; Fisher et al., 2007).

19.3.2.4 Distribution of market impacts

Global market impacts mask substantial variation in market impacts at the continental, regional, national and local scales. Even if gross world product were to change just a few percent, national economies could be altered by relatively large amounts.

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[4] The following confidence symbols are used: *** very high confidence, ** high confidence, * medium confidence, • low confidence.

For example, Maddison (2003) reports increases in cost of living in low-latitude areas and decreases in high-latitude areas from a 2.5°C warming. All studies with regional detail show Africa, for example, with climate damages of the order of several percent of gross domestic product (GDP) at 2°C increase in GMT or even lower levels of warming (*). As noted below, very small economies such as Kiribati face damages from climate change in the range of 20% of their GDP (•) (see Chapter 16 Section 16.4.3). The distributional heterogeneity in market system impacts reflects the equity criterion described in Section 19.2 when considering which impacts may be considered 'key'.

19.3.2.5 Societal systems

With regard to vulnerability of societal systems, there are myriad thresholds specific to particular groups and systems at specific time-frames beyond which they can be vulnerable to variability and to climate change (Yamin et al., 2005). These differences in vulnerability are a function of a number of factors. Exposure is one key factor. For example, crops at low latitudes will have greater exposure to higher temperatures than crops at mid- and high latitudes. Thus, yields for grain crops, which are sensitive to heat, are more likely to decline at lower latitudes than at higher latitudes. Social systems in low-lying coastal areas will vary in their exposure and adaptive capacities, yet most will have increased vulnerability with greater warming and associated sea-level rises or storm surges.

A second key factor affecting vulnerability is the capacity of social systems to adapt to their environment, including coping with the threats it may pose, and taking advantage of beneficial changes. Smit et al. (2001) identified a number of determinants of adaptive capacity, including such factors as wealth, societal organisation and access to technology (see also Yohe and Tol, 2002). These attributes differentiate vulnerability to climate change across societies facing similar exposure. For example, Nicholls (2004) and Nicholls and Tol (2006) found that level of development and population growth are very important factors affecting vulnerability to sea-level rise. The specific vulnerabilities of communities with climate-related risks, such as the elderly and the poor or indigenous communities, are typically much higher than for the population as a whole (see Section 14.2.6)

Even though some cold-related deaths and infectious disease exposure are likely to be reduced, on balance there is medium confidence that global mortality will increase as a result of climate change. It is estimated that an additional 5-170 million people will be at risk of hunger by the 2080s as a consequence of climate change (Chapter 5 Section 5.6.5). There is medium to high confidence that some other climate-sensitive health outcomes, including heatwave impacts, diarrhoeal diseases, flood-related risks, and diseases associated with exposure to elevated concentrations of ozone and aeroallergens, will increase with GMT (Chapter 8 Section 8.4.1). Development and adaptation are key factors influencing human health risk (Chapter 8 Section 8.6).

Vulnerability associated with water resources is complex because vulnerability is quite region-specific. In addition, the level of development and adaptation and social factors determining access to water are very important in determining vulnerability in the water sector. Studies differ as to whether climate change will increase or decrease the number of people living in water-stressed areas (e.g., Parry et al., 1999; Arnell, 2004; Hitz and Smith, 2004; Alcamo et al., 2007). Hundreds of millions of people are estimated to be affected by changes in water quantity and quality (Chapter 3 Section 3.4.3; Arnell, 2004) but uncertainties limit confidence and thus the degree to which these risks might be labelled as 'key'. Floods and droughts appear to have increased in some regions and are likely to become more severe in the future (Chapter 3 Section 3.4.3).

19.3.3 Regional vulnerabilities

Many of the societal impacts discussed above will be felt within the regions assessed as part of the AR4. At a regional and sub-regional scale, vulnerabilities can vary quite considerably. For example, while mid- and high-latitude areas would have increased crop yields up to about 3°C of warming, low-latitude areas would face decreased yields and increased risks of malnutrition at lower levels of warming (•/*) (Chapter 5 Section 5.4.2; Parry et al., 2004).

Africa is likely to be the continent most vulnerable to climate change. Among the risks the continent faces are reductions in food security and agricultural productivity, particularly regarding subsistence agriculture (Chapter 9 Sections 9.4.4 and 9.6.1; Parry et al., 2004; Elasha et al., 2006), increased water stress (Chapter 9 Section 9.4.1) and, as a result of these and the potential for increased exposure to disease and other health risks, increased risks to human health (Chapter 9 Section 9.4.3). Other regions also face substantial risks from climate change. Approximately 1 billion people in South, South-East, and East Asia would face increased risks from reduced water supplies (•) (Chapter 10 Section 10.4.2), decreased agricultural productivity (•) (Chapter 10 Section 10.4.1.1), and increased risks of floods, droughts and cholera (*) (Chapter 10 Section 10.4.5). Tens of millions to over a hundred million people in Latin America would face increased risk of water stress (•) (Chapter 13 Section 13.4.3). Low-lying, densely populated coastal areas are very likely to face risks from sea-level rise and more intense extreme events (Chapter 13 Section 13.4.4). The combination of land-use changes and climate change is very likely to reduce biodiversity substantially (Chapter 13 Section 13.2.5.1).

There is very high confidence that human settlements in polar regions are already being adversely affected by reduction in ice cover and coastal erosion (Chapter 15 Section 15.2.2). Future climate change is very likely to result in additional disruption of traditional cultures and loss of communities. For example, warming of freshwater sources poses risks to human health because of transmission of disease (*) (Martin et al., 2005). Shifts in ecosystems are very likely to alter traditional use of natural resources, and hence lifestyles.

Small islands, particularly several small island states, are likely to experience large impacts due to the combination of higher exposure, for example to sea-level rise and storm surge, and limited ability to adapt (Chapter 16 Sections 16.ES, 16.2.1 and 16.4). There is very high confidence that many islands are already experiencing some negative effects of climate change (Chapter 1 Section 1.3.3; Chapter 16 Section 16.4). The long-term sustainability of small-island societies is at great risk from climate change, with sea-level rise and extreme events posing particular challenges on account of their limited size, proneness to natural hazards and external shocks combined with limited adaptive capacity and high costs relative to GDP. Subsistence and commercial agriculture on small islands is likely to be adversely affected by climate change and sea-level rise, as a result of inundation, seawater intrusion into freshwater lenses, soil salinisation, decline in water supply and deterioration of water quality (Chapter 16 Executive Summary and Section 16.4). A group of low-lying islands, such as Tarawa and Kiribati, would face average annual damages of 17 to 18% of its economy by 2050 under the SRES A2 and B2 scenarios (•) (Chapter 16 Section 16.4.3).

Even in developed countries, there are many vulnerabilities. Arnell (2004) estimated a 40 to 50% reduction in runoff in southern Europe by the 2080s (associated with a 2 to 3°C increase in global mean temperature). Fires will very likely continue to increase in arid and semi-arid areas such as Australia and the western USA, threatening development in wildland areas (Chapter 4 Section 4.4.4; Chapter 11 Section 11.3.1; Chapter 14 Box 14.1 and Section 14.4.4; Westerling et al., 2006). Climate change is likely to increase the frequency and intensity of extreme heat events, as well as concentrations of air pollutants, such as ozone, which increase mortality and morbidity in urban areas (see Chapters 8, 11, 12 and 14).

19.3.4 Ecosystems and biodiversity

There is high confidence that climate change will result in extinction of many species and reduction in the diversity of ecosystems (see Section 4.4) Vulnerability of ecosystems and species is partly a function of the expected rapid rate of climate change relative to the resilience of many such systems. However, multiple stressors are significant in this system, as vulnerability is also a function of human development, which has already substantially reduced the resilience of ecosystems and makes many ecosystems and species more vulnerable to climate change through blocked migration routes, fragmented habitats, reduced populations, introduction of alien species and stresses related to pollution.

There is very high confidence that regional temperature trends are already affecting species and ecosystems around the world (Chapter 1 Sections 1.3.4 and 1.3.5; Parmesan and Yohe, 2003; Root et al., 2003; Menzel et al., 2006) and it is likely that at least part of the shifts in species observed to be exhibiting changes in the past several decades can be attributed to human-induced warming (see Chapter 1; Root et al., 2005). Thus, additional climate changes are likely to adversely affect many more species and ecosystems as global mean temperatures continue to increase (see Section 4.4). For example, there is high confidence that the extent and diversity of polar and tundra ecosystems is in decline and that pests and diseases have spread to higher latitudes and altitudes (Chapter 1 Sections 1.3.5 and 1.5).

Each additional degree of warming increases disruption of ecosystems and loss of species. Individual ecosystems and species often have different specific thresholds of change in temperature, precipitation or other variables, beyond which they are at risk of disruption or extinction. Looking across the many ecosystems and thousands of species at risk of climate change, a continuum of increasing risk of loss of ecosystems and species emerges in the literature as the magnitude of climate change increases, although individual confidence levels will vary and are difficult to assess. Nevertheless, further warming is likely to cause additional adverse impacts to many ecosystems and contribute to biodiversity losses. Some examples follow.

- About half a degree of additional warming can cause harm to vulnerable ecosystems such as coral reefs and Arctic ecosystems * (Table 4.1).
- A warming of 1°C above 1990 levels would result in all coral reefs being bleached and 10% of global ecosystems being transformed (Chapter 4 Section 4.4.11).
- A warming of 2°C above 1990 levels will result in mass mortality of coral reefs globally *** (Chapter 4 Section 4.4; Chapter 6 Box 6.1), with one-sixth of the Earth's ecosystems being transformed (Leemans and Eickhout, 2004) **, and about one-quarter of known species being committed to extinction *. For example, if Arctic sea-ice cover recedes markedly, many ice-dependent Arctic species, such as polar bears and walrus, will be increasingly likely to be at risk of extinction; other estimates suggest that the African Succulent Karoo is likely to lose four-fifths of its area (Chapter 4 Section 4.4.11 and Table 4.1). There is low confidence that the terrestrial biosphere will become a net source of carbon (Chapter 4 Section 4.4.1).
- An additional degree of warming, to 3°C, is likely to result in global terrestrial vegetation becoming a net source of carbon (Chapter 4 Section 4.4.1), over one-fifth of ecosystems being transformed * (Chapter 4 Section 4.4.11; Leemans and Eickhout, 2003), up to 30% of known species being committed to extinction * (Chapter 4 Section 4.4.11 and Table 4.1; Thomas et al., 2004; Malcolm et al., 2006, estimate that 1 to 43% of species in 25 biodiversity hotspots are at risk from an approximate 3 to 4°C warming) and half of all nature reserves being unable to meet conservation objectives * (Chapter 4 Table 4.1). Disturbances such as fire and pests are very likely to increase substantially (Chapter 4 Section 4.4).
- There is very high confidence that warming above 3°C will cause further disruption of ecosystems and extinction of species.

19.3.5 Geophysical systems

A number of Earth-system changes may be classified as key impacts resulting in key vulnerabilities.

19.3.5.1. Global biogeochemical cycles

The sensitivity of the carbon cycle to increased CO_2 concentrations and climate change is a key vulnerability due to its magnitude, persistence, rate of change, low adaptive capacity and the level of confidence in resulting impacts. Models suggest that the overall effect of carbon–climate interactions is a positive feedback (Denman et al., 2007 Section 7.1.5). As CO_2 concentrations increase and climate changes, feedbacks from terrestrial stores of carbon in forests and grasslands, soils, wetlands, peatlands and permafrost, as well as from the ocean, would reduce net uptake of CO_2 (Denman et al., 2007 Sections 7.3.3 and 7.3.4). Hence the predicted atmospheric CO_2 concentration in 2100 is higher (and consequently the climate is warmer) than in models that do not include these couplings (Denman et al., 2007 Section 7.1.5). An intercomparison of ten climate models with a representation of the land and ocean carbon cycle forced by the SRES A2 emissions scenario (Denman et al., 2007 Section 7.3.5; Meehl et al., 2007 Section 10.4.1) shows that, by the end of the 21st century, additional CO_2 varies between 20 and 200 ppm for the two extreme models, with most of the models projecting additional CO_2 between 50 and 100 ppm (Friedlingstein et al., 2003), leading to an additional warming ranging between 0.1 and 1.5°C. A similar range results from estimating the effect including forcing from aerosols and non-CO_2 greenhouse gases (GHGs). Such additional warming would increase the number and severity of impacts associated with many key vulnerabilities identified in this chapter. In addition, these feedbacks reduce the emissions (Meehl et al., 2007 Section 10.4.1) compatible with a given atmospheric CO_2 stabilisation pathway (**)

At the regional level (see Chapters 4, 10, 11, 12 and 14), important aspects of the carbon–climate interaction include the role of fire (Denman et al., 2007 Section 7.3.3.1.4) in transient response and possible abrupt land-cover transitions from forest to grassland or grassland to semi-arid conditions (Claussen et al., 1999; Eastman et al., 2001; Cowling et al., 2004; Rial et al., 2004).

Warming destabilises permafrost and marine sediments of methane gas hydrates in some regions according to some model simulations (Denman et al., 2007 Section 7.4.1.2), as has been proposed as an explanation for the rapid warming that occurred during the Palaeocene/Eocene thermal maximum (Dickens, 2001; Archer and Buffett, 2005). A rising eustatic (global) contribution to sea level is estimated to stabilise hydrates to some degree. One study (Harvey and Huang, 1995) reports that methane releases may increase very long-term future temperature by 10-25% over a range of scenarios. Most studies also point to increased methane emissions from wetlands in a warmer, wetter climate (Denman et al., 2007 Section 7.4.1.2).

Increasing ocean acidity due to increasing atmospheric concentrations of CO_2 (Denman et al., 2007 Section 7.3.4.1; Sabine et al., 2004; Royal Society, 2005) is very likely to reduce biocalcification of marine organisms such as corals (Hughes et al., 2003; Feely et al., 2004). Though the limited number of studies available makes it difficult to assess confidence levels, potentially severe ecological changes would result from ocean acidification, especially for corals in tropical stably stratified waters, but also for cold water corals, and may influence the marine food chain from carbonate-based phytoplankton up to higher trophic levels (Denman et al., 2007 Section 7.3.4.1; Turley et al., 2006).

19.3.5.2 Deglaciation of West Antarctic and Greenland ice sheets

The potential for partial or near-total deglaciation of the Greenland and the West Antarctic ice sheets (WAIS) and associated sea-level rise (Jansen et al., 2007 Sections 6.4.3.2 and 6.4.3.3; Meehl et al., 2007 Sections 10.6.4, 10.7.4.3 and 10.7.4.4; Alley et al., 2005; Vaughan, 2007), is a key impact that creates a key vulnerability due to its magnitude and irreversibility, in combination with limited adaptive capacity and, if substantial deglaciation occurred, high levels of confidence in associated impacts. Ice sheets have been discussed specifically in the context of Article 2 (O'Neill and Oppenheimer 2002; Hansen, 2005; Keller et al., 2005; Oppenheimer and Alley, 2005). Near-total deglaciation would eventually lead to a sea-level rise of around 7 m and 5 m (***) from Greenland and the WAIS, respectively, with wide-ranging consequences including a reconfiguration of coastlines worldwide and inundation of low-lying areas, particularly river deltas (Schneider and Chen, 1980; Revelle, 1983; Tol et al., 2006; Vaughan, 2007). Widespread deglaciation would not be reversible except on very long time-scales, if at all (Meehl et al., 2007 Sections 10.7.4.3 and 10.7.4.4). The Amundsen Sea sector of the WAIS, already experiencing ice acceleration and rapid ground-line retreat (Lemke et al., 2007 Section 4.6.2.2), on its own includes ice equivalent to about 1.5 m sea-level rise (Meehl et al., 2007 Section 10.7.4.4; Vaughan, 2007). The ability to adapt would depend crucially on the rate of deglaciation (**). Estimates of this rate and the corresponding time-scale for either ice sheet range from more rapid (several centuries for several metres of sea-level rise, up to 1 m/century) to slower (i.e., a few millennia; Meehl et al., 2007 Section 10.7.4.4; Vaughan and Spouge, 2002), so that deglaciation is very likely to be completed long after it is first triggered.

For Greenland, the threshold for near-total deglaciation is estimated at 3.2-6.2°C local warming (1.9-4.6°C global warming) relative to pre-industrial temperatures using current models (Meehl et al., 2007 Section 10.7.4.3). Such models also indicate that warming would initially cause the Antarctic ice sheet as a whole to gain mass owing to an increased accumulation of snowfall (*; some recent studies find no significant continent-wide trends in accumulation over the past several decades; Lemke et al., 2007 Section 4.6.3.1). Scenarios of deglaciation (Meehl et al., 2007 Section 10.7.4.4) assume that any such increase would be outweighed by accelerated discharge of ice following weakening or collapse of an ice shelf due to melting at its surface or its base (*). Mean summer temperatures over the major West Antarctic ice shelves are about as likely as not to pass the melting point if global warming exceeds 5°C (Meehl et al., 2007 Section 10.7.4.4). Some studies suggest that disintegration of ice shelves would occur at lower temperatures due to basal or episodic surface melting (Meehl et al., 2007 Sections 10.6.4.2 and 10.7.4.4; Wild et al., 2003). Recent observations of unpredicted, local acceleration and consequent loss of mass from both ice sheets (Alley et al., 2005) underscores the inadequacy of existing ice-sheet models, leaving no generally agreed basis for projection, particularly for WAIS (Lemke et al., 2007 Section 4.6.3.3; Meehl et al., 2007 Sections 10.6.4.2 and 10.7.4.4; Vieli and Payne, 2005). However, palaeoclimatic evidence (Denman et al., 2007 Sections 6.4.3.2 and 6.4.3.3; Overpeck et al., 2006; Otto-Bliesner et al., 2006) suggests that Greenland and possibly the WAIS contributed to a sea-level rise of 4-6 m during the last interglacial, when polar temperatures were 3-5°C warmer, and the global mean was not notably warmer, than at present (Meehl et al., 2007 Sections

10.7.4.3 and 10.7.4.4). Accordingly, there is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the WAIS, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more (Meehl et al., 2007 Sections 10.7.4.3 and 10.7.4.4; Oppenheimer and Alley, 2004, 2005; Hansen, 2005).

Current limitations of ice-sheet modelling also increase uncertainty in the projections of 21st-century sea-level rise (Meehl et al., 2007 Section 10.6.4.2) used to assess coastal impacts in this report. An illustrative estimate by WGI of the contribution of processes not represented by models yielded an increase of 0.1-0.2 m in the upper ranges of projected sea-level rise for 2100 (Meehl et al., 2007 Section 10.6.4.2). Other approximation methods would yield larger or smaller adjustments, including zero.

19.3.5.3 Possible changes in the North Atlantic meridional overturning circulation (MOC)

The sensitivity of the North Atlantic meridional overturning circulation (MOC) (cf., WGI AR4 Glossary; Bindoff et al., 2007 Box 5.1) to anthropogenic forcing is regarded as a key vulnerability due to the potential for sizeable and abrupt impacts (Tol, 1998; Keller et al., 2000; Mastrandrea and Schneider, 2001; Alley et al., 2003; Rahmstorf et al., 2003; Link and Tol, 2004, 2006; Higgins and Schneider, 2005; Sathaye et al., 2007).

Palaeo-analogues and model simulations show that the MOC can react abruptly and with a hysteresis response, once a certain forcing threshold is crossed (Randall et al., 2007; Meehl et al., 2007). Estimates of the forcing threshold that would trigger large-scale and persistent MOC changes rely on three main lines of evidence. The first, based on the analysis of coupled Atmosphere-Ocean General Circulation Models (AOGCMs), do not show MOC collapse in the 21st century (Meehl et al., 2007 Box 10.1). Assessing the confidence in this is, however, difficult, as these model runs sample only a subset of potentially relevant uncertainties (e.g., Challenor et al., 2006) and do not cross the forcing thresholds suggested by the second line of evidence: simulations using Earth system models of intermediate complexity (EMICs) (Randall et al., 2007 Section 8.8.3; Meehl et al., 2007 10.3.4). EMIC simulations, which use simplified representations of processes to explore a wider range of uncertainties, suggest that the probability that forcing would trigger an MOC threshold response during the 21st century could exceed estimates derived from AOGCM runs alone (e.g., Challenor et al., 2006). The third line of evidence, not assessed by Working Group I, relies on expert elicitations (sometimes combined with the analysis of simple climate models). These MOC projections show a large spread, with some suggesting a substantial likelihood of triggering a MOC threshold response within this century (Arnell et al., 2005; Rahmstorf and Zickfeld, 2005; McInerney and Keller, 2006; Schlesinger et al., 2006; Yohe et al., 2006).

Potential impacts associated with MOC changes include reduced warming or (in the case of abrupt change) absolute cooling of northern high-latitude areas near Greenland and north-western Europe, an increased warming of Southern Hemisphere high latitudes, tropical drying (Vellinga and Wood, 2002, 2006; Wood et al., 2003, 2006), as well as changes in marine ecosystem productivity (Schmittner, 2005), terrestrial vegetation (Higgins and Vellinga, 2004), oceanic CO_2 uptake (Sarmiento and Le Quéré, 1996), oceanic oxygen concentrations (Matear and Hirst, 2003) and shifts in fisheries (Keller et al., 2000; Link and Tol, 2004). Adaptation to MOC-related impacts is very likely to be difficult if the impacts occur abruptly (e.g., on a decadal time-scale). Overall, there is high confidence in predictions of a MOC slowdown during the 21st century, but low confidence in the scale of climate change that would cause an abrupt transition or the associated impacts (Meehl et al., 2007 Section 10.3.4). However, there is high confidence that the likelihood of large-scale and persistent MOC responses increases with the extent and rate of anthropogenic forcing (e.g., Stocker and Schmittner, 1997; Stouffer and Manabe, 2003).

19.3.5.4 Changes in the modes of climate variability

Change in the modes of climate variability in response to anthropogenic forcing can lead to key impacts because these modes dominate annual-to-decadal variability, and adaptation to variability remains challenging in many regions. For example, some studies suggest that anthropogenic forcings would affect El Niño-Southern Oscillation (ENSO) variability (Timmermann et al., 1999; Fedorov and Philander, 2000; Fedorov et al., 2006; Hegerl et al., 2007 Section 9.5.3.1; Meehl et al., 2007 Section 10.3.5.3-5). Current ENSO projections are marked by many uncertainties, including

- the potential for an abrupt and/or hysteresis response,
- the direction of the shift,
- the level of warming when triggered.

ENSO shifts would affect agriculture (Cane et al., 1994; Legler et al., 1999), infectious diseases (Rodo et al., 2002), water supply, flooding, droughts (Kuhnel and Coates, 2000; Cole et al., 2002), wildfires (Swetnam and Betancourt, 1990), tropical cyclones (Pielke and Landsea, 1999; Emanuel, 2005), fisheries (Lehodey et al., 1997), carbon sinks (Bacastow et al., 1980) and the North Atlantic MOC (Latif et al., 2000).

The North Atlantic Oscillation (NAO) and the Annular Mode in both the Northern and Southern Hemispheres (also known as the Arctic Oscillation, AO, and the Antarctic Oscillation, AAO; Meehl et al., 2007 Section 10.3.5.6; Hartmann et al., 2000; Thompson and Wallace, 2000; Fyfe et al., 1999; Kushner et al., 2001; Cai et al., 2003; Gillett et al., 2003; Kuzmina et al., 2005) are likely to be affected by greenhouse forcing and ozone depletion. For example, the average of the IPCC WGI AR4 simulations from thirteen models shows a positive trend for the Northern Annular Mode that becomes statistically significant early in the 21st century (Meehl et al., 2007 Section 10.3.5.6). Such changes would affect surface pressure patterns, storm tracks and rainfall distributions in the mid and high latitudes of both hemispheres, with potentially serious impacts on regional water supplies, agriculture, wind speeds and extreme events. Implications are potentially severe for water resources and storminess in Australia, New Zealand, southern Africa, Argentina and Chile, southern Europe, and possibly parts of the USA where Mediterranean-type climates prevail.

Current forcing may have caused changes in these modes but observed changes are also similar to those simulated in AOGCMs in the absence of forcing (Cai et al., 2003). There is some evidence for a weakening of major tropical monsoon circulations (AR4 WGI 3.7.1, 9.5.3.5). Projections of monsoon precipitation show a complex pattern of increases (e.g., Australia in the southern summer and Asia), and decreases (e.g., the Sahel in the northern summer) (Meehl et al., 2007 Section 10.3.5.2). Confidence in projections of specific monsoonal changes is low to medium.

19.3.6 Extreme events

As discussed in WGI AR4 Technical Summary (Solomon et al., 2007) Box TS.5 and Table TS.4, various extreme events are very likely to change in magnitude and/or frequency and location with global warming. In some cases, significant trends have been observed in recent decades (Trenberth et al., 2007 Table 3.8).

The most likely changes are an increase in the number of hot days and nights (with some minor regional exceptions), or in days exceeding various threshold temperatures, and decreases in the number of cold days, particularly including frosts. These are virtually certain to affect human comfort and health, natural ecosystems and crops. Extended warmer periods are also very likely to increase water demand and evaporative losses, increasing the intensity and duration of droughts, assuming no increases in precipitation.

Precipitation is generally predicted in climate models to increase in high latitudes and to decrease in some mid-latitude regions, especially in regions where the mid-latitude westerlies migrate polewards in the summer season, thus steering fewer storms into such ‘Mediterranean climates’ (Meehl et al., 2007 Section 10.3.2.3). These changes, together with a general intensification of rainfall events (Meehl et al., 2007 Section 10.3.6.1), are very likely to increase the frequency of flash floods and large-area floods in many regions, especially at high latitudes. This will be exacerbated, or at least seasonally modified in some locations, by earlier melting of snowpacks and melting of glaciers. Regions of constant or reduced precipitation are very likely to experience more frequent and intense droughts, notably in Mediterranean-type climates and in mid-latitude continental interiors.

Extended warm periods and increased drought will increase water stress in forests and grasslands and increase the frequency and intensity of wildfires (Cary, 2002; Westerling et al., 2006), especially in forests and peatland, including thawed permafrost. These effects may lead to large losses of accumulated carbon from the soil and biosphere to the atmosphere, thereby amplifying global warming (**) (see Sections 4.4.1, 19.3.5.1; Langmann and Heil, 2004; Angert et al., 2005; Bellamy et al., 2005).

Tropical cyclones (including hurricanes and typhoons), are likely to become more intense with sea surface temperature increases, with model simulations projecting increases by mid-century (Meehl et al., 2007 Section 10.3.6.3). However, despite an ongoing debate, some data reanalyses suggest that, since the 1970s, tropical cyclone intensities have increased far more rapidly in all major ocean basins where tropical cyclones occur (Trenberth et al., 2007 Section 3.8.3), and that this is consistently related to increasing sea surface temperatures. Some authors have questioned the reliability of these data, in part because climate models do not predict such large increases; however, the climate models could be underestimating the changes due to inadequate spatial resolution. This issue currently remains unresolved. Some modelling experiments suggest that the total number of tropical cyclones is expected to decrease slightly (Meehl et al., 2007 Section 10.3.6.3), but it is the more intense storms that have by far the greatest impacts and constitute a key vulnerability.

The combination of rising sea level and more intense coastal storms, especially tropical cyclones, would cause more frequent and intense storm surges, with damages exacerbated by more intense inland rainfall and stronger winds (see Section 6.3.2). Increasing exposure occurs as coastal populations increase (see Section 6.3.1).

Many adaptation measures exist that could reduce vulnerability to extreme events. Among them are dams to provide flood protection and water supply, dykes and coastal restoration for protection against coastal surges, improved construction standards, land-use planning to reduce exposure, disaster preparedness, improved warning systems and evacuation procedures, and broader availability of insurance and emergency relief (see Chapter 18). However, despite considerable advances in knowledge regarding weather extremes, the relevant adaptation measures are underused, partly for reasons of cost, especially in developing countries (White et al., 2001; Sections 7.4.3, 7.5 and 7.6). Despite progress in reducing the mortality associated with many classes of extremes, human societies, particularly in the developing world, are not well adapted to the current baseline of climate variability and extreme events, such as tropical cyclones, floods and droughts, and thus these impacts are often assessed as key vulnerabilities.

19.3.7 Update on ‘Reasons for Concern’

The TAR (Smith et al., 2001; IPCC, 2001b) identified five ‘reasons for concern’ about climate change and showed schematically how their seriousness would increase with global mean temperature change. In this section, the ‘reasons for concern’ are updated.

Unique and threatened systems

The TAR concluded that there is medium confidence that an increase in global mean temperature of 2°C above 1990 levels or less would harm several such systems, in particular coral reefs and coastal regions.

Since the TAR, there is new and much stronger evidence of observed impacts of climate change on unique and vulnerable systems (see Sections 1.3.4 and 1.3.5; Parmesan and Yohe, 2003; Root et al., 2003, 2005; Menzel et al., 2006), many of which are described as already being adversely affected by climate change. This is particularly evident in polar ecosystems (e.g., ACIA, 2005). Furthermore, confidence has increased that an increase in global mean temperature of up to 2°C relative to 1990 temperatures will pose significant risks to many unique and vulnerable systems, including many biodiversity hotspots (e.g., Hare, 2003; Leemans and Eickhout, 2004; Malcolm et al., 2006). In summary, there is now high confidence that a warming of up to 2°C above 1990-2000 levels would have significant impacts on many unique and vulnerable systems, and is likely to increase the endangered status of many threatened species, with increasing adverse impacts and confidence in this conclusion at higher levels of temperature increase.

Extreme events

The TAR concluded that there is high confidence that the frequency and magnitude of many extreme climate-related events (e.g., heatwaves, tropical cyclone intensities) will increase with a temperature increase of less than 2°C above 1990 levels; and that this increase and consequent damages will become greater at higher temperatures.

Recent extreme climate events have demonstrated that such events can cause significant loss of life and property damage in both developing and developed countries (e.g., Schär et al., 2004). While individual events cannot be attributed solely to anthropogenic climate change, recent research indicates that human influence has already increased the risk of certain extreme events such as heatwaves (**) and intense tropical cyclones (*) (Stott et al., 2004; Emanuel, 2005; Webster et al., 2005; Trenberth et al., 2007; Bindoff et al., 2007). There is high confidence that a warming of up to 2°C above 1990-2000 levels would increase the risk of many extreme events, including floods, droughts, heatwaves and fires, with increasing levels of adverse impacts and confidence in this conclusion at higher levels of temperature increase.

Distribution of impacts

Chapter 19 of the WGII TAR (Smith et al., 2001) concluded that there is high confidence that developing countries will be more vulnerable to climate change than developed countries; medium confidence that a warming of less than 2°C above 1990 levels would have net negative impacts on market sectors in many developing countries and net positive impacts on market sectors in many developed countries; and high confidence that above 2 to 3°C, there would be net negative impacts in many developed countries and additional negative impacts in many developing countries.

There is still high confidence that the distribution of impacts will be uneven and that low-latitude, less-developed areas are generally at greatest risk due to both higher sensitivity and lower adaptive capacity. However, recent work has shown that vulnerability to climate change is also highly variable within individual countries. As a consequence, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C (see, e.g., Section 12.4.). For instance, indigenous populations in high-latitude areas are already faced with significant adverse impacts from climate change to date (see Section 14.4; ACIA, 2005), and the increasing number of coastal dwellers, particularly in areas subject to tropical cyclones, are facing increasing risks (Christensen et al., 2007 Box 11.5; Section 11.9.5). There is high confidence that warming of 1 to 2°C above 1990-2000 levels would include key negative impacts in some regions of the world (e.g., Arctic nations, small islands), and pose new and significant threats to certain highly vulnerable population groups in other regions (e.g., high-altitude communities, coastal-zone communities with significant poverty levels), with increasing levels of adverse impacts and confidence in this conclusion at higher levels of temperature increase.

Aggregate impacts

Chapter 19 of the WGII TAR (Smith et al., 2001) concluded that there is medium confidence that with an increase in global mean temperature of up to 2°C above 1990 levels, aggregate market sector impacts would be plus or minus a few percent of gross world product, but most people in the world would be negatively affected. Studies of aggregate economic impacts found net damages beyond temperature increases of 2 to 3°C above 1990 levels, with increasing damages at higher magnitudes of climate change.

The findings of the TAR are consistent with more recent studies, as reviewed in Hitz and Smith (2004). Many limitations of aggregated climate impact estimates have already been noted in the TAR, such as difficulties in the valuation of non-market impacts, the scarcity of studies outside a few developed countries, the focus of most studies on selected effects of a smooth mean temperature increase, and a preliminary representation of adaptation and development. Recent studies have included some of these previously unaccounted for aspects, such as flood damage to agriculture (Rosenzweig et al., 2002) and damages from increased cyclone intensity (Climate Risk Management Limited, 2005). These studies imply that the physical impacts and costs associated with these neglected aspects of climate change may be very significant. Different analytic techniques (e.g., Nordhaus, 2006) can result in estimates of higher net damages; inclusion of indirect effects can increase the magnitude of impacts (e.g., Fankhauser and Tol, 2005; Stern, 2007). Other studies reinforce the finding of potential benefits at a few degrees of warming, followed by damages with more warming (Maddison, 2003; Tol, 2005). However, long-term costs from even a few degrees of warming, such as eventual rise in sea level (e.g., Overpeck et al., 2006), are not included in aggregate damage estimates. In addition, the current literature is limited in accounting for the economic opportunities that can be created by climate change.

On balance, the current generation of aggregate estimates in the literature is more likely than not to understate the actual costs of climate change. Consequently, it is possible that initial net market benefits from climate change will peak at a lower magnitude and sooner than was assumed for the TAR, and it is likely that there will be higher damages for larger magnitudes of global mean temperature increases than estimated in the TAR.

The literature also includes analysis of aggregate impacts of climate change other than monetary effects. Parry et al. (1999) found that climate change could adversely affect hundreds of millions of people through increased risk of coastal flooding, reduction in water supplies, increased risk of malnutrition and increased risk of exposure to disease. All of these impacts would directly affect human health. The 'Global Burden of Disease' study estimated that the climate change that has occurred since 1990 has increased mortality, and that projected climate change will increase future disease burdens even with adaptation

(McMichael et al., 2004). There is low to medium confidence that most people in the world will be negatively affected at global mean temperature increases of 1-2°C above 1990-2000 levels, with increasing levels of adverse impacts and confidence in this conclusion at higher levels of temperature increase.

Large-scale singularities

The TAR concluded that there is low to medium confidence that a rapid warming of over 3°C would trigger large-scale singularities in the climate system, such as changes in climate variability (e.g., ENSO changes), breakdown of the thermohaline circulation (THC – or equivalently, meridional overturning circulation, MOC), deglaciation of the WAIS, and climate–biosphere–carbon cycle feedbacks. However, determining the trigger points and timing of large-scale singularities was seen as difficult because of the many complex interactions of the climate system.

Since the TAR, the literature offers more specific guidance on possible thresholds for partial or near-complete deglaciation of the Greenland and West Antarctic ice sheets. There is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the WAIS, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more (Section 19.3.5.2; Jansen et al., 2007 Section 6.4; Meehl et al., 2007 Sections 10.7.4.3 and 10.7.4.4; Oppenheimer and Alley, 2004, 2005; Hansen, 2005; Otto-Bliesner et al., 2006; Overpeck et al., 2006). Since the TAR, there is more confidence in projections of the climate consequences of feedbacks in the carbon cycle (see Section 19.3.5.1).

19.4 Assessment of response strategies to avoid key vulnerabilities

This section reviews the literature addressing the linkages between key vulnerabilities and response strategies in order to avoid or reduce them. This section is structured as follows. Section 19.4.1 reviews the literature on the role of adaptation to avoid key vulnerabilities. As discussed in Section 19.2, the lack of adaptive capacity, or the inability to adapt, is one of the criteria relevant for the selection of key vulnerabilities. Section 19.4.2 reviews the literature that specifically addresses the avoidance of key vulnerabilities through mitigation of climate change. Section 19.4.3 synthesises the knowledge about avoiding key vulnerabilities of climate change.

The principal response strategies – mitigation of climate change and adaptation – are often portrayed as having largely different foci in terms of their characteristic spatial and temporal scales. Other important strategies include investing in gaining knowledge (e.g., improving predictions and the understanding of options) and investing in capacity-building (improving ability and tools to make good decisions under uncertainty). Finally, some have suggested geo-engineering as a backstop policy option (see, e.g., Izrael, 2005; Cicerone, 2006; Crutzen, 2006; Kiehl, 2006; Wigley, 2006, for an update on this debate).

Given the integrating nature of this section at the interface between climate change impacts and vulnerabilities, mitigation, and adaptation, there are important links with other chapters of the IPCC AR4. Most importantly, WGII Chapter 17 discusses the role of adaptation to climate change; WGII Chapter 18, WGIII Chapter 2 Section 2.5 and Chapter 3 Section 3.5 discuss the links between mitigation and adaptation; WGIII Chapter 1 Section 1.2 and Chapter 2 Section 2.2 discuss the characteristics of the challenge and some decision-making problems in responding to global climate change, respectively; WGII Chapter 2 Section 2.2.7 and WGIII Chapter 2 Section 2.3 discuss methods to address uncertainties in this context; WGIII Chapter 3 Section 3.3 and Chapter 3 Section 3.6 discuss climate change mitigation from a long-term and a short-term perspective, respectively; and WGII Chapter 2 Section 2.4.6 discusses methods of evaluating impacts associated with mitigation scenarios.

19.4.1 Adaptation as a response strategy

How much can anticipatory and autonomous adaptation achieve? What is the potential for, and limitations of, adaptation to reduce impacts and to reduce or avoid key vulnerabilities?

The scientific literature on these questions is less well developed than for mitigation, and the conclusions are more speculative in many cases. It is clear, however, that there is no simple comprehensive response to the adaptation question, and that the answers are often place-specific and very nuanced, and are likely to become more so as research advances.

In agriculture, for example, previous IPCC assessments have generally concluded that, in the near to medium term, aggregate world food production is not threatened (IPCC, 1996, 2001a). However, considerable regional variation in impacts and adaptive capacity suggests that severe impacts and food scarcity could occur in some regions, especially at low latitudes, where large numbers of poorer people are already engaged in agriculture that is not currently viable (see Section 5.4.2). In global terms, agriculture has been extremely resilient and world food production has expanded rapidly to keep pace with world population growth. Of course, there is debate on the sustainability of these trends, as they depend in part on the growing demand for meat and meat products as well as potential competition between agricultural resources for producing food versus those used for producing energy. Nevertheless, even where shortages have occurred, the reasons are rarely to be found in an absolute lack of food but are more due to lack of purchasing power and failures of the distribution system.

Attention to adaptation in agriculture has tended to focus on specific measures at the farm level, and some progress is being made in the incorporation of climate risks into agricultural practices. On the other hand, the processes of globalisation and technological change are placing adaptation more in the hands of agri-business, national policy-makers, and the international political economy, including such factors as prices, tariffs and subsidies, and the terms of international trade (Apuuli et al., 2000; Burton and Lim, 2005).

The record of past success in agriculture is often seen in other sectors, particularly in developed countries and, in many regions it is evident that current climate variability falls largely within the coping range (Burton and Lim, 2005). One possible exception is in the case of extreme events where monetary losses (both insured and uninsured – Munich Re, 2005) have been rising sharply, although mortality has been falling. In such cases, adaptation has not been so successful, despite major improvements in understanding the risks and in forecasts and warnings (White et al., 2001). One reason is the decline in local concern and thus a reduced propensity to adopt proactive adaptation measures, as the memory of specific disaster events fades. Related to this lack of appreciation of possible risks is that governments and communities can still be taken by surprise when extreme events occur, even though scientific evidence of their potential occurrence is widely available (Bazermann, 2005). Economic damage and loss of life from Hurricane Katrina in 2005, the European heatwave of 2003, and many other similar events are due in large measure to a lack of sufficient anticipatory adaptation, or even maladaptation in some cases. So while the overall record of adaptation to climate change and variability in the past 200 or so years has been successful overall, there is evidence of insufficient investments in adaptation opportunities, especially in relation to extreme events (Burton, 2004, Burton and May, 2004; Hallegatte et al., 2007). While economic losses have increased, there has been considerable success in reducing loss of life; and despite the recent spate of deadly extreme weather events, the general trend in mortality and morbidity remains downwards.

It is clear that in the future there is considerable scope for adaptation, provided that existing and developing scientific understanding, technology and know-how can be effectively applied. It might be expected that the slower the rate of climate change, the more likely it is that adaptation will be successful. For example, even a major rise in sea level might be accommodated and adjusted to by human societies if it happens very slowly over many centuries (Nicholls and Tol, 2006). On the other hand, slow incremental change can still involve considerable costs and people might not be sufficiently motivated to take precautionary action and bear the associated costs without some more dramatic stimulus. Paradoxically, therefore, the full array of human adaptation potential is not likely to be brought to bear when all the market, social, psychological and institutional barriers to adaptation are taken into account.

In terms of the key vulnerabilities identified in Table 19.1, it is clear that adaptation potential is greater the more the system is under human management and control. Major geophysical changes leave little room for human-managed adaptation. Fortunately these changes are likely to unfold relatively slowly, thus allowing more time for adaptation to their eventual impacts. There is somewhat greater adaptive capacity in biological systems, but it is still very limited. Biodiversity and ecosystems are likely to be impacted at a much faster rate than geophysical systems without a commensurately larger adaptive capacity for such impacts. It seems likely, therefore, that the greatest impacts in the near to medium term, where adaptation capacity is very limited, will occur in biological systems (Leemans and Eickhout, 2004; Smith, 2004; see Chapter 4). As we move into human social systems and market systems, adaptive capacity at the technical level increases dramatically. However, the understanding of impacts, adaptive capacity, and the costs of adaptation is weaker in social systems than in biological systems, and the uncertainties are high. This is especially the case for synergistic or cross-cutting impacts. Considered in isolation, the potential for agricultural adaptation may appear to be good. When related impacts in water regimes, droughts and floods, pest infestations and plant diseases, human health, the reliability of infrastructure, poor governance, as well as other non-climate-related stresses are taken into account, the picture is less clear.

A general conclusion on the basis of the present understanding is that for market and social systems there is considerable adaptation potential, but the economic costs are potentially large, largely unknown and unequally distributed, as is the adaptation potential itself. For biological and geophysical systems, the adaptation potential is much less than in social and market systems, because impacts are more direct and therefore appear more rapidly. A large proportion of the future increase in key vulnerabilities is likely to be recorded first in biological systems (see Chapter 1). This does not mean that key vulnerabilities will not occur in social and market systems. They depend on biological systems, and as ecosystems are affected by mounting stresses from climate change and concomitant factors such as habitat fractionation, and the spread of plant diseases and pest infestations, then the follow-on, second-order effects on human health and safety, livelihoods and prosperity, will be considerable (*/**).

19.4.2 Mitigation

This subsection reviews the growing literature (see, e.g., Schellnhuber et al., 2006) on mitigation of climate change as a means to avoid key vulnerabilities or dangerous anthropogenic interference (DAI) with the climate system. A more general review of the literature on climate change mitigation is found in the WGIII AR4 Chapter 3 (Fisher et al., 2007) Sections 3.3.5 (on long-term stabilisation scenarios), 3.5.2 and 3.5.3 (on integrated assessment and risk management) and 3.6 (on linkages between short-term and long-term targets).

19.4.2.1 Methodological approaches to the assessment of mitigation strategies

A variety of methods is used in the literature to identify response strategies that may avoid potential key vulnerabilities or DAI (see also Fisher et al., 2007, Section 3.5.2). These methods can be characterised according to the following dimensions.

- *Targeted versus non-targeted*
  In this section, targeted approaches refer to the determination of policy strategies that attempt to avoid exceeding pre-defined targets for key vulnerabilities or DAI thresholds, whereas non-targeted approaches determine the implications for key vulnerabilities or DAI of emissions or concentration pathways selected without initial consideration of such targets or thresholds. Targeted approaches are sometimes referred to as 'inverse' approaches, as they are working backwards from a specified outcome (e.g., an impact threshold not to be exceeded) towards the origin of the cause–effect chain that links GHG emissions with climate impacts.

- *Deterministic versus set-based versus probabilistic*
  Deterministic analyses are based on best-guess estimates for uncertain parameters, whereas probabilistic analyses explicitly consider key uncertainties of the coupled socio-natural system by describing one or more parameters in terms of probability distributions. Uncertainty can also be treated discretely by set-based methods that select different possible values without specifying any probability distribution across the members of that set. For a more detailed discussion of the role of uncertainty in the assessment of response strategies, see Box 19.3.

- *Optimising versus adaptive versus non-optimising*
  Optimising analyses determine recommended policy strategies based on a pre-defined objective, such as cost minimisation; whereas non-optimising analyses do not require the specification of such an objective function. Adaptive analyses optimise near-term decisions under the assumption that future decisions will consider new information as and when it materialises.

Table 19.2 characterises the main methods applied in the relevant literature based on two of the three dimensions defined above, because deterministic, set-based and probabilistic approaches can be applied to each of these methods. The remainder of Section 19.4 reviews literature pertaining to these methods that examines mitigation strategies to avoid key vulnerabilities or DAI.

19.4.2.2 Scenario analysis and analysis of stabilisation targets

Scenario analysis examines the implications of specified emissions pathways or concentration profiles for future climate change, e.g., magnitude and rate of temperature increase. Some studies focus on the key radiative forcing agent CO_2, while

Box 19.3. Uncertainties in the assessment of response strategies

Climate change assessments and the development of response strategies face multiple uncertainties and unknowns (see Fourth Assessment Working Group II Chapter 2 and Working Group III Chapter 2). The most relevant sources of uncertainty in this context are:

(i) Natural randomness,
(ii) Lack of scientific knowledge,
(iii) Social choice (reflexive uncertainty),
(iv) Value diversity.

Some sources of uncertainty can be reasonably represented by probabilities, whereas others are more difficult to characterise probabilistically. The natural randomness in the climate system can be characterised by frequentist (or objective) probabilities, which describe the *relative frequency* (sometimes referred to as ‘likelihood’) of a repeatable event under known circumstances. There are, however, limitations to the frequentist description, given that the climate system is non-stationary at a range of scales and that past forcing factors cannot be perfectly known. The reliability of *knowledge* about uncertain aspects of the world (such as the ‘true’ value of climate sensitivity) cannot be empirically represented by frequentist probabilities alone. It is possible to construct probability distributions of climate sensitivity that look like frequency representations, but they will always have substantial elements of subjectivity embedded (Morgan and Keith, 1995; Allen et al., 2001). The inherent need for probabilistic analyses in a risk-management framework becomes problematic when some analysts object in principle to even assessing probabilities in situations of considerable lack of data or other key ingredients for probabilistic assessment. To help bridge this philosophical conflict, it has been suggested that making subjective elements transparent is an essential obligation of assessments using such an approach (e.g., Moss and Schneider, 2000). One method of characterising uncertainty due to a lack of scientific knowledge is by Bayesian (or subjective) probabilities, which refer to the *degree of belief* of experts in a particular statement, considering the available data. Another approach involves non-probabilistic representations such as imprecise probabilities (e.g., Hall et al., 2006). Whether probabilities can be applied to describe future social choice, in particular uncertainties in future greenhouse gas emissions, has also been the subject of considerable scientific debate (e.g., Allen et al., 2001; Grubler and Nakićenović, 2001; Lempert and Schlesinger, 2001; Pittock et al., 2001; Reilly et al., 2001; Schneider, 2001, 2002). Value diversity (such as different attitudes towards risk or equity) cannot be meaningfully addressed through an objective probabilistic description. It is often assessed through sensitivity analysis or scenario analysis, in which different value systems are explicitly represented and their associated impacts contrasted.

The probabilistic analyses of DAI reported in this section draw substantially on (subjective) Bayesian probabilities to describe key uncertainties in the climate system, such as climate sensitivity, the rate of oceanic heat uptake, current radiative forcing, and indirect aerosol forcing. See WGI Chapter 9 (Hegerl et al., 2007) and Chapter 10 (Meehl et al., 2007) for a more detailed discussion. While these uncertainties prevent the establishment of a high-confidence, one-to-one linkage between atmospheric greenhouse gas concentrations and global mean temperature increase, probabilistic analyses can assign a subjective probability of exceeding certain temperature thresholds for given emissions scenarios or concentration targets (e.g., Meinshausen, 2005; Harvey, 2007).

Table 19.2. *Methods to identify climate policies to avoid key vulnerabilities or DAI.*

Method	Description	Optimising approach?	Targeted approach?
Scenario analysis, analysis of stabilisation targets	Analyse the implications for temperature increase of specific concentration stabilisation levels, concentration pathways, emissions scenarios, or other policy scenarios.	No	No
Guardrail analysis	Derive ranges of emissions that are compatible with predefined constraints on temperature increase, intolerable climate impacts, and/or unacceptable mitigation costs.	No	Yes
Cost–benefit analysis including key vulnerabilities and DAI	Include representations of key vulnerabilities or DAI in a cost-optimising integrated assessment framework.	Yes	No
Cost-effectiveness analysis	Identify cost-minimising emissions pathways that are consistent with pre-defined constraints for GHG concentrations, climate change or climate impacts.	Yes	Yes

others include additional gases and aerosols in their analysis, often representing concentrations in terms of CO_2-equivalent ppm or radiative forcing in W/m^2 (see Forster et al., 2007 Section 2.3). Dynamic analyses include information about the trajectories of GHG emissions and development pathways, GHG concentrations, climate change and associated impacts. Related static analyses examine the relationship between stabilisation targets for GHG concentrations and equilibrium values for climate parameters (typically the increase in global mean temperature). Note that the term 'GHG stabilisation' is used here with a time horizon of up to several centuries. Over a longer time period without anthropogenic GHG emissions, CO_2 concentrations may return to values close to pre-industrial levels through natural processes (Brovkin et al., 2002; Putilov, 2003; Semenov, 2004a,b; Izrael and Semenov, 2005, 2006).

The shape over time of the specified emissions pathway or concentration profile is of particular relevance when considering key vulnerabilities, as it influences transient climate change and associated climate impacts (see, e.g., O'Neill and Oppenheimer, 2004; Meinshausen, 2005; Schneider and Mastrandrea, 2005; Mastrandrea and Schneider, 2006). Two general categories can be distinguished in studies that specifically consider CO_2 concentrations or temperature thresholds associated with key vulnerabilities or DAI: stabilisation scenarios, which imply concentrations increasing smoothly from current levels to a final stabilisation concentration (e.g., Enting et al., 1994; Schimel et al., 1996; Wigley et al., 1996; Morita et al., 2000; Swart et al., 2002; O'Neill and Oppenheimer, 2004) and peaking or overshoot scenarios, where a final concentration stabilisation level is temporarily exceeded (Harvey, 2004; Kheshgi, 2004; O'Neill and Oppenheimer, 2004; Wigley, 2004; Izrael and Semenov, 2005; Kheshgi et al., 2005; Meinshausen et al., 2005; Frame et al., 2006). Overshoot scenarios are necessary for the exploration of stabilisation levels close to or below current concentration levels.

Some studies treat the uncertainty in future GHG emissions and climate change by analysing a discrete range of scenarios. O'Neill and Oppenheimer (2002) examined ranges of global mean temperature increase in 2100 associated with 450, 550 and 650 ppm CO_2 concentration stabilisation profiles, as reported in the TAR (Cubasch et al., 2001). They concluded that none of these scenarios would prevent widespread coral-reef bleaching in 2100 (assumed to have a threshold 1°C increase above current levels), and that only the 450 ppm CO_2 stabilisation profile is likely to be associated with avoiding both deglaciation of West Antarctica (assumed to have a threshold of 2°C above current levels) and collapse of the MOC (assumed to have a threshold of 3°C increase within 100 years). Lowe et al. (2006) consider a suite of climate scenarios based on a 'perturbed parameter ensemble' of Hadley Centre climate models, finding that, for stabilisation close to 450 ppm, 5% of their scenarios exceed a threshold for deglaciation of West Antarctica (assumed to be 2.1°C local warming above 1990-2000 levels). Corfee-Morlot and Höhne (2003) review the current knowledge about climate impacts for each 'reason for concern' at different levels of global mean temperature change and CO_2 stabilisation, based on published probability density functions (PDFs) of climate sensitivity, finding that any CO_2 stabilisation target above 450 ppm is associated with a significant probability of triggering a large-scale climatic event. An inverse analysis of the implications of reaching CO_2 stabilisation at 450 ppm concludes that more than half of the SRES emissions scenarios leave this stabilisation target virtually out of reach as of 2020. A robust finding across such studies is that the probability of exceeding thresholds for specific key vulnerabilities or DAI increases with higher stabilisation levels for GHG concentrations.

Other studies quantify uncertainty using probability distributions for one or more parameters of the coupled social-natural system. Figure 19.1, for instance, depicts the likelihood of exceeding an equilibrium temperature threshold of 2°C above pre-industrial levels based on a range of published probability distributions for climate sensitivity. To render eventual exceedence of this exemplary threshold 'unlikely' (<33% chance), the CO_2-equivalent stabilisation level must be below 410 ppm for the majority of considered climate sensitivity uncertainty distributions (range between 350 and 470 ppm).

Key caveat: The analysis in Figure 19.1 employs a number of probability distributions taken from the literature. The WGI AR4 has assessed the body of literature pertaining to climate sensitivity, and concludes that the climate sensitivity is 'likely' to lie in the range 2-4.5°C, and is 'very likely' to be above 1.5°C (Meehl et al., 2007 Executive Summary). For fundamental physical reasons, as well as data limitations, values substantially higher than 4.5°C still cannot be excluded, although agreement with observations and proxy data is generally worse for those high values than for values in the 2-4.5°C range (Meehl et al., 2007 Executive Summary). 'Likely' in IPCC usage has been defined as a 66 to 90% chance, and 'very likely' has been defined as a 90 to 99% chance. Therefore, implicit in the information given by WGI is a 10 to 34% chance that climate sensitivity is outside the 'likely' range, with equal probability (5 to 17%) that it is below 2°C or above 4.5°C. Furthermore, the WGI assessment assigns a 90 to 99% chance that the climate sensitivity is above 1.5°C. However, the shape of the distribution to the right of 4.5°C – crucial for risk-management analyses – is, as noted by WGI, so uncertain given the lack of scientific knowledge, that any quantitative conclusion reached based on probability functions beyond 4.5°C climate sensitivity would be very low confidence. For these reasons, we assign no more than low confidence to any of the distributions or results presented in this section, particularly if the result depends on the tails of the probabilty distribution for climate sensitivity. Nevertheless, as noted here, a risk-management framework requires input of (even if low-probability, low-confidence) outlier information. Therefore, we present the literature based on probabilistic analyses to demonstrate the framework inherent in the risk management approach to assessing key vulnerabilities.

The temperature threshold for DAI can itself be represented by a subjective probability distribution. Wigley (2004) combined probability distributions for climate sensitivity and the temperature threshold for DAI in order to construct a distribution for the CO_2 stabilisation level required to avoid DAI. Under this assumption set, the median stabilisation level for atmospheric CO_2 concentrations is 536 ppm, and there is a 17% chance that the stabilisation level necessary to avoid DAI is below current atmospheric CO_2 levels. A similar analysis by Harvey (2006, 2007) added the explicit normative choice of an 'acceptable' probability (10%) for exceeding the probabilistic temperature threshold for DAI. With similar assumptions about the probability distributions for climate sensitivity and the DAI temperature threshold, he finds that the allowable CO_2 stabilisation concentration is between 390 and 435 ppm, depending on assumptions about aerosol forcing. Of course, these results are quite sensitive to all the assumptions made, as both authors explicitly acknowledge.

Finally, significant differences in environmental impacts are anticipated between GHG concentration stabilisation trajectories that allow overshoot of the stabilisation concentration versus those that do not, even when they lead to the same final concentration. For example, Schneider and Mastrandrea (2005) calculate the probability of at least temporarily exceeding a target of 2°C above pre-industrial (1.4°C above 'current') by 2200 to be 70% higher (77% instead of 45%) for an overshoot scenario rising to 600 ppm CO_2-equivalent and then stabilising in several centuries at 500 ppm CO_2-equivalent, compared with a non-overshoot scenario stabilising at the same level (Figure 19.2, top panel). Overshoot scenarios induce higher transient temperature increases, increasing the probability of temporary or

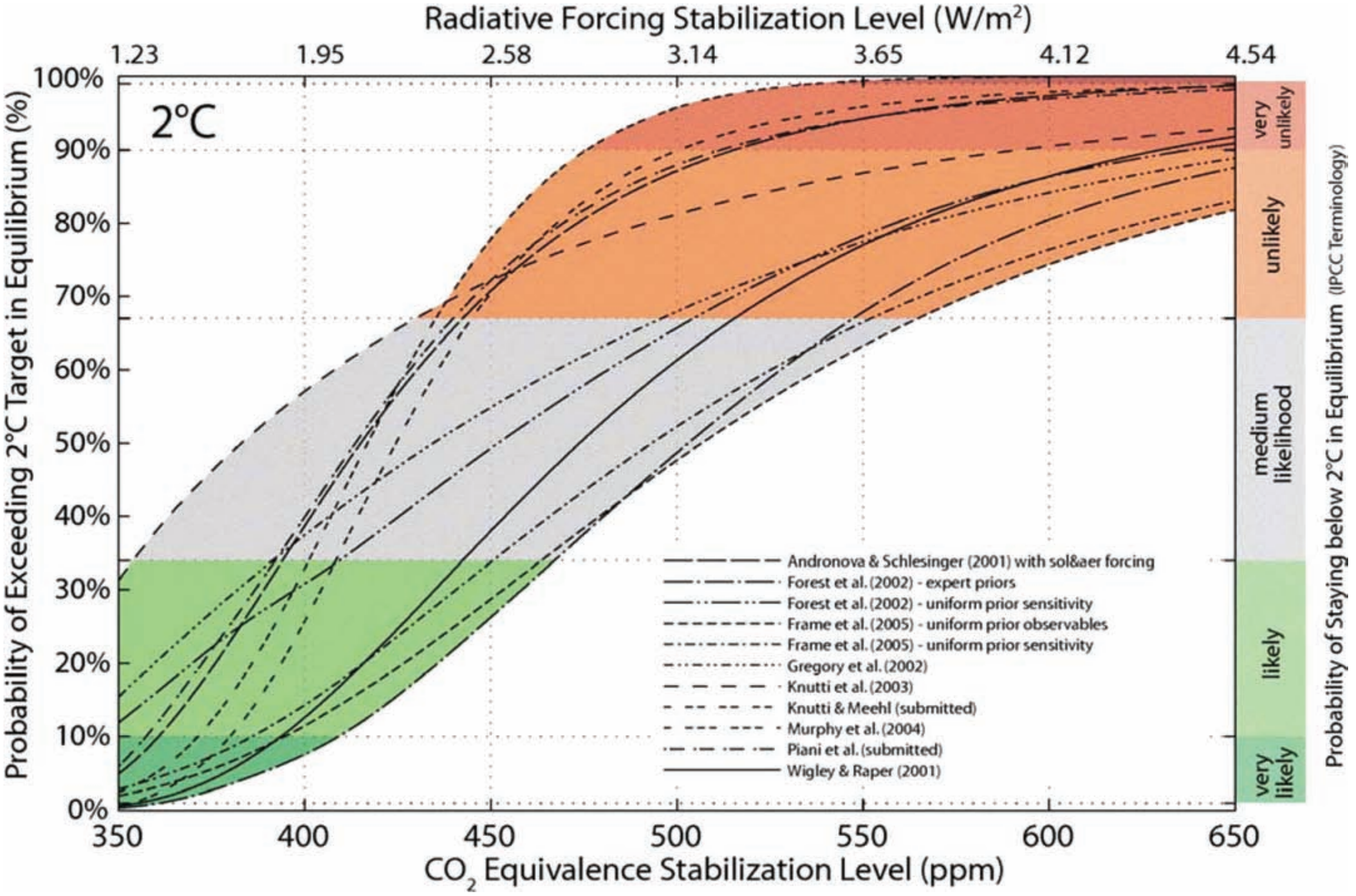

Figure 19.1. *Probability (see 'Key caveat' above on low confidence for specific quantitatitive results) of exceeding an equilibrium global warming of 2°C above pre-industrial (1.4°C above 1990 levels), for a range of CO_2-equivalent stabilisation levels. Source: Hare and Meinshausen (2005).*

permanent exceedence of thresholds for key vulnerabilities or DAI (e.g, Hammitt and Shlyakhter, 1999; Harvey, 2004; O'Neill and Oppenheimer, 2004; Hare and Meinshausen, 2005; Knutti et al., 2005). With this in mind, Schneider and Mastrandrea (2005) suggested two metrics – maximum exceedence amplitude and degree years – for characterising the maximum and cumulative magnitude of overshoot of a temperature threshold for DAI, as shown for an illustrative scenario in Figure 19.2 (bottom panel). Since the rate of temperature rise is important to adaptive capacity (see Section 19.4.1) and thus impacts, the time delay between now and the date of occurrence of the maximum temperature (year of MEA on Figure 19.2b) is also relevant to the likelihood of creating key vulnerabilities or exceeding specified DAI thresholds.

19.4.2.3 Guardrail analysis

Guardrail analysis comprises two types of inverse analysis that first define targets for climate change or climate impacts to be avoided and then determine the range of emissions that are compatible with these targets: tolerable windows analysis (Toth, 2003) and safe landing analysis (Swart et al., 1998). The tolerable windows approach allows the assessment of the implications of multiple competing climate policy goals on the mid-term and long-term ranges of permissible greenhouse gas emissions. It has initially been applied to several normative thresholds for climate impacts, which are analysed together with socio-economic constraints that aim at excluding unacceptable mitigation policies. Toth et al. (2003) analyse the interplay between thresholds for the global transformation of ecosystems, regional mitigation costs and the timing of mitigation. They show that following a business-as-usual scenario of GHG emissions (which resembles the SRES A2 scenario) until 2040 precludes the possibility of limiting the worldwide transformation of ecosystems to 30%, even under optimistic assumptions regarding willingness to pay for the mitigation of GHG emissions afterwards. Toth et al. (2003) show that mitigation of GHG emissions has to start no later than 2015 if a reduction in agricultural yield potential in South Asia of more than 10% is to be avoided. This result, however, is contingent on the regional climate change projection of the specific GCM applied in this analysis (HadCM2) and the accuracy of the impact models. The consideration of regional and local climate impacts in inverse analyses raises challenges as to the treatment of the significant uncertainties associated with them.

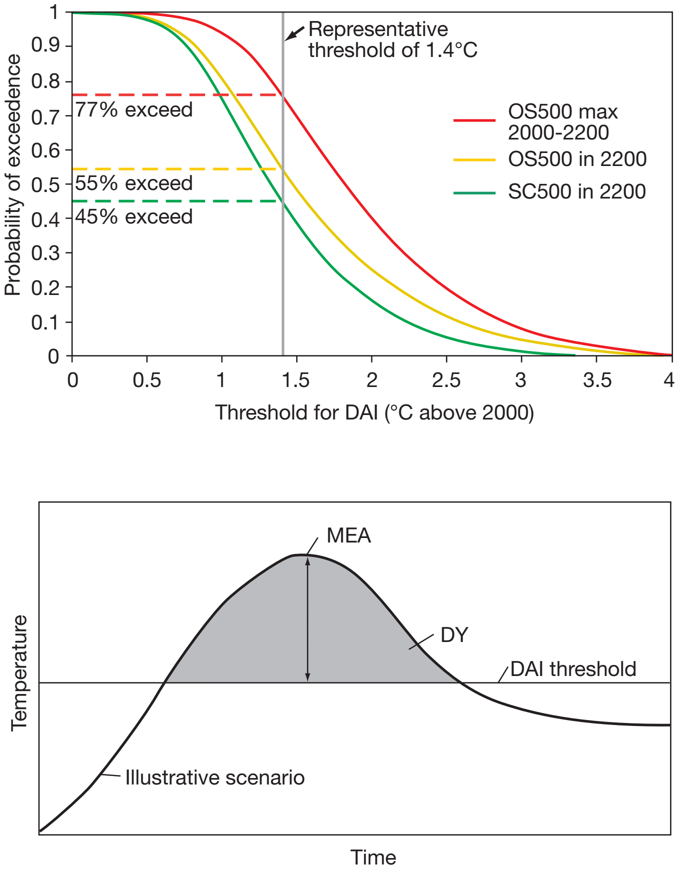

Figure 19.2. *Top panel: Probability of exceedence of a range of temperature thresholds for overshoot (OS500) and non-overshoot (SC500) scenarios, derived from probability distributions for climate sensitivity (see 'Key caveat' above on low confidence for specific quantitatitive results). OS500 Max is derived from the maximum overshoot temperature that occurs during the transient response before 2200, whereas OS500 in 2200 and SC500 in 2200 are derived from temperatures in 2200. While model-dependent, these results demonstrate the importance of considering transient temperature change when evaluating mitigation strategies to avoid key vulnerabilities. Bottom panel: Visualisation of maximum exceedence amplitude (MEA) and degree years (DY) for an illustrative overshoot temperature profile. Source: Schneider and Mastrandrea (2005).*

The tolerable windows approach has also been applied in connection with systematic climate thresholds, predominantly for probabilistic analyses of the stability of the thermohaline ocean circulation (Zickfeld and Bruckner, 2003; Bruckner and Zickfeld, 2004; Rahmstorf and Zickfeld, 2005). Rahmstorf and Zickfeld (2005) conclude that the SRES A2 emissions scenario exceeds the range of emissions corresponding to a 5% and 10% likelihood of inducing a commitment to a circulation shutdown around 2035 and 2065, respectively. A 2% risk of shutdown can no longer be avoided, even with very stringent emission reductions, given the assumptions in their models.

19.4.2.4 Cost–benefit analysis

Cost–benefit analyses (CBAs) of climate change in general are reviewed in Fisher et al., 2007 Section 3.5.3.3. The discussion here focuses on the suitability of CBA for avoiding key vulnerabilities and DAI. Most early cost–benefit analyses of climate change have assumed that climate change will be a gradual and smooth process. This assumption has prevented these analyses from determining a robust optimal policy solution (Hall and Behl, 2006), as it neglects important key vulnerabilities. Recognising the restrictions of this assumption, an extensive literature has developed extending cost–benefit analyses and related decision-making (e.g., Jones, 2003) in the context of Article 2, with a particular emphasis on abrupt change at global and regional scales (Schneider and Azar, 2001; Higgins et al., 2002; Azar and Lindgren, 2003; Baranzini et al., 2003; Wright and Erickson, 2003).

Several papers have focused on incorporating damages from large-scale climate instabilities identified as key vulnerabilities, such as climate-change-induced slowing or shutdown of the MOC (Keller et al., 2000, 2004; Mastrandrea and Schneider, 2001; Link and Tol, 2004). For example, quantifying market-based damages associated with MOC changes is a difficult task, and current analyses should be interpreted as order-of-magnitude estimates, with none carrying high confidence. These preliminary analyses suggest that significant reductions in anthropogenic greenhouse gas emissions are economically efficient even if the damages associated with a MOC slowing or collapse are less than 1% of gross world product. However, model results are very dependent on assumptions about climate sensitivity, the damage functions for smooth and abrupt climate change and time discounting, and are thus designed primarily to demonstrate frameworks for analysis and order-of-magnitude outcomes rather than high-confidence quantitative projections.

Several researchers have implemented probabilistic treatments of uncertainty in cost–benefit analyses; recent examples include Mastrandrea and Schneider (2004) and Hope (2006). These probabilistic analyses consistently suggest more aggressive mitigation policies compared with deterministic analyses, since probabilistic analyses allow the co-occurrence of high climate sensitivities (see *Key caveat* in Section 19.4.2.2 on low confidence for specific quantitatitive results) with high climate-damage functions.

19.4.2.5 Cost-effectiveness analysis

Cost-effectiveness analysis involves determining cost-minimising policy strategies that are compatible with pre-defined probabilistic or deterministic constraints on future climate change or its impacts. Comparison of cost-minimal strategies for alternative climate constraints has been applied to explore the trade-offs between climate change impacts and the associated cost of emissions mitigation (e.g., Keller et al., 2004; McInerney and Keller, 2006). The reductions in greenhouse-gas emissions determined by cost-effectiveness analyses incorporating such constraints are typically much larger than those suggested by most earlier cost–benefit analyses, which often do not consider the key vulnerabilities underlying such constraints in their damage functions. In addition, cost–benefit analysis assumes perfect substitutability between all costs and benefits of a policy strategy, whereas the hard constraints in a cost-effectiveness analysis do not allow for such substitution.

Some cost-effectiveness (as well as cost–benefit) analyses have explored sequential decision strategies in combination with the avoidance of key vulnerabilities or thresholds for global temperature change. These strategies allow for the resolution of key uncertainties in the future through additional observations and/or improved modelling. The quantitative results of these analyses cannot carry high confidence, as most studies represent uncertain parameters by two to three discrete values only and/or employ rather arbitrary assumptions about learning (e.g., Hammitt et al., 1992; Keller et al., 2004; Yohe et al., 2004). In a systematic analysis, Webster et al. (2003) finds that the ability to learn about damages from climate change and costs of reducing greenhouse gas emissions in the future can lead to either less restrictive or more restrictive policies today. All studies report the opinions of their authors to be that the scientific uncertainty by itself does not provide justification for doing nothing today to mitigate potential climate damages.

19.4.3 Synthesis

The studies reviewed in this section diverge widely in their methodological approach, in the sophistication with which uncertainties are considered in geophysical, biological and social systems, and in how closely they approach an explicit examination of key vulnerabilities or DAI. The models involved range from stand-alone carbon cycle and climate models to comprehensive integrated assessment frameworks describing emissions, technologies, mitigation, climate change and impacts. Some frameworks incorporate approximations of vulnerability but none contains a well-established representation of adaptation processes in the global context.

It is not possible to draw a simple summary from the diverse set of studies reviewed in this section. The following conclusions from literature since the TAR, however, are more robust.

- A growing literature considers response strategies that aim at preventing damage to particular key elements and processes in geophysical, biological and socio-economic systems that are sensitive to climate change and have limited adaptation potential; policy-makers may want to consider insights from the literature reviewed here in helping them to design policies to prevent DAI.
- In a majority of the literature, key impacts are associated with long-term increases in equilibrium global mean surface temperature above the pre-industrial equilibrium or an increase above 1990-2000 levels. Transient temperature changes are more instructive for the analyses of key vulnerabilities, but the literature is sparse on transient assessments relative to equilibrium analyses. Many studies provide global mean temperature thresholds that would lead sooner or later to a specific key impact, i.e., to disruption/shutdown of a vulnerable process. Such thresholds are not known precisely, and are characterised in the literature by a range of values (or occasionally by probability functions). Assessments of whether emissions pathways/GHG concentration profiles exceed given temperature thresholds are characterised by significant uncertainty. Therefore, deterministic studies alone cannot provide sufficient information for a full analysis of response strategies, and probabilistic approaches should be considered. Risk analyses given in some recent studies suggest that there is no longer high confidence that certain large-scale events (e.g., deglaciation of major ice sheets) can be avoided, given historical climate change and the inertia of the climate system (Wigley, 2004, 2006; Rahmstorf and Zickfeld, 2005). Similar conclusions could also be applied to risks for social systems, though the literature often suggests that any thresholds for these are at least as uncertain.
- Meehl et al., 2007 Table 10.8 provide likely ranges of equilibrium global mean surface temperature increase for different CO_2-equivalent stabilisation levels, based on their expert assessment that equilibrium climate sensitivity is likely to lie in the range 2-4.5°C (Meehl et al., 2007 Executive Summary). They present the following likely

ranges (which have been converted from temperature increase above pre-industrial to equilibrium temperature increase above 1990-2000 levels – see Box 19.2); 350 ppm CO_2-equivalent: 0-0.8°C above 1990-2000 levels; 450 ppm CO_2-equivalent: 0.8-2.5°C above 1990-2000 levels; 550 ppm CO_2-equivalent: 1.3-3.8°C above 1990-2000 levels; 650 ppm CO_2-equivalent: 1.8-4.9°C above 1990-2000 levels; 750 ppm CO_2-equivalent: 2.2-5.8°C above 1990-2000 levels. Some studies suggest that climate sensitivities larger than this likely range (which would suggest greater warming) cannot be ruled out (Meehl et al., 2007 Section 10.7.2), and the WGI range implies a 5-17% chance that climate sensitivity falls above 4.5°C (see *Key caveat* in Section 19.4.2.2 for further information).

- While future global mean temperature trajectories associated with different emissions pathways are not projected to diverge considerably in the next two to four decades, the literature shows that mitigation activities involving near-term emissions reductions will have a significant effect on concentration and temperature profiles over the next century. Later initiation of stabilisation efforts has been shown to require higher rates of reduction if they are to reduce the likelihood of crossings levels of DAI (Semenov, 2004a,b; Izrael and Semenov, 2005, 2006). Substantial delay (several decades or more) in mitigation activities makes achievement of the lower range of stabilisation targets (e.g., 500 ppm CO_2-equivalent and lower) infeasible, except via overshoot scenarios (see Figure 19.2, bottom panel). Overshoot scenarios induce higher transient temperature increases, increasing the probability of temporary or permanent exceedence of thresholds for key vulnerabilities (Hammitt, 1999; Harvey, 2004; O'Neill and Oppenheimer, 2004; Hare and Meinshausen, 2005; Knutti et al., 2005; Schneider and Mastrandrea, 2005).
- There is considerable potential for adaptation to climate change for market and social systems, but the costs and institutional capacities to adapt are insufficiently known and appear to be unequally distributed across world regions. For biological and geophysical systems, the adaptation potential is much lower. Therefore, some key impacts will be unavoidable without mitigation.

19.4.4 Research needs

The knowledge-base for the assessment of key vulnerabilities and risks from climate change is evolving rapidly. At the same time, there are significant gaps in our knowledge with regard to impacts, the potential and nature of adaptation, and vulnerabilities of human and natural systems. However, as this chapter has tried to bring out, a growing base of information that is likely to be of significance and value to the ongoing policy dialogue does exist.

In this concluding section of the chapter, some of the research priorities from the different domains are highlighted. Clearly, this can only be an indicative list, suggesting areas where new knowledge may have immediate utility and relevance as far as the objective of this chapter is concerned.

This chapter has suggested that key vulnerabilities may be a useful concept for informing the dialogue on dangerous anthropogenic interference. Further elucidation of this concept requires highly interdisciplinary, integrative approaches that are able to capture bio-geophysical and socio-economic processes. In particular, it is worth noting that the socio-economic conditions which determine vulnerability (e.g., number of people at risk, wealth, technology, institutions) change rapidly. Better understanding of the underlying dynamics of these changes at varying scales is essential to improve understanding of key vulnerabilities to climate change. The relevant research questions in this context are not so much how welfare is affected by changing socio-economic conditions, but rather how much change in socio-economic conditions affects vulnerability to climate change. In other words, a key question is how future development paths could increase or decrease vulnerability to climate change.

As this chapter has brought out through the criteria for identifying key vulnerabilities, the responses of human and natural systems, both autonomous and anticipatory, are quite important. Consequently, it is important that the extant literature on this issue is enriched with contributions from disciplines as diverse as political economy and decision theory. In particular, one of the central problems is a better understanding of adaptation and adaptive capacity, and of the practical, institutional, and technical obstacles to the implementation of adaptation strategies. This improvement in understanding will require a richer characterisation of the perception–evaluation–response process at various levels and scales of decision-making, from individuals to households, communities and nations. In this context, it is worth noting that new research approaches may be required. For example, with regard to adaptation, a learning-by-doing approach may be required so that the development of theory occurs in parallel with, and supported by, experience from practice.

A significant category of key vulnerabilities is associated with large-scale, irreversible and systemic changes in geophysical systems. Large-scale changes such as changes in the West Antarctic and Greenland ice sheets, could lead to significant impacts, particularly due to long-term large sea-level rise. Therefore, to obtain improved estimates of impacts from both 21st-century and long-term sea-level rise, new modelling approaches incorporating a better understanding of dynamic processes in ice sheets are urgently needed, as already noted by WGI. Furthermore, central to nearly all the assessments of key vulnerabilities is the need to improve knowledge of climate sensitivity – particularly in the context of risk management – the right-hand tail of the climate sensitivity probability distribution, where the greatest potential for key impacts lies.

Finally, the elucidation and determination of dangerous anthropogenic interference is a complex socio-political process, involving normative judgments. While information on key vulnerabilities will inform and enrich this process, there may be useful insights from the social sciences that might support this process, such as better knowledge of institutional and organisational dynamics, and diverse stakeholder inputs. Also needed are assessments of vulnerability and adaptation that combine top-down climate models with bottom-up social vulnerability assessments.

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