IPCC WGII Fourth Assessment Report – Draft for Expert Review

Chapter 19: Assessing Key Vulnerabilities and the Risk from Climate Change

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Executive Summary

The purpose of this chapter is to introduce the concept of "key vulnerabilities" and to provide an assessment of:

- interpretations of the concept, and criteria for identifying key vulnerabilities
- specific climatic impacts, physical/biological processes, and climate-sensitive systems that could be identified as key vulnerabilities
- adaptation and mitigation response strategies to deal with key vulnerabilities.

The identification of key vulnerabilities is intended to provide guidance for identifying levels and rates of climate change that could potentially be considered "dangerous" by different sets of decision-makers. Ultimately, the definition of "dangerous anthropogenic interference with the climate system" (DAI) cannot be based on scientific arguments alone, but must incorporate value judgments and therefore be made through a political process that is informed by the state of science knowledge.

Key vulnerabilities are a product of the exposure of systems and populations to climate change, the sensitivity of those systems and populations to such influences, and the capacity of those systems and populations to adapt to them. Changes in these factors can increase or decrease vulnerability. Assessments of key vulnerabilities need to account for the spatial scales and timescales over which impacts occur, the distribution of impacts among groups as well as the temporal relationship between causes, impacts, and potential responses. No single metric can adequately describe the diversity of key vulnerabilities. This chapter identifies six objective and subjective criteria for assessing and defining key vulnerabilities:

- magnitude
- timing
- persistence and reversibility
- likelihood and confidence
- potential for adaptation
- importance of the vulnerable system.

Some key vulnerabilities are associated with "systemic thresholds" in either the climate system, the socio-economic system, or coupled socio-natural systems (e.g., a collapse of the West Antarctic Ice Sheet or the cessation of sea ice touching the shore in the Arctic that eliminates a major prerequisite for the hunting culture of indigenous people in the region). Other key vulnerabilities can be associated with "normative thresholds," which are defined by groups concerned with a steady increase in adverse impacts caused by an increasing magnitude of climate change (e.g., a magnitude of sea level rise no longer considered acceptable by low-lying coastal dwellers).

This chapter synthesizes information from the relevant literature and from the regional and sectoral chapters of WG II, identifying key vulnerabilities in many climate-sensitive systems, including global biogeochemical cycles, ice sheets, modes of oceanic and atmospheric circulation, water resources, ecosystems and biodiversity, food production, coastal systems, health, and regional systems. General conclusions include:

- Global mean temperature changes associated with different key vulnerabilities that are global in scale typically range from 1.5 to 4°C above pre-industrial temperature (corresponding to ~0.8 to 3.3ºC above current temperatures). Temperature changes associated with different key vulnerabilities that are regional or local in scale range from 0.5 to >5ºC above pre-industrial levels.

- Some impacts of climate change that are already underway have been identified in some studies as key vulnerabilities. Among these are loss of glaciers, adverse impacts on biodiversity, increases in severity of extreme events, and loss of cultural amenities.
- World regions that are already at high risk from current climate variability are more likely to be adversely affected by anthropogenic climate change in the near future.

Finally, this chapter assesses current scientific knowledge of the development and analysis of adaptation and mitigation response strategies specifically regarding key vulnerabilities.

Planned adaptation can significantly reduce many potentially dangerous impacts of climate change and reduce the risk from many key vulnerabilities. However, the technical and financial resources and political motivation necessary for planning and implementing effective adaptations are currently quite limited in many regions, in particular in developing countries. In addition, the risk-reducing potential of planned adaptation is very limited for some plausible key vulnerabilities, such as loss of biodiversity, melting of mountain glaciers or disintegration of major ice sheets. On the other hand, especially in developed countries, the capacity to implement coastal protection, agricultural crop changes or irrigation systems is considered much higher—if the obstacles mentioned above can be overcome. The literature is divided into more and less favourable views of the potential for adaptation to abate key vulnerabilities, though it is consistent in suggesting that it will be much more difficult to adapt to climatic warming above a few degrees than less than a few degrees, and that adaptation will be more difficult and expensive for fast warming rates than for a slower warming.

Several frameworks are available for assessing the complex relationship between mitigation strategies and key vulnerabilities of climate change. No one approach provides a full picture of all the issues involved. This chapter identifies four methodological categories: Scenario analysis and analysis of stabilization targets, “guardrail” analysis, integrated assessment of key vulnerabilities, and cost-effectiveness analysis. Though these categories encompass a very diverse set of studies, several conclusions are more robust:

- Given the uncertainties in factors such as climate sensitivity, regional climate change, and vulnerability from climate impacts, a risk management framework is generally the most appropriate approach to address key vulnerabilities. But, the assignment of probabilities to specific key vulnerabilities is often very difficult, and sometimes impossible, because of the large uncertainties involved.
- Reductions in greenhouse gas emissions will reduce the risk of key vulnerabilities and DAI. Postponement of emissions reductions, in contrast, increases the risk of key vulnerabilities and DAI, and, depending on the rate of learning that brings down costs of low-GHG emitting technologies, makes achievement of the lower range of stabilization targets (e.g., less than 500ppm CO2-equivalent) increasingly expensive or infeasible (except via overshoot scenarios).
- Some large-scale singularities (e.g., abrupt or essentially irreversible changes) of the climate system can no longer be avoided with certainty. Given historical climate change and the inertia of the climate system, a small probability (of the order of several percent) of triggering such events remains even for stringent emission reductions. Research results using different analytical methods indicate a high confidence that CO2 stabilization levels above 450 ppm eventually (in equilibrium) are likely to produce global mean warming in excess of 1ºC above current levels (corresponding to ~1.7°C above pre-industrial levels).
- The “reasons for concern” identified in the TAR remain viable. The information assessed in this chapter suggests the following updates to the “reasons for concern”:
  1. Unique and Threatened Systems. Since the TAR, there is new and much stronger

evidence of observed impacts of climate change on unique and vulnerable systems, many of which are described as already adversely affected by climate change to date. This is particularly evident in polar ecosystems and mountain-top ecosystems. Furthermore, confidence has increased that a 1 to 2°C increase in global mean temperature above current levels will pose significant risks to many unique and vulnerable systems, including many biodiversity hotspots. A qualitative review results in a threshold target for overall risks to unique and threatened species of 1ºC-2ºC global mean temperature warming above 1990 levels. In summary, there is now high confidence that a warming of 1-2°C would have adverse impacts on many unique and vulnerable systems.

2 Extreme Events. Recent extreme climate events have demonstrated that such events can cause significant loss of life and property damage in developing as well as developed countries. While individual events cannot be attributed solely to anthropogenic climate change, recent research has shown that human influence has already significantly increased the risk of certain extreme events (e.g., heat waves, tropical cyclone intensity increases).

3 Distribution of Impacts. There is still high confidence that the distribution 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. For instance, indigenous populations in high-latitude areas are already faced with significant adverse impacts from climate change to date, and coastal dwellers are facing increasing risks.

4 Aggregate Impacts. The findings of the TAR are broadly consistent with more recent studies. 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 temperature increases, and an overly simple representation of adaptation. Recent studies have included some of these previously unaccounted for aspects, such as flood damage to agriculture and damages from increased cyclone intensity. These studies imply that the physical impacts and costs associated with these neglected aspects of climate change may be very significant. Hence, the current generation of aggregate estimates in the literature could well understate the actual costs of climate change. However, current studies also may overlook some positive impacts of climate change or underestimate the potential of adaptation to reduced damages from climate change. In summary, there is now lower confidence in most assessments of aggregate effects than in the TAR; in particular, there is greater uncertainty in estimates that show aggregated benefits from climate change below a few degrees of warming.

5 Large-Scale Singularities. Since the TAR, the literature indicates that thresholds for at least one of these events, deglaciation of West Antarctica, may be lower than reported in the TAR. While there is no consensus yet, some studies indicate that a 2 to 4°C global warming above current levels could begin WAIS deglaciation (low to medium confidence). Recent observations also suggest that the Greenland ice sheet is losing mass at its periphery faster than previously thought, and that rapid deglaciation could be triggered by GMT increases of about 1°C above current levels. The literature on thresholds for triggering a slowdown of meridional overturning circulation (MOC) or net biogenic feedbacks on the carbon cycle is consistent with the TAR, but still is not reporting high confidence conclusions.

19.1 Introduction: Basic Concepts and Perspectives

19.1.1 UNFCCC and Determining "Dangerous Anthropogenic Interference"

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) calls for stabilization of greenhouse gas concentrations at a level that would prevent "dangerous anthropogenic interference with the climate system" (see Box 19.1). Any specific level of greenhouse gas concentrations in the atmosphere that can be considered "dangerous" is subject to change with new information about climate processes, the severity and distribution of impacts, the prospects for successful adaptation, the perception of risk, and human values and priorities. Defining this objective so as to guide policy decisions requires, first, a scientific analysis of what impacts are expected for different level of greenhouse gas concentrations or global climate change. Second, it requires a normative evaluation of which impacts are important enough to constitute, individually or in combination, "dangerous anthropogenic interference".

BOX 19.1:

UNFCCC Article 2:
"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.

This stabilization 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."

The regional and sectoral chapters of this report provide substantial evidence that climate change is expected to result in a wide range of impacts experienced by a variety of social and natural systems, in different timeframes and across different geographic scales. The focus of this chapter is on synthesizing this information to provide policy-makers and other end users with an understanding of impacts that may be considered "key" for the assessment of "dangerous anthropogenic interference" and the formulation of response strategies. In this chapter, these impacts are denoted as "key vulnerabilities".

[Note to readers of this First Order Draft: Of necessity, this is an integrating chapter and depends to a considerable extent on information in regional and sectoral chapters of WG II, as well as some chapters of WGs I & III. Unfortunately, this usually means that we are one generation lagged from the information in other chapters, as they are preparing their FODs in parallel with us. Thus, we often refer to information from their Zero Order Drafts, as the FOD updates of these chapters were generally not available in time for us in the FOD writing stage. Thus, it must be understood by readers of the FOD that the ZOD references we frequently cite are in essence placeholders for updated information we will get from other chapters before we prepare our next draft. Thank you for understanding this unavoidable situation, and please keep

it in mind if reviewing this draft. Thank you.]

19.1.2 Role of scientific analysis of the IPCC

The assessment of key vulnerabilities of climate change is challenged by uncertainty regarding future climate change. Evaluating the consequences of anthropogenic climate change outcomes to determine those that may be considered "dangerous" is a complex undertaking, involving substantial uncertainties and judgements about social preferences. It involves specification of important non-climatic changes including development paths which affect greenhouse gas emissions and adaptive capacity, of the response of biophysical and socio-economic systems to changes in climatic and non-climatic conditions over time, of the impacts that may result from projected climate changes, of the distribution of such impacts and the potential for effective adaptation across regions, sectors and social groupings, and, not least, of value judgments about the acceptability or unacceptability of potential risks implied by the whole chain of linked processes starting with forcing scenarios and concluding with projections of impacts and their implications. These uncertainties can, in principle, be addressed by additional scientific and policy research, although the values, perceptions and political priorities represent moving targets which are subject to change even as knowledge of them improves.

The assessment of key vulnerabilities also involves important value judgments about the acceptability of risks and various trade-offs involved in policy choices. Scientific analysis can inform the policy process with assessments of risks, their distribution across sectors, regions and groups, and their implications. Nevertheless, the perception of which impacts are "key" and preferences for policies appropriate for addressing them, necessarily involves normative choices or value judgements. IPCC has repeatedly emphasized this point. The IPCC Synthesis Report of its Third Assessment Report stated: "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." (TAR, p. 2). Accordingly, this chapter presents the state of knowledge about climate impacts and their socially determined consequences or outcomes, focusing on the identification of key vulnerabilities and the current understanding of the range of policy choices relevant to Article 2. It is therefore germane, while considering the role of scientific analysis in supporting decisions pertaining to Article 2, to include aspects from social sciences relevant to the perception and management of risk—decision-making under uncertainty and the socio-political process that will underlie the decision-making. The inclusion of such social science understanding underlines the fact that what is to be considered "dangerous" has to be periodically revisited and reassessed both in scientific and in policy terms—as already is routine in other environmental science and policy issues such as ozone depletion, water quality standards or air pollution regulations.

19.1.3. What are "Key Vulnerabilities"?

The various research communities addressing the climate change problem conceptualize the term "vulnerability" in many different ways. In the TAR, the vulnerability of a system to climate change was characterized as being comprised of three factors: exposure to climatic stimuli, sensitivity to these stimuli, and adaptive capacity (Glossary, WG II TAR). The pertinent literature uses the term "key vulnerability" broadly in the context of potentially severe impacts of climate change that endanger the lives or well-being of people or other valued attributes of climate-sensitive systems. Such systems include social communities and population groups, geographical regions, economic sectors, and natural and managed ecosystems. We note that various research communities use the term "vulnerability" more specifically to describe properties of a system or community that make them susceptible to a range of hazards, as shown in Figure 19.1 for the case of flood hazards.

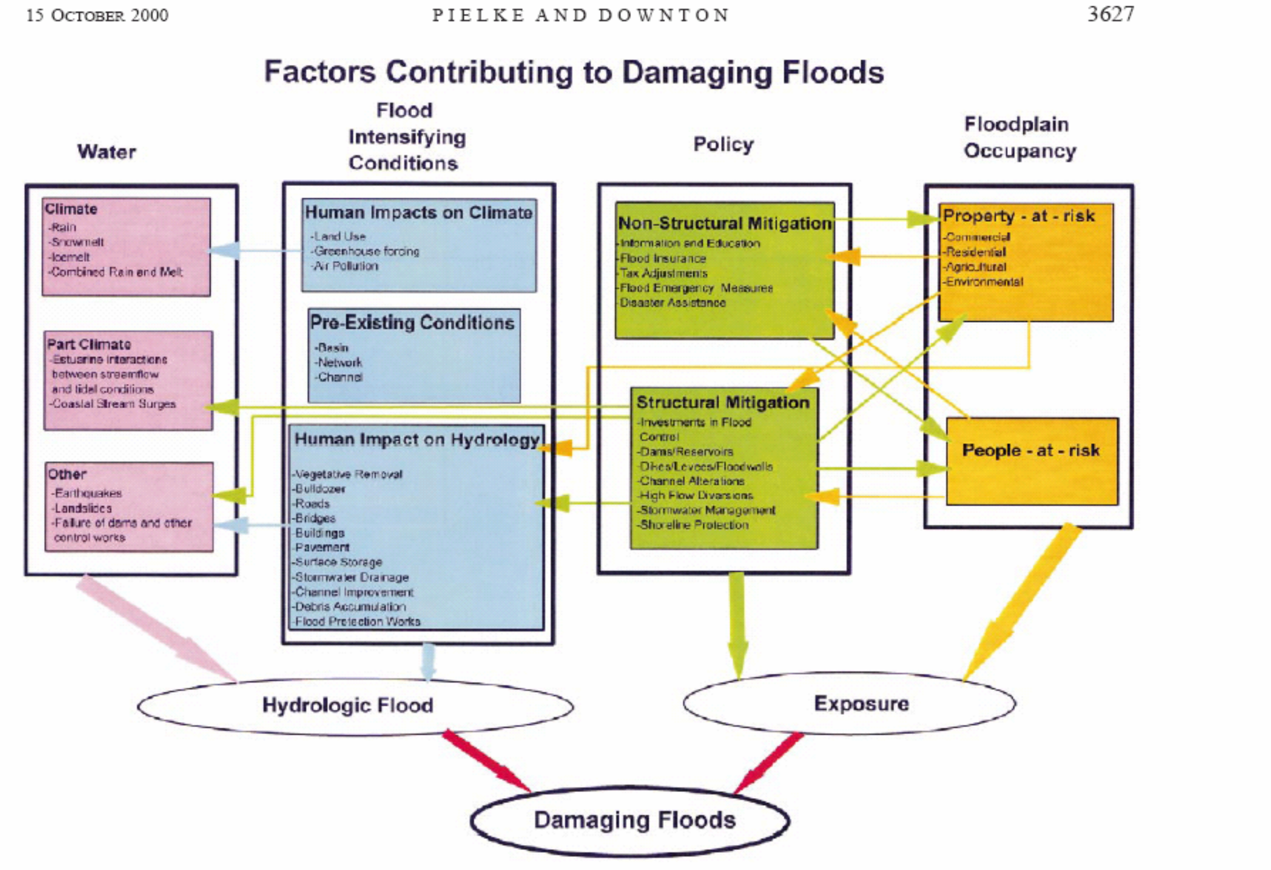

FIG. 2. Framework for understanding the interrelated factors responsible for the occurrence of damaging flood.

Figure 19.1: *Factors contributing to damaging floods. Source: Pielke and Downton (2000).*

The causal relationship between greenhouse gas emissions and climate impacts is often complex, involving a cascade of interrelated knock-on effects. For instance, large warming induced by increasing greenhouse gas concentrations may cause disintegration of the West Antarctic Ice Sheet, leading to substantial rise in sea levels and the eventual inundation of extensive coastal lands. This may trigger massive coastal defense works in densely populated areas where such works would be technically and economically feasible. Where such protection is not feasible, for instance in many low-lying islands and in extensive agricultural delta lands in Asia and Africa, flooding would necessitate internal and/or international migration. Several points along this cause-effect chain have been denoted in the literature as "key vulnerabilities", including 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 West Antarctic Ice Sheet). Some key vulnerabilities involve thresholds in the vulnerable system whereas others do not (see Section 19.2.3).

In this chapter, we pragmatically follow the broad use of the term “key vulnerability” in the pertinent literature, referring to the vulnerable system, the severity of the impact, or the causal mechanism. The identification of “key vulnerabilities” is intended to provide guidance for identifying levels and rates of climate change that may or may not be considered "dangerous" by different sets of decision-makers. The decision whether certain vulnerability is "key" involves objective as well as subjective elements (Patwardhan *et al*., 2003). For a discussion of the criteria used to identify “key vulnerabilities” in the context of this chapter, see Section 19.2.1. It should also be noted that the list here of “key” vulnerabilities is not intended to be exhaustive, nor does it constitute a list of “dangerous” impacts. Key vulnerabilities may or may not be regarded by different decision makers as leading to dangerous impacts. The judgement as to what is dangerous is another value judgement.

19.1.4. Context: IPCC TAR and other assessments and processes

The IPCC Third Assessment Report (TAR; Smith *et al*., 2001) identified five “reasons for concern”, which individually, or in combination, could be used to determine a “dangerous” level of climate change. The five reasons for concern each addressed the relationship between an increase in global mean temperature and:

1. risks to unique and threatened systems
2. risks from extreme climate events
3. distribution of impacts
4. aggregate impacts
5. risks from future large-scale discontinuities.

Section 19.3.5 summarizes the main conclusions of the TAR as well as how recent research has updated them.

The all-encompassing nature of climate change means that it intersects with a broad range of issue areas on the international agenda, including other environmental problems as well as social, economic development and trade concerns. Since the Third Assessment Report, an increased awareness of these inter-linkages within the research and policy community has led to actions to enhance scientific understanding of climate change in an integrated context and also to promote greater institutional and policy coherence between the climate change regime and other multilateral environmental regimes (MEAs) as well as with wider initiatives in the UN system (Yamin and Depledge, 2004). This section provides a brief overview of the main research and policy linkages between climate change and other UN processes and international scientific assessments that bear on the assessment of key vulnerabilities discussed in this chapter.

The World Summit on Sustainable Development (WSSD) held in Johannesburg in 2002 was intended to renew the commitment and support for sustainable development and to promote accelerated implementation of sustainable development across the UN system. The WSSD Plan of Implementation includes references to climate change and implicates climate change in the context of the “WEHAB initiative”, which puts forward five areas as priority themes for sustainable development: Water and sanitation, Energy, Health, Agriculture and Biodiversity.

The Millennium Summit of the UN held in 2000 took an integrated approach to global problems aiming to address a wide spectrum of issues such as peace, poverty eradication, and gender equality, as well as protecting the environment. The Summit agreed on eight Millennium Development Goals (MDGs), including the goal to “ensure environmental sustainability” with the target to "integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources".

As they address issues relevant to the assessment of key vulnerabilities, dedicated processes dealing with specific groups of vulnerable countries, such as the Programme of Action for the Least Developed Countries (LDCs) adopted by the UN in 2001 and the January 2005 Mauritius Declaration and Strategy for the Further Implementation of the Programme of Action for the Sustainable Development of Small Island States (SIDs) are also relevant in the context of climate change. Additionally, a number of efforts driven by the development assistance community – that is bilateral and multilateral development agencies -- have begun to assess the implications of development for climate change and climate change for conventional development (Sperling, 2003; Klein, 2001; Agrawala *et al*., 2005)

Attempts to assess environmental stressors, which can make a wide range of systems more vulnerable to climate and non-climate hazards, include:

1 The Millennium Ecosystem Assessment (MA), completed in 2005 (Millennium Ecosystem Assessment, 2005 a and b), which has assessed the state of the world's ecosystems, and of the goods and services they provide for humanity.
2 "Safeguarding The Ozone Layer And The Global Climate System: Issues Related To Hydrofluorocarbons And Perfluorocarbons", also published in 2005 by the IPCC and the Technology and Economic Assessment Panel (TEAP) of the Ozone Secretariat (the Secretariat for the Vienna Convention for the Protection of the Ozone Layer and for the Montreal Protocol on Substances that Deplete the Ozone Layer), which explores the linkages between climate change and stratospheric ozone depletion.
3 Convention of Biological Diversity (http://www.biodiv.org/default.shtml).

19.1.5 Roadmap to the chapter

The purpose of this chapter is to elaborate on the concept of key vulnerabilities in order to show the wide variety of ways in which the concept may be defined, used and interpreted. There is no scientific basis for the specification or selection of a single metric in which vulnerabilities can be divided into those that are "key" and those that are "not key". The chapter therefore describes a range of possible criteria for the identification of key vulnerabilities (Section 19.2) and then applies these criteria to a wide range of vulnerabilities identified in other chapters of this WG II assessment as well as in the WG I assessment (Section 19.3). Many vulnerabilities that may potentially be identified as "key" are seen to be "key vulnerabilities" in terms of some but not all of the possible criteria. Finally, the literature on the methods employed in the development and analysis of the two major response strategies (mitigation and adaptation) is assessed. Mitigation is directly addressed in Section 19.4, whereas adaptation is primarily addressed in section 19.3, including within Table 19.1 (Section 19.3.4).

This assessment identifies some important knowledge gaps and eventually will address a possible research agenda (Section 19.5).

19.2. Identifying and Evaluating Key Vulnerabilities: Methods and Concepts

This section provides an overview of criteria that have been used in the literature to identify "key" vulnerabilities, or impacts of climate change that are considered to constitute "dangerous anthropogenic interference with the climate system”. The question of which impacts might satisfy the criteria of Article 2 has attracted much attention only recently, and the literature still remains relatively sparse (Oppenheimer and Petsonk 2005)**.** Furthermore, Article 2 leaves the definition of “dangerous” flexible, thereby allowing different interpretations and reinterpretations of what is dangerous (Oppenheimer, 2005; Leiwserowitz, 2005). Therefore, even if it were possible for the present generation to agree on a specific threshold of dangerous climate change -- a global mean temperature increase of 2°C over pre-industrial levels is often cited in the literature -- this target might be changed in the future based on changes in scientific knowledge, social values and political priorities. The IPCC has addressed a number of these issues in Chapter 19 of Working Group II in the Third Assessment Report (Smith *et al.*, 2001).

19.2.1. Criteria for Assessing Key Vulnerabilities

In Section 19.1.3, key vulnerabilities of climate change were defined as those climate impacts or vulnerable systems that are particularly significant in the context of Article 2. Studies of vulnerabilities and impacts of climate change have explicitly or implicitly highlighted certain characteristics as providing meaningful measures of harm (Corfee-Morlot and Höhne, 2003; Schneider *et al.*, 2000), and these are reflected in various tabulations of key indicators, vulnerabilities, or dangers (Smith *et al.*, 2001; Corfee-Morlot and Höhne, 2003; Oppenheimer and Petsonk, 2003, 2005; Hare, 2003; Leemans and Eickhout, 2004; Hitz and Smith, 2004; ECF, 2004; DEFRA, 2005).

Any assessment of what impacts of climate change are “key” and what is “dangerous” involves factual and normative elements, which have sometimes been equated with the “external” and “internal,” or “subjective,” dimensions of risk (Patwardhan *et al.*, 2003; Dessai *et al.*, 2004, Pittini and Rahman, 2004). More objective criteria include the scale, magnitude, timing and persistence of the harmful impact, and the level of confidence in the climate change-impact relationship (Parry *et al.*, 1996; Kenny *et al.*, 2000; OECD, 2003; Schneider, 2003; Corfee-Morlot and Hohne, 2003; Oppenheimer 2005; Moss and Schneider, 2000). Examples of more subjective or normative criteria are the uniqueness and importance of the threatened system, the degree of risk aversion, equity considerations regarding the distribution of impacts, and assumptions regarding the feasibility and effectiveness of potential adaptations (OECD, 2003; Tol *et al.*, 2004; Pearce, 2003; IPCC WG II TAR). Normative criteria are, obviously, influenced by socially-mediated perceptions of risk, which are culturally and socially context specific (e.g. Slovic, 2000).

Moreover, different groups may have differing views on what should even be included in the definition of “vulnerable system” with, to dichotomize for sake of making a clear distinction, “anthropocentrists” focusing on human systems as the only ones that should be classified as “vulnerable”, whereas those with more “nature-centric” values would consider a species of no clear utility to human societies--but whose survival is threatened by climate change--as legitimately part of the definition of a “vulnerable system”. The Greenland Ice Sheet is another example that those holding nature-centric views would likely consider a potentially vulnerable system, whereas anthropocentrists would likely consider this a higher order impact that might eventually have some relationship to societal utility. It is important for decisonmakers to be aware of these often-implicit value dichotomies in reading the literature on vulnerability and when considering possible policies and measures to respond (Füssel, 2005).

Different decision makers are thus likely to perceive different vulnerabilities as “key”. From the point of view of this chapter, accepting that decision makers bring different underlying normative frameworks to the table does not mean agreement on normative elements is not possible, rather it signals the need for explication of how such normative frameworks can influence decision-making, including the role played by such frameworks in the generation of biases, preferences and gaps in knowledge. All the above characteristics are reflected in judgements made by the regional and sectoral chapters of this assessment (chapters 3-16) in proposing certain vulnerabilities as "key" (see Table 19.1); we attempt, as far as possible to, explain the criteria giving rise to "key" choices as used in the literature. In the remainder of this section, we discuss the most important of these criteria.

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). Many studies have associated key vulnerabilities or dangerous anthropogenic interference with large-scale changes in the climate system. Well-known examples include possible deglaciation of the ice sheets in Greenland (AR4 WGI Ch. 4,5,10; Gregory *et al.*, 2004, Hansen, 2005) or West Antarctica (AR4 WGI Ch 4,5,10; Oppenheimer, 1998; Oppenheimer and Alley, 2004, 2005), changes of global biogeochemical cycles (AR 4 WGI Ch.7; Cox *et al.*, 2000, 2004; Cramer, 2001; Freidlingstein, 2003; Cowling *et al.*, 2004) that may result in positive feedbacks on the climate, and major changes of large-scale patterns of oceanic and atmospheric circulation such as the thermohaline circulation (AR4 WGI Ch.10; Rahmstorf and Zickfeld, 2005), and the intensity of tropical cyclones (e.g., Emanuel, 2005), ENSO (Timmerman *et al.*, 1999), and other normal modes of climate variability. Other examples might include widely distributed local effects such as negative impacts on food production or water supply, which in total are expected to affect many people. The global or hemispheric scale of such impacts weighs in any selection of what could be assessed as "key." Other studies have associated key vulnerabilities with the loss of unique human cultures, even if the number of people affected is limited. Examples include small island nations at risk of flooding from sea-level rise (Chapter 16) or the Inuit people of the North American Arctic (Chapter 15) having to cope with the receding of sea-ice that is central to their socio-cultural environment. We do not attempt to develop a rule specifying the scale of impacts on vulnerable systems that designates them as "key," but rather present examples at many scales and for many natural and social systems.

Various metrics are used to describe the magnitude of climate impacts. The most widely used quantitative measures for climate impacts are monetary units such as income or revenue losses (Nordhaus and Boyer, 2000), costs of anticipating and adapting to low probability but high-impact occurrences like a very large sea level rise (Nicholls, 2004), and contingent valuation (i.e., estimates of people's willingness to pay to avoid such impacts) of non-market impacts (see, e.g., Tol, 2002). Another aggregated indicator is the number of people affected by certain impacts such as food and water shortages, morbidity and mortality from diseases, and forced migration (Parry *et al.*, 2004, Arnell, 2004; Lieshout *et al.*, 2004; Schär and Jendritzky, 2004; Stott *et al.*, 2004, Barnett, 2003). "Natural" units for expressing climate impacts include agricultural yield changes (AR 4WGII Ch 5; Parry *et al.*, 2004) and species extinction numbers or rates (AR4 WGII Ch.4; Thomas *et al.*, 2004). The use of several metrics simultaneously conveys a more comprehensive picture of the current knowledge about regional impacts of climate change than any single measure.

For some impacts, qualitative rankings of magnitude are more appropriate than quantitative ones. Qualitative methods (or both qualitative and quantitative valuation) have been applied to reflect social preferences related to potential loss of cultural or national identity, loss of cultural heritage sites, and loss of biodiversity (Schneider *et al*., 2000). The magnitude of impacts as viewed from the perspective of fairness, justice, or equity (Jamieson, 1992; Gardiner, 2004) clearly have a strong value-laden aspect. These magnitudes are more likely to be assessed and expressed qualitatively but can also be expressed quantitatively, for example, in terms of numbers of people whose rights to a secure environment may be put at risk as a result of climate change (Goldberg and Wagner, 2004).

Timing

A harmful impact is more likely to be considered "key" if it is expected to happen soon rather than in the far distant future (Bazerman 2005; Weber 2005). For example, climate change is accelerating deglaciation in many mountain regions, whether in Peru, Tanzania, the Alps, or the Himalayas, which will be accompanied by shifts in coming decades of hydrological resources and mountain ecosystems and which, in turn, are affecting the livelihoods of people in these areas (see WGII Chapters 3, 4, 9, 10, 12, 13; Corfee-Morlot and Agrawala, 2005).

Impacts occurring further in the future, but which may be triggered by nearer-term events, also may be considered "key." An often cited example is the disintegration of Greenland ice sheets, which may be triggered in the coming decades but produce few or no observable effects until the longer term, after which it is too late to reverse. This phenomenon is denoted as delayed irreversibility. In economic models of climate change, the valuation of impacts at different points in time is often represented by positive time discounting (see WG III Chapter 3), but this is controversial, and discounting may be inappropriate or highly uncertain where delayed impacts may be severe. For example, deglaciation of a major ice sheet would likely induce significant economic and ecological damages several centuries from now, though under standard discounting, these damages would have a low present value, and thus would not be seen by some as deserving priority attention for corrective actions.

Another important aspect of timing is the rate at which impacts occur. In general, impacts occurring suddenly are perceived as more dangerous than impacts that occur gradually, as they limit the potential for adaptation for both human and (especially) natural systems. 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. Early warning of hazardous "surprise" events, such as tsunamis, lowers fatalities and damage, and the relative absence of such warnings were a key component in the high numbers of deaths in the 2004 Asian Tsunamis.

Persistence and reversibility

A harmful impact is more likely to be considered "key" if it is persistent, or even irreversible. Examples of impacts that become "key" due to persistence include emergence of regions with near-permanent drought conditions (e.g. in semi-arid and arid regions in Africa; Nyong, 2005) and areas subject to intensified cycles of extreme flooding that were previously regarded as "one-off" events (e.g., in parts of the Indian sub-continent; Lal, 2002).

Examples of climate impacts that are irreversible, at least on the time scales of many generations of humans, include shifts in regional or global biogeochemical cycles (AR 4 WGI Ch 7; Rial *et al.*, 2004), the loss of major ice sheets (Oppenheimer 1998; Gregory *et al.*, 2004). the breakdown of the thermohaline ocean circulation (AR4 WGI Ch 10; Stocker and Schmittner 1997; Rahmstorf and Zickfeld, 2005), the extinction of species (Thomas *et al.*, 2004, Lovejoy and

Hannah, 2005), the flooding of populated regions due to sea-level rise (Nicholls, 2004), certain land cover changes (Cowling *et al.*, 2004), and the loss of unique cultures (Barnett and Adger, 2003).

Likelihood and confidence

The future rate and magnitude of climate change is associated with a substantial level of uncertainty, though the occurrence of some climate change is highly likely (see Section 19.4.1). In the assessment of key vulnerabilities, two components of uncertainty need to be distinguished: likelihood and confidence (Moss and Schneider, 2000). In an expert elicitation of subjective probabilities of certain climate events (Morgan and Keith, 1995) or impacts (Nordhaus, 1994), the likelihood could be framed as the central value of the probability distribution, whereas the confidence is reflected primarily by its spread. Other things being equal, an impact with a high likelihood is more apt to be seen as “key” then an impact of similar size and magnitude but with a lower likelihood of occurrence. Other things being equal, a risk-averse stakeholder will likely give more attention to highly uncertain, but potentially highly damaging impacts, than to more certain, but lower damaging impacts, whereas a risk-prone stakeholder would likely have an opposite view.

Potential for adaptation

To assess potential harm caused by climate change, the ability of individuals, groups and societies to adapt to or ameliorate adverse impacts must be considered. The lower the likelihood of effective adaptations, the more likely such impacts would be characterized as “key vulnerabilities”. Adaptation assessments need to consider not only the technical feasibility of certain adaptations but also the availability of required resources, the costs and side effects of adaptation, the knowledge about those adaptations, their timeliness, the incentives for the adaptation actors to actually implement them, and their compatibility with individual or cultural preferences.

Impact sectors differ in the potential for adaptation to ameliorate the impacts of climate change. While there is considerable scope for adaptation in agriculture and in some other sectors in which technical and social instruments are available to be deployed to reduce impacts, there is much less scope for adaptation in the case of biodiversity preservation and some impacts of sea-level rise (see Chapter 17).

As noted in the discussion within Table 19.1 below, the adaptation literature can, for the sake of making a clear distinction, be dichotomized 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 many difficult social, financial and technical obstacles that might inhibit the actual implementation of the many adaptation options those holding more favourable views suggest are possible. This chapter simply reports the range of views and literature on adaptive capacity relative to the assessment of key vulnerabilities, and notes that these very different views contribute to the large uncertainties that accompany most assessments of key vulnerabilities.

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. Some factors are widely recognized as indicating the importance of a system. The transformation of an existing natural ecosystem, for instance, is more likely to be regarded as important if that ecosystem is the unique habitat of several endemic species or contains an endangered charismatic species. Where livelihoods of people depend crucially on the functioning of a natural system, it may be regarded as more important than one in an isolated area (e.g., a mountain snow pack system with large downstream use of the melt water versus an equally large snow pack system with only a small population downstream using the melt water). However, any assessment of importance will also include normative criteria. For instance, some nature-centric stakeholders may see ecosystems as valuable in their own right while others (i.e., those more anthropocentric) may judge importance primarily based on their provision of goods and services to humans.

19.2.2. Key Vulnerabilities and Dangerous Anthropogenic Interference

The guiding objective in Article 2 of the UNFCCC necessitates decision-making that invokes normative judgements about the geographic, temporal, social and ecological distribution of climate impacts at different scales of governance. References in Article 2 to sustainable development, food production and natural ecosystems provide a degree of explicit normative guidance about which impacts may constitute “dangerous anthropogenic interference with the climate system” (DAI), as does the reference to time-frames to allow ecosystems to adapt naturally.

Key vulnerabilities of climate change were defined in Section 19.1 as potential impacts of climate change at different scales that are expected to be relevant for (some) decision-makers in their determination of what constitutes “dangerous anthropogenic interference with the climate system” (DAI) in the context of Article 2 UNFCCC. DAI refers to a level of global climate change or global greenhouse gas concentrations that is considered unacceptable because it is associated with one or more key vulnerabilities. While some large-scale key vulnerabilities (e.g., melting of large ice sheets) may constitute DAI by themselves, decision-makers may also base their judgement of what level of global climate change constitutes DAI on an implicit or explicit aggregation of key vulnerabilities identified in different regions, sectors, and population groups. Hence, the step from individual key vulnerabilities to DAI generally involves considerations of the distribution of impacts across different regions, population groups, and/or generations, and methods for valuing and aggregating these impacts. The potential contributions, as well as the limitations of different methods for valuing and aggregating impacts, are presented below.

Distribution and Equity

Vulnerability to climate change differs considerably across population groups, thus raising important questions about equity. Their limited capacities and access to resources tend to make today’s poor generically vulnerable to a wide range of climate and non-climate related sources of risk, stress and shocks. The social, cultural, and ethical dimensions of DAI have drawn increasing attention recently (Jamieson 1992, 1996; Rayner and Malone, 1998; Gupta *et al.*, 2003; Adger, 2001; Gardiner, 2005). In the context of key vulnerabilities and Article 2, climate studies have tended to focus on aggregate impacts emphasizing groups of developing countries with special needs or situations, like island nations faced with sea level rise (Barnett and Adger, 2003), countries in semi-arid regions with a marginal agricultural base, indigenous populations facing regionalized threats (AMAP, 2005), or least developed countries (LDCs); Huq *et al*., 2003).

The distinction between poverty and vulnerability can be helpful in understanding the spatial, temporal and social distribution of underlying factors that bear on poverty and vulnerability dynamics (Lambrou and Laub 2004; Bohle *et al*., 1994; Dessai, 2004; Bunyavanich *et al*., 2003).

Although meanings differ across disciplines and policy communities, “poverty” often refers to deprivation, lack, or want, whilst “vulnerability” often refers to “defencelessness, insecurity, and exposure to risk, shocks and stress.” (Chambers, 1989, Yamin, 2005, Schoon, 2005). But poverty, of course, is not the only factor that leads to vulnerability: other factors such as geographical location, communal conflict, social or ethnic association or dependence on climate related assets or livelihoods can make people vulnerable to climate change--even if they might not be considered poor. Vulnerability research in developed countries has often focused on groups of people, such as those living in coastal or flood prone regions (UKCIPS, 2004) or socially vulnerable groups, like the elderly, who suffered disproportionately in the 2004 European heatwave.

Aggregation and Classification

Aggregation of impacts across different sectors, regions, and population groups provides a useful overall, time-bound “snapshot” of the expected consequences of climate change even though many policy-making purposes require more detailed information about who, when and where climate impacts will strike hardest. Aggregation requires an understanding of (or assumptions about) the relative importance of impacts in different sectors, in different regions, and at different times. The value judgments that underlie regional aggregation, for example, have been examined extensively (Azar and Sterner 1996; Fankhauser *et al.*, 1997, 1998; Azar 1998a). Due to the critical importance of value judgements in aggregation processes, no single metric for climate impacts can provide a commonly accepted basis for climate policy decision-making (Schneider *et al*., 2000; Jacoby, 2004).

19.2.3 Key Vulnerabilities and Thresholds

Discussions about “dangerous interference with the climate system” and “key vulnerabilities” are often framed around thresholds or critical limits (Patwardhan *et al*., 2003; Izrael, 2004). For instance, 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”. Such a level may be denoted as “normative climate threshold”, as it is based not only on scientific assessments of climate change but also on normative evaluations of the results of this analysis. The threshold concept typically applied in the natural sciences refers to “systemic thresholds”, which refer to the crossing of boundaries where a system shifts from one state to another in ways that affect its ability to perform certain functions associated with its original state. These thresholds can, in principle, be defined quantitatively by reference to natural processes. An example of a well-known systemic threshold is the melting point of ice at 0°C that is important in the context of many climate impacts such as sea-level rise, changes to the carbon cycle, natural and managed ecosystems, infrastructure, indigenous people, and tourism, to name a few.

Critical levels of climate impacts are another type of normative thresholds, which are based on social, political, economic and cultural processes establishing that certain impacts are considered unacceptable and should therefore be avoided. Examples of critical impact limits are limiting sea-level rise until 2200 to 50 cm above present levels or limiting the extinction of species in the Capensis floral kingdom to 10% of endemic plant species.

The identification of key vulnerabilities and DAI for the purpose of Article 2 UNFCCC involves the integration of systemic thresholds (i.e., intrinsic properties of natural systems) with normative thresholds (i.e., socially determined levels of unacceptable impacts). Patwardhan *et* *al*., (2003) distinguished two types of critical impact limits depending on whether they coincide with systemic thresholds. "Type I thresholds refer to smooth responses of climate-sensitive systems to climatic changes that after some point lead to damages that are considered 'unacceptable' by particular policy-makers." For instance, even a gradual and smooth increase of sea-level rise will eventually reach a level where small island nations would consider it unacceptable (i.e. crossing a normative impact threshold). Type I thresholds may be more accurately referred to as "socioeconomic limits" because they are inherently negotiable in a political sense, and generally do not involve the sort of discontinuities implied in the term "threshold". Type II thresholds are linked directly to nonlinear processes of the climate system itself, such as sudden changes in the Asian monsoon. These thresholds have often been used in integrated assessments of climate change in the context of Article 2 UNFCCC (see Section 19.4). From the point of view of key vulnerabilities, both types of impact thresholds are important in shedding light on the totality of impacts of climate change relevant to defining ”dangerous” levels of climate change or atmospheric greenhouse gas concentrations.

19.3 Identification and Assessment of Key Vulnerabilities

This section synthesizes the literature on key vulnerabilities from climate change. Relevant information is drawn from the regional and sectoral chapters in Working Group II, as well as related chapters from the Working Group I report. This examination is also informed by previous discussions of climate impacts in the context of key vulnerabilities and Article 2 (Smith *et al.*, 2001; Corfee-Morlot and Höhne, 2003; Oppenheimer and Petsonk, 2003, 2005; Hare, 2003; Leemans and Eickhout, 2004; Hitz and Smith, 2004; ECF, 2004; DEFRA, 2005).

[Note to readers: As explained in section 19.1, of necessity this integrating chapter cannot import the latest draft material from sectoral and regional chapters as they are being written simultaneously. This draft is heavily dependent on the Zero Order Drafts of other chapters, an unfortunate but unavoidable consequence of the lag of one drafting generation that occurs when all chapters are written on parallel tracks. The next draft will be better able to incorporate the emerging conclusions from other chapters in the AR4 relevant to key vulnerabilities.]

Various approaches can be taken to classify the large quantity of information about expected impacts of and vulnerability to climate change. The IPCC has, in its TAR, proposed a framework for structuring the knowledge about climate change that is motivated by the human perception and interpretation of complex risks: the five reasons for concern (see 19.1.4; Smith *et al*., 2001). In this chapter, we distinguish global, sectoral, and regional key vulnerabilities. This classification allows presentation of relevant information at a greater level of disaggregation than the five reasons for concern, though we do continue to discuss key vulnerabilities using that framework. Section 19.3.1 presents those vulnerabilities with effects across the globe, Section 19.3.2 addresses sectoral vulnerabilities, which may be either global or restricted to certain regions, and Section 19.3.3 presents vulnerabilities that are critical for individual regions or sub-regions. Section 19.3.4 summarizes information about all key vulnerabilities discussed so far. Section 19.3.5 updates the five reasons for concern presented in the IPCC TAR based on the information from the previous sections, thus characterizing some of the progress made in the impacts literature since the TAR.

When comparing potential temperature thresholds and stabilization levels, care must be taken to maintain consistency in metrics. Thresholds for global mean temperature change have been variously presented as changes with respect to: pre-industrial temperatures; the average temperature level of the 1961-1990 period; or with respect to "current" temperatures, usually anchored within the 1990-2000 period. The best estimate for the increase above pre-industrial levels in the 1961-1990 period and in the 1990-2000 "current" period are 0.3°C and 0.6°C, respectively (Folland *et al*., 2001). Therefore, to illustrate this via a specific example, limiting global mean temperature change to, say, 2°C above pre-industrial levels corresponds to a 1.4°C increase above 2000 levels, and perhaps only 1.3^{o}C above 2006 levels. Impact studies may also assess changes relative to regional warming which can differ significantly from changes in global mean temperature. Unless specified otherwise, this chapter refers to global mean temperature change above 1990-2000 "current" levels. This reflects the most common metric used in the literature.

Box 19.2 Confidence Levels and State of Knowledge

Quantitative Assessment of Confidence Levels

In applying the quantitative approach, authors of the report assign a confidence level that represents the degree of belief among the authors in the validity of a conclusion, based on their collective expert judgment of observational evidence, modeling results, and theory that they have examined. Five confidence levels are used. In the tables of the Technical Summary, symbols are substituted for words:

Very High (*****)	95% or greater
High (****)	67-95%
Medium (***)	33-67%
Low (**)	5-33%
Very Low (*)	5% or less

Qualitative Assessment of the State of Knowledge

In applying the qualitative approach, authors of the report evaluate the level of scientific understanding in support of a conclusion, based on the amount of supporting evidence and the level o agreement among experts about the interpretation of the evidence. Four qualitative classifications are employed:

- *Well-established:* Models incorporate known processes, observations are consistent with models or multiple lines of evidence support the finding.
- *Established but incomplete:* Models incorporate most known processes, although some parameterizations may not be well tested; observations are somewhat consistent bur incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes, although some parameterizations may not be well tested; observations are somewhat consistent but incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes over time is considerable; or only one or a few lines of evidence support the finding.
- *Competiting explanations:* Different model representations account for different aspects of observations or evidence or incorporate different aspects of key processes, leading to competiting explanations.
- *Speculative:* Conceptually plausible ideas that are not adequately represented in the literature or that contain many difficult to reduce uncertainties

"Note to FOD readers: The precise language and calibration of terms used to describe levels of confidence and the state of knowledge is currently being finalized across Working Groups in conjunction with the cross-cutting group on uncertainties. Therefore, this FOD still uses the respective terminology from the TAR, as defined in Box 2 from the Technical Summary of the WG II contribution to the TAR (see below) on the basis of Moss and Schneider (2000). This terminology will be adjusted after IPCC-wide policy is set for AR4."

19.3.1 Global Key Vulnerabilities

19.3.1.1. Global biogeochemical cycles

Both the carbon and the nitrogen biogeochemical cycles are affected by (and in turn affect) the course of climate change (AR4 WGI section 7.1.4). Changes in net primary productivity of terrestrial vegetation as climate changes and CO_2 increases could lead to a net negative or positive feedback on warming (AR4 WGI section 7.2.2.1.4; Matthews *et al.*, 2005; White *et al.*, 1999; Cramer *et al.*, 2001) depending on the balance among CO_2 fertilization, increased primary production and respiration, and ecosystem shifts. The positive effects of carbon fertilization on natural ecosystems may be short-lived (e.g., Schlesinger and Lichter, 2001) or limited by the variations of co-factors like air pollution levels. Simulations with 7 coupled climate-dynamic global vegetation models indicate that land carbon storage is sensitive to global mean warming (AR 4 WGI figure 7.17). They yield a total release of carbon ranging from 100-300 GtC for a warming of 3^{o}C for six of the models. Results from a seventh model (HadCM3) indicate release of 400 GtC for 3^{o}C warming and 1100 GTC for 5^{o}C warming. Reasons for this high sensitivity have been examined (Jones *et al.*, 2004; Zeng *et al.*, 2004; Cox *et al.*, 2004) but are not yet clear. Nor is it clear which model outcome may be more realistic.

These results suggest that it is likely that positive feedbacks on the carbon cycle from warming would exceed negative feedbacks beyond the middle of this century, increasing atmospheric carbon dioxide concentrations, and further enhancing warming (moderate confidence). An amplification of CO_2 emissions by 2100 in the range 13–25% is typical of recent results, but with larger positive feedbacks possible, albeit with low likelihood (AR4 WGI). This could increase the probability of temperatures and concentrations near or beyond the high end of the TAR range (Cox *et al.*, 2000, Friedlingstein, *et al.*, 2003), although no runaway greenhouse effect is obtained in any of the model simulations. A runaway greenhouse (such as on Venus) would imply a continuously amplifying positive feedback effect leading to drastic warming and a fundamental change in the chemical state of the atmosphere, a condition that has no support in the literature.

Warming of marine sediments currently at low temperature and high pressure may destabilize methane gas hydrates in some regions (AR 4 WGI section 7.2.2.2.8), as may have occurred during the latest Paleocene thermal maximum 55 million years BP (Dickens, 2001, Archer and Buffet 2005). Warming would tend to destabilise methane hydrates, but rising sea level would tend to stabilise them. That is, increased hydrostatic pressure due to sea level rise would produce a compensating effect that would reduce the risk of such an occurrence. Which effect dominates depends in part on the rate of warming, since sea-level rise lags behind warming, and the result may be quite location-specific. The likelihood of destabilization and its effect on future climate remain very uncertain. One study (Harvey and Huang, JGR 1995) estimates that methane releases increase distant future temperature by 10-25% over a range of scenarios. To date, there is only low confidence in any quantitative conclusions.

Increasing ocean acidity (decreasing pH) due to increasing atmospheric concentrations of CO_2 (AR4 WGI section 7.2.2.2.3) has been cited in the context of Article 2 (Turley, 2005). Resulting consequences may include reduction in biocalcification of marine organisms such as corals (Hughes *et al*., 2003) and other calcifiers. Reduction in $CaCO_3$ production could result in shifts in species composition and major ecological impacts. The destruction of wide areas of bottom and sediment fauna also could occur. Indirect effects on the marine food chain are also possible through the influence of pH on the solubility of the micronutrient iron (Liu and Millero, 2002). Given that ocean acidity changes are well-understood but ecosystem and nutrient effects research is in its early stages, we cautiously assign medium confidence to the supposition that changes in marine organisms and processes are likely to produce significant effects on the global carbon cycle.

Enhanced production of nitrous oxide in response to climate change may also merit consideration in the context of key vulnerabilities (Barnard and Leadley, 2005). N_2O adds to radiative forcing and also is an important factor in stratospheric ozone chemistry. Nitrous oxide production in freshwater systems is sensitive to regional climate changes (Donner *et al*., 2004) that cause changes in river flows but the global magnitude of this effect is not yet clear. Estuarine nitrogen loading and cycling is also sensitive to climate change (Struyf *et al*., 2004), and several pathways by which climate change may affect N_2O production during nitrification and denitrification in marine environments have been noted (AR4 WGI section 7.2.2.2.7). Given uncertainties in modelling the nitrogen cycle, we suggest low confidence in any quantitative estimate of significant effects on atmospheric N_2O concentrations from climate change.

Other regional scale terrestrial responses to climate change including abrupt land cover transitions from forest to grassland or grassland to semi-arid conditions (Claussen *et al.,* 1999; Eastman *et al.,* 2001; Rial *et al.,* 2004; Cowling *et al.,* 2004) may feed back to global climate by enhancing production of greenhouse gases and aerosols. However, no quantitative estimates of this regional-to-global coupling are available. All such changes in trace gas emissions feed back on atmospheric chemistry in a manner that influences global oxidation capacity (Rial *et al.*, 2004) and may in turn influence global climate in yet-to-be quantified ways (AR4 WGI section 7.3).

An important mechanism for rapid changes to land cover and carbon storage is increased frequency, intensity and spread of wildfire (Williams *et al*., 2001; Cary, 2002: Lavorel, 2003; Fried, *et al*. 2004: Myer and Pierce, 2003; Whitlock, *et al*., 2003; Tolhurst, 2003). Despite some local complicating effects (Campbell and Campbell, 2000), and lack of explicit modelling of changes in the fire regime in many climate change simulations, effects could be widespread especially in Mediterranean-type climates and at the southern edges of the great boreal forests. High confidence can be attached to the well-established connection between increased temperatures and increased wildfire potential. However, as the potential for wild fire also depends on altered precipitation regimes, and as less confidence is typically expressed in precipitation projections than for temperature projections, overall confidence in any quantitative estimation of increased wild fire with warming is medium, though there is a growing literature suggesting fire as a major impact from anthropogenic climate change, particularly in dry regions.

PLACEHOLDER FOR SOD: Another positive feedback in the carbon cycle involves melting of *permafrost peat soils, which store large amounts of methane.*

19.3.1.2 Deglaciation of West Antarctic and Greenland ice sheets

The potential for partial or complete deglaciation of the Greenland and the West Antarctic (Vaughan, 2005) ice sheets and associated sea level rise, have been analyzed specifically in the context of key vulnerabilities and Article 2 (Oppenheimer and Alley 2004, 2005; O'Neill and Oppenheimer 2002; Hansen, 2004, 2005) and scenarios for future warming (Gregory *et al.,* 2004). Resulting eventual sea level rise would be 7m and 4-6m for deglaciation of Greenland and West Antarctica, respectively. The impact of such a large sea level rise has long been postulated (Schneider and Chen, 1980; Revelle, 1983), would be pervasive, and ability to adapt would depend crucially on the rate of deglaciation (Atlantis, 2005), which is estimated as ranging from rapid (a few centuries) to slow (a few millennia; see also AR4 IPCC WGI sections 4.7.4, 10.6.3, Vaughan and Spouge, 2002; Huybrechts and de Wolde, 1999; Oppenheimer, 1998).

Recent evidence (see AR4 WGI section 4.7.4) supporting the notion of a physical threshold for rapid deglaciation of West Antarctica comes from observation of the response of glaciers and ice streams to disintegration of floating ice shelves along the Antarctic Peninsula (Scambos *et al.,* 2004) and in the Amundsen Sea-Pine Island Bay drainage (Thomas, 2004). The Larsen ice shelf in particular disintegrated very rapidly, possibly in response to attainment of a critical temperature generating surface melting (Scambos *et al.,* 2003), although basal melting may also have played a role (Shepherd *et al.,* 2003). Further acceleration of grounded ice in the Amundsen Sea drainage, or replication of these processes in the Ross or Filchner-Ronne ice shelves, could trigger partial or total deglaciation on multi-century timescales (Oppenheimer, 1998).

Assuming that future ice shelf loss would be initiated by surface rather than basal melting, and that grounded ice would respond on a sustained basis, it has been projected that a global warming of 4^0C above today's level would result in disintegration of WAIS within several centuries (Oppenheimer and Alley, 2004, 2005). If basal melting were important, this could lead to a lower temperature limit (see below). No quantitative uncertainty range or confidence levels were given, and are difficult to infer.

An alternative scenario, more consistent with models of the whole ice sheet, assumes the response to ice shelf loss will not be sustained over time and that the mass balance would be a smooth function of temperature. In such models, WAIS shows little shrinkage until local temperatures warm by about 10^0C. The timescale for deglaciation and accompanying sea level rise at such temperatures is at least a millennium (Huybrechts, 2004; Huybrechts and de Wolde, 1999). But existing ice sheet models do not reproduce important dynamical features of WAIS such as ice streams, or the fast local ice losses noted above (AR4 WGI 10.6.3).

There have been two attempts to construct cumulative probability functions for either complete deglaciation of West Antarctica or for sea level rise attributable to partial deglaciation (Titus and Narayanan, 1996, Vaughan and Spouge, 2002) both studies preceding recent findings of rapid ice loss. In both the literature survey and the Delphi exercise, the probability of WAIS collapse is very low in this century but rises above 10% within 200 to 300 years. The probability of a one meter contribution to sea level from WAIS rises above 5% by 2250 in the Delphi exercise. Note that these studies do not address the question of when radiative forcing will grow to levels sufficient to cause WAIS to collapse at a later time. Furthermore, the Delphi elicitation did not follow a Bayesian approach of assuming a particular emissions scenario, so that the probability of loss of WAIS through natural processes (MacAyeal, 1992) is implicitly included.

Ice sheet models project virtually complete loss of the Greenland ice sheet for local warming exceeding ~3^0C above current temperature (Huybrechts and de Wolde, 1999). The rate of deglaciation is temperature-dependent and the timescale is projected to range from several to as little as one millennium for warming up to 8^0C (Church and Gregory, 2001). In this model, deglaciation largely proceeds via melting at the surface and an altitude-temperature feedback from the resulting ice surface lowering. The probability of deglaciation has been estimated accordingly for a particular set of concentration stabilization scenarios that begin as each of the SRES during this century. (Gregory *et al.*, 2004). Stabilization scenarios based on all but the lowest SRES eventually lead to loss of the Greenland ice sheet, though assumptions of future emissions beyond the SRES time frame (until 2100) are problematic.
However, melting on the ice sheet surface may supply water, and hence lubrication, directly to the ice sheet base on a short timescale (Zwally *et al.*, 2001; AR4 WGI section 4.7.4). This process could result in rapid deglaciation if melting became widespread over the ice sheet in a relatively short time period (centuries) or if melting and ice loss at the periphery led to a sustained dynamical response of inland ice. The probability of a rapid deglaciation as a function of temperature has not been quantified. As is the case for WAIS, models of the Greenland ice sheet underestimate the dynamical response to melting and thus underestimate the current rate of ice loss (Thomas *et al.*, 2001; Krabill *et al.*, 2004; Rignot *et al.*, 2004), although the likelihood of a sustained dynamic response has been questioned (van der Ween, 2001).

As an alternative to scenario and model-based approaches, paleoclimate proxies have been examined for evidence of deglaciation and higher sea level during two earlier interglacial periods, about 125Kyr BP and 400Kyr BP, respectively (Scherer *et al.*, 1998, 2003; Cuffey and Marshal, 2000). Local paleoclimatic evidence drawn from the two ice sheets neither provides clear cut support for the proposition that one or the other ice sheet was much smaller than it is currently, nor is it inconsistent with this possibility. Likewise, the evidence that sea level was high enough to require large scale deglaciation of either Greenland or West Antarctica is also controversial (Oppenheimer and Alley, 2005). Part of the problem of interpretation arises from the lack of synchronization between temperature and sea level chronologies. While paleoclimatic proxies can contribute to identification of levels of climate change associated with large-scale physical changes such as deglaciation, they can only provide information about climate system dynamics and impacts from different rates and magnitudes of forcing at different time scales. Paleoclimatic analysis provides a useful backdrop against which to calibrate models used for future projections, but cannot generally provide an analogy for the time-evolving changes in ice induced by anthropogenic radiative and land-use forcing, since such forcing is unique to the present and did not occur when past paleoclimatic events transpired.

One assessment of such evidence (Hansen 2004, 2005) asserts that a 1^0C warming above current levels “would likely constitute ‘dangerous anthropogenic interference’” due to large-scale ice sheet loss and resulting sea level rise greater than 2 meters on a multi-century timescale, most likely from Greenland. Another assessment (Oppenheimer and Alley 2004, 2005), based on a different interpretation of palaeoclimate proxies, presents evidence for 2^0C above current levels as a “danger” limit due to disintegration of WAIS, possibly triggered by basal melting under the ice shelves. The temperatures reported above may or may not correspond to thresholds in the physical system. Instead, they correspond to temperatures above which each study inferred the possible absence of one or both ice sheets at earlier times based on interpretation of highly uncertain proxy data (Oppenheimer, 2005).

A number of studies have connected deglaciation with the onset of earthquakes in close proximity to former ice masses (Arvidsson, 1996: Muir-Wood, 2000; Sauber and Molnia, 2004; Stewart *et al*., 2000; Wu *et al*., 1999). The loss of these ice masses leads to glacial rebound or uplift which adds stress to existing faults.

This evidence taken together suggests the possibility that greenhouse-induced deglaciation of the Greenland and West Antarctic ice sheets may lead to major earthquakes some centuries to millennia from now, and that minor local earthquakes could be triggered in the near vicinity of smaller ice masses such as southern Alaska and Patagonia that are suffering considerable wastage at present.

19.3.1.3 Possible Changes in the North Atlantic Meridional Overturning Circulation (MOC)

Anthropogenic changes in the North Atlantic meridional overturning circulation (MOC—also widely known as thermohaline circulation--THC) provide a key example of a potential threshold response of the climate system in the context of Article 2 and key vulnerabilities (Alley *et al*., 2003; O'Neill and Oppenheimer 2002). Model predictions and the paleo-record (AR 4 WGI sections 10.3.4 and 10.5) suggest three main conclusions that are especially relevant for the assessment of climate change risks. First, paleo-analogs and simplified models suggest that the MOC might react abruptly and with a hysteresis response, once a certain forcing threshold is crossed (Stocker and Schmittner 1997). According to AOGCM simulations, the risk of triggering at least a temporary MOC shutdown increases considerably, above a globally averaged warming above a few ^{o}C (AR 4 WGI chapter 10. More extensive exploration with a simplified model with high hydrological sensitivity indicates a threshold that is dependent on absolute warming and its rate, e.g., 3^{0}C warming within a century (Stocker and Schmittner, 1997). Second, specific scenarios of future MOC behavior are deeply uncertain and based – to a large extent – on subjective probability functions (Mastrandrea and Schneider, 2002; Rahmstorf and Zickfeld 2005) in which confidence in specific quantitative results is low. Furthermore, in simplified models, the predictability of the system decreases as the MOC approaches a threshold for collapse (Knutti and Stocker 2002; Schaeffer *et al*., 2002).

Third, impacts of a MOC weakening would likely occur on a global scale but the knowledge about the consequences of this event is at this time rather limited, though there is an emerging literature (Tol, 1998, Keller *et al*., 2000, Rahmstorf *et al*., 2003, Link and Tol, 2004, Higgins and Schneider, 2005). Relevant examples include northern high latitude relative cooling near Greenland and NW Europe, southern hemisphere high latitude warming, and tropical drying, all over limited areas (Vellinga and Wood 2002, Wood *et al*., 2003), changes in productivity of marine ecosystems (Schmittner, 2005), and of potential terrestrial vegetation (Higgins and Vellinga 2004), shifts in oceanic CO_2 uptake and oxygen concentrations (Matear and Hirst 2003; Sarmiento and Le Quéré 1996), as well as in fisheries (Link and Tol 2004). Some of these studies consider changes associated with MOC changes alone [*Vellinga and Wood*, 2002] such as occur in AOGCM “hosing” experiments where a fixed amount of fresh water is added to the northern ocean at high latitudes (Stouffer, WGI model intercomparison) while others analyze outcomes in a forced climate where MOC changes are superimposed on greenhouse warming. In the latter case, the extent of predicted surface climate changes depends on a competition between the rate of warming and the hydrological sensitivity of the modeled MOC. The rate of Greenland melting and the connections between thermohaline circulation in the northern and southern hemispheres are also important uncertainties.

The above uncertainties, particularly insofar as they affect spatial and temporal scales of impacts, introduce nontrivial challenges for the analysis of the socio-economic impacts of MOC changes as well as the design of risk management strategies. Overall there is moderate confidence that a slowdown of the MOC will occur during the 21st century, but generally a low confidence in specific projections of either a recovery or full-scale collapse of the MOC beyond 2100.

19.3.1.4 Modes of Climate Variability (ENSO, NAO, AO and AAO)

Anthropogenic greenhouse gas emissions may cause a shift in the El Niño Southern Oscillation (ENSO) properties (e.g., mean, variance, or the shape of the distribution) (AR4 WGI section 10.x, Timmermann *et al*., 1999; Fedorov and Philander 2000). ENSO shifts would affect numerous aspects of human and climate systems such as agriculture (Legler, Bryant, and O'Brien 1999), infectious diseases (Rodo *et al*., 2002), water supply and flooding (Cole *et al*., 2002; Kuhnel and Coates 2000), 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). Predictions about possible anthropogenic shifts in ENSO properties are marked by many uncertainties (Fedorov and Philander 2000, Cane 2005), including (i) whether the ENSO changes would be abrupt and characterized by a hysteresis response, (ii) the directions of the shift, and (iii) at what forcing threshold such a response would be triggered.
Analyses of the economic damages of potential anthropogenic ENSO shifts have focused primarily on agriculture and fisheries so far. For example, the annual estimated cost of the ENSO shifts predicted by Timmermann *et al*., (1999) on global agriculture range between 100’s of millions and over $ 1 billion, depending on the specific assumptions about the affected ENSO properties and the ability to anticipate the changes (Chen *et al*., 2001). Analyses of the policy implications of potential ENSO shifts have focused predominantly on the question of adaptation and the value of information from relatively short-term (i.e., annual) predictions (Costello *et al*., 1998; Chen *et al*., 2001), as well as the balance of costs and benefits (Chagnon, 1999). This is in contrast to the analysis of the policy implications of potential MOC and WAIS changes that have addressed primarily the question how to reduce the risk of crossing a forcing threshold that might trigger a threshold response (Keller *et al*., 2005).

Enhanced greenhouse warming and stratospheric ozone depletion are now thought likely to affect two other important modes of climatic variability, namely the North Atlantic Oscillation (NAO) and the Annular Mode in both the northern and southern hemispheres (otherwise known respectively as the Arctic Oscillation, AO, and the Antarctic Oscillation, AAO) (AR 4 WGI Ch 10, 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).

These effects have been connected to both the enhanced greenhouse forcing and stratospheric ozone depletion increasing the low-to-high latitude gradient of surface radiative forcing (Houghton *et al*., 2001, chapter 6), leading to increased poleward transport of angular momentum, a strengthening of the circum-polar westerlies and their contraction polewards (i.e., a more positive Annular Mode). This would change the surface pressure patterns, storm tracks and rainfall distributions in the mid- to high-latitudes of both hemispheres, with potentially serious impacts on regional water supplies, agriculture, wind speeds and extreme events.
Mediterranean-type climates that obtain winter rains from the westerlies will in general become more arid. In the southern hemisphere this effect would be approximately uniform with longitude, but in the northern hemisphere it would be modulated by the less uniform circulation

around longitude circles due to the land-sea distribution, thus affecting the NAO, which is a standing wave pattern (a pattern that varies with longitude) in the circulation (with a pressure contrast between the Icelandic low and the Azores high).

Early evidence for these effects was discussed in Houghton *et al.*, 2001, chapter 9.3.5.2. Observational evidence that such trends are already occurring in pressure patterns and storm tracks can be found in Hartmann *et al.*, (2000), Thompson and Solomon (2002), Gillett *et al.*, (2003), Marshall (2003), Ostermeier and Wallace (2003), Geng and Sugi (2003) and Fyfe (2003). It is likely that these trends have already led to reduced rainfall in south-western and possibly south-eastern Australia (Sadler *et al*., 1988; Sadler 2002; Sadler 2003; McInnes *et al*., 2002; Wright and Jones, 2003; Pittock, 2003), where serious rural and urban water supply problems are emerging. However, the extent to which greenhouse forcing has caused these trends remains uncertain, as such trends have been simulated in models without climate change forcing (Cai *et al*., in press).

Continuation or amplification of such trends in the NAO, AO and AAO would have potentially severe implications for water resources and storminess in Australia, New Zealand, Southern Africa, Argentina and Chile, southern Europe and possibly parts of the US, where Mediterranean-type climates prevail. In the southern hemisphere it is likely that such trends will reverse once stabilisation of greenhouse gas concentrations occurs, due to the continued warming of the Southern Ocean, which would reverse the trend in the north-south temperature gradient in the southern hemisphere (Cai *et al.*, 2003).

19.3.1.5 Transformation of continental monsoons

Monsoons

Monsoons are critically important for agriculture in parts of the tropics and subtropics and are an important factor in vulnerability to flooding (Palmer and J. Räisänen 2002). Monsoon variability is therefore an ongoing concern, and any future trend of either increased or decreased monsoon intensity in one or more regions may create a key vulnerability. A zero-order assumption is that summer monsoons would be expected to intensify and winter monsoons weaken in this century due to relative warming of land versus sea surface. However, changes in humidity and regional atmospheric circulation accompanying greenhouse gas forcing are projected to lead to a more complex pattern of changes. Model simulations tend to indicate a general increase of summer precipitation over East and South Asia (IPCC FAR WGI section 10.4.2.2; Meehl and Arblaster 2003) but decreases in some locations (There is paleoclimatic evidence that the Asian summer monsoon has already intensified as the northern hemisphere warmed over the past four centuries, Anderson *et al.*, 2002). Assumptions about aerosol and black carbon concentrations have a strong influence on expected trends, and thus the confidence of projections of monsoonal changes is only low to medium.

19.3.2. Sectoral Impacts

19.3.2.1 Water Resources

Water supplies and quality are highly sensitive to climate variability and change. Relatively small changes in precipitation, evapotranspiration, snowmelt, sea-level rise, and other factors can have a substantial impact on the supply and quality of water resources.

Temperature will be an important factor in determining key vulnerabilities for water resources. Higher temperatures will speed the hydrologic cycle, increasing evapotranspiration and hence increasing the risk of developing more intense droughts and more intense precipitation events (IPCC TAR, Working Group 1). Higher temperatures will also result in more precipitation falling as rain rather than snow and in a shorter season for precipitation falling as snow. This could have important consequences for regions dependent on snowpack (Stewart *et al*., 2004).

Clearly, changes in precipitation will have a very important impact on determining key vulnerabilities. For example, Eheart and Tornil (1999) found that irrigation withdrawals in the US Midwest, assuming profit-maximizing behaviour, is more sensitive to a 25% decrease in precipitation than a 4°C increase in temperature. However, in a Mediterranean climate like California, where most of the precipitation occurs in the winter half year, summer temperatures, which, as noted above, drive evapotranspiration, are a very important factor in determining key vulnerabilities in the hydrological sector (e.g., Hayhoe, *et al*., 2004). Thus, depending on circumstances, temperature, precipitation or a combination of changes may be of paramount importance, and therefore it is difficult to assign high confidence to broad generalizations on hydrological vulnerability to climate change, but rather a regional context is needed for projections of specific vulnerabilities. While global precipitation will rise with higher temperatures, and broad patterns of change in precipitation are becoming clearer (e.g., Ruosteenoja *et al*., 2003; Tebaldi *et al*., 2004), there is still substantial uncertainty about how regional patterns of precipitation will change. Nonetheless, some statements can be made about differences in vulnerability to changes in water supplies across some regions. For example, based on Ruosteenoja, by 2010 to 2039 relative to 1961-90, the climate models used in the analysis tend to show increases in precipitation greater than the range of natural climate variability as calculated by climate models in high latitudes for the entire year and in summer monsoons over South and Southeast Asia. In contrast, many arid and semi-arid regions, such as southern Africa, Australia, and the Mediterranean, are projected by these climate models to face a decrease in precipitation greater than the range of natural climate variability. However, as noted above, the substantial uncertainties in model projections of regional precipitation changes often reduce confidence in specific projected outcomes.

However, changes in socioeconomic conditions, such as population growth, improved technology, and application of practices such as detection of leaks from water systems can substantially affect the supply and demand for water resources. Thus, the effect of different socioeconomic factors in the SRES scenarios can have a larger effect on availability of, demand for, and quality of water resources than the change in climate itself. For example, Arnell (2004) found that differences in population projections across SRES scenarios has a greater impact on the increase in the number of people facing water stress than does difference in emissions scenarios. By 2050, the increase in global mean temperature by the A2 and B2 scenarios is almost indistinguishable. Yet, under A2, 1.1 to 2.8 billion people face increased water stress, while under B2 the increase in population at risk is estimated to be 700 million to 1.5 billion, since the B2 scenario projects a lower population size.

Among other key vulnerabilities in water resources are:

- Reduction in the security of supply for public water systems, where either the volumes are reduced or the timing of streamflow and groundwater recharge change. This is a particularly important vulnerability where pressures on resources are already high such as in megacities in developing countries. As urbanization increases over the 21st century the vulnerability of these areas to climate change may increase as well

- Reduction in the availability of safe rural water supply in dry regions, where streamflow or recharge is reduced
- Increases in the frequency and magnitude of flood losses, due to increases in the volume or changes in the timing of river flows or flash floods. Poor countries and poor populations within countries are particularly vulnerable and have limited ability to recover
- Irrigation could be vulnerable through increases in demand and reductions in availability of suitable water at desired times, as a result of higher temperatures and changes in the volume or timing of precipitation, streamflow and recharge
- Reduction in hydropower generation if the volume of flows reduces and timing of flow changes. This could be a critical vulnerability for the many nations or regions that draw a significant portion of their electricity production from hydropower
- Sea-level rise will adversely affect water supplies in many coastal regions due to salinisation of groundwater in estuaries, low-lying islands and coastal plains
- Decreased snowpack and melting of glaciers will adversely affect seasonal water storage in many mountainous regions, threatening water supplies in dependent communities and requiring management of water storages more for winter and spring flood control than for summer irrigation.

Hitz and Smith’s (2004) review of global impact studies could not find clear relationship between changes in water supply and increases in GMT. Results from global studies in this sector are highly inconsistent with some studies quite sensitive to the climate model and mode of aggregation (e.g., Arnell 1999 and Arnell 2004) and others showing little net global impact (Vorosmarty *et al*., 2000; Doll and Siebert, 2002). Hitz and Smith concluded that higher magnitudes of climate change are likely to increase stress for water resources. This is due in part to the fact that current water resource infrastructure is generally designed for today’s climate.

19.3.2.2 Ecosystems and Biodiversity

Ecosystems are highly vulnerable to climate change. That vulnerability is partly a function of the expected rapid rate of climate change relative to the resilience of many such systems. It is also a function of human development, which has already substantially reduced 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 of pollution.

A warming of 1-2°C above current levels would likely result in accelerated amphibian species extinction, loss of diversity in freshwater systems, and wide-spread disappearance of mountain glacier melt systems with associated species loss of aquatic and dependent amphibious and terrestrial species.

Extinctions are already being observed, but a significant threshold could be associated with mountain glacier disappearance. These impacts will be especially significant in those systems dependent on glacier ice melt. Freshwater systems vulnerable to pollution could face increasing concentrations of pollutant and stagnation in many regions (CH 5 ZOD). Of particular concern are the following:

- *Biodiversity hotspots*. These are areas that have particularly high concentrations of biodiversity (e.g., Myers *et al*., 2000). No comprehensive analysis exists on the relationship between changes in temperature and loss of species in biodiversity hotspots. However, reviews of many studies on the sensitivity of particular ecosystems to climate change indicate that many biodiversity hotspots would experience significant biodiversity losses for a global temperature increase of 1-2°C (Hare, 2003, Lovejoy and Hannah, 2005).

- *Coral Reefs*. A 1 to 2^{o}C increase in sea surface temperature is expected to result in widespread bleaching and loss of coral reefs (medium confidence). Frequent bleaching will kill corals and jeopardize the integrity of coral ecosystems. Pollution, over-fishing, and other human activities also contribute to vulnerability of coral reefs.
- *Polar ecosystems*. A 1^{o}C warming is projected to lead to reductions in ice cover and snow thickness (ACIA, 2004; High confidence). This reduced ice cover influences polar ecosystems and threatens the livelihood of many species, such as penguins and polar bears. Impacts are already becoming evident.
- *Migratory species*. Impacts are already evident (Parmesan and Yohe, 2003; Root *et al.*, 2003 and 2005). Climate change is expected to result in a mismatch between the life-cycle of migratory species in their different regions (Visser and Holleman, 2001). This will alter competitive interactions among migratory and non-migratory species, possibly leading to increased extinction rates.
- *Freshwater systems and amphibious fauna*. A warming of 1-2°C above current levels is projected to result in accelerated amphibian species extinction, loss of diversity in freshwater systems, and complete disappearance of glacier melt systems with associated species loss of aquatic and dependent amphibious and terrestrial species. An intensified level of impacts would follow glacier disappearance, as noted above.
- *Arid and semi-arid fringe and mountain-top ecosystems*. Information in the literature (e,g., Pounds *et al.*, 2005) suggests that at less than 2^{o}C of warming, there would be reduction in the geographic range of less mobile species and increased rates of extinction in both ecosystems. Many thousand species could be at risk in mountainous areas around the world, many in the southern Hemisphere (Sekercioglu, submitted).
- *Tundra ecosystems*. A warming of 1 to 2^{o}C will result in many tundra ecosystems being replaced by forested or other ecosystems. Such a change is already becoming evident in some polar areas(ACIA, 2004).
- *Pathogen-host ecosystems*. A warming of 1 to 2^{o}C is projected to result in rapid range extensions of mobile pathogens, allowing invasion of new geographic ranges before natural hosts can develop resistance. This could result in a rapid mass mortality in key systems such as forests, and resulting switches in ecosystem structure, function, and potential loss of goods and services.
- *Tree-grass ecosystems*. A warming of 1 to 2^{o}C could result in a switch from grasslands to trees and shrubs in many areas. This would have substantial impacts on flora, fauna, and biodiversity. The effects are most likely in the Southern Hemisphere. However, increased fires could offset this impact.
- *Fire-prone ecosystems*. A warming of 1 to 2^{o}C could result in switches in ecosystem structure towards systems of shorter stature, soil exposure and erosion, community composition change and possible extinctions. Accelerated tree and shrub growth caused by higher CO_2 concentrations could offset this impact, though may increase fuel loading available in wildfires.

A 3˚C increase in global mean temperature is estimated to lead to a significant change in eco-climatic class in almost 50% of terrestrial biosphere in general (Halpin, 1997) and in nature reserves (Leemans and Eickhout, 2004), which would reduce their capacity to meet their original conservation objectives. Thomas *et al.*, (2004) assess extinction risks for sample regions that cover 20% of the Earth's terrestrial surface and conclude that 15-37% of species in those regions would be committed to extinction under a mid range climate change scenario by 2050 (1.8-2.0˚C warming over late 20th Century temperatures). Based on a review of regional studies, Hare (2003) finds a continuum of impacts on ecosystems and quite varied sensitivities. Many ecosystems appear sensitive, even to less than 1°C further global mean warming and are estimated to be quite vulnerable to climate changes above 2°C.

Several studies have used global vegetation models as part of integrated assessment models to assess shifts in ecosystems caused by climate change and elevated CO_2 concentrations (e.g. Fuessel and van Minnen, 2001; Fuessel *et al*., 2003; Fuessel, 2003; Leemans and Eickhout, 2004). On the global level, a warming of 1ºC, 2ºC, and 3ºC is simulated to cause major and permanent ecosystem shifts in about 15%, 30%, and 40%, respectively, of the land surface with little variation across climate scenarios (Low to Medium Confidence), but with large differences across regions (Leemans and Eickhout, 2004).

19.3.2.3 Food Production

Ensuring that "food production is not threatened" is one of the objectives mentioned in Article 2. However, the Article does not state the scale at which this applies. In this section, we examine literature on global and regional production of food.

Global Agricultural Production

The TAR concluded that a "a few degrees C" increase in GMT would result in a net decline in global agricultural production and an increase in global food prices. Such an increase in food prices would mean that many people, particularly in poor regions would have increased difficulty either growing food for themselves or purchasing sufficient food supplies.

Hitz and Smith (2004) surveyed several studies of the potential impacts of climate change on global agriculture. They examined Rosenzweig *et al*., (1994), Darwin *et al*., (1995), and Parry *et al*., (1999). While the studies differ considerably in their methods, and results vary by type of crop, Hitz and Smith (2004) concluded that the relationship between global food production and GMT is parabolic: production could rise with a small rise in temperature and decrease at higher levels. A key reason for this is the carbon fertilization effects assumed in the studies--which by itself was assumed to increase crop yields and decrease water demand by crops (but note some cautionary recent results mentioned below when multiple factors are considered in CO_2 fertilization experiments). At higher CO_2 concentrations this effect begins to saturate allowing the stresses of higher temperatures to reduce crop yields. Assumptions about adaptation, such as changing farm level management, crop switching, and shifting crop production polewards, are key factors in the estimation of climate impacts on agriculture. Parry *et al.,* (1999) and Parry *et al*., (2004) indicate that the threshold for net reduction in agricultural production could be lower than 2.5°C (see Box 19.3).

Box 19.3: Implications of SRES scenarios for food production and equity (Source: Pittock, 2005)

The impacts of climate change on food production, prices and numbers at risk of hunger depend on a number of factors. These include regional climate change, biological effects of increasing atmospheric CO_2, changes in floods, droughts and other extreme events, existing agricultural systems, adaptive capacity, changes in population, economic growth and technological innovation. In a large international study, Parry *et al.,* made rough estimates using the SRES family of scenarios of greenhouse gas emissions and socio-economic change.

The study used a linked system of climate scenarios, agricultural models, and national, regional and global economic models. Adaptation was at the farm level, such as changes in planting dates, fertiliser applications and irrigation, and at the regional level via new cultivars and irrigation systems. Economic adjustments included changes in national and regional investment in agriculture, crop switching, and price responses.

Results for all SRES scenarios driving the HADCM3 climate model showed small percentage gains (3 to 8%) in average crop yields in developed countries by 2080, but decreases in developing countries of -1 to -7%. This increased the inequity, measured by changes in yield, by between 7 and 10%. The authors state that "While global production appears stable, regional differences in crop production are likely to grow stronger through time, leading to significant polarisation of effects, with substantial increases in prices and risk of hunger amongst the poorer nations, especially under scenarios of greater inequality (A1F1 and A2)." Cereal price increases by 2080 under most scenarios were between 8 and 20%.

Clearly, as the developed countries taken together have a far smaller population than the developing countries taken together, the majority of people will be worse off.

Results are highly dependent on full realisation in the field of benefits from increased CO_2 concentrations as measured in experiments, which is uncertain, and on effects of pests and diseases, which have not been estimated. It should be noted that these results are for climate change scenarios simulated with only one climate model, that from the Hadley Centre in the UK. Other climate models would give different results. These results are broadly consistent with the conclusions of the IPCC TAR. Given the uncertainties mentioned, medium confidence is suggested.

There are important caveats to conclusions about particular thresholds for agriculture, some of which have already been mentioned above. The studies cited above only examine changes in average climate. They do not consider increased variability or changes in location of pests and diseases. Recent work on carbon fertilization of crops conducted through the Free Air Carbon Exchange (FACE) program indicates that the degree to which CO_2 increases crop yields in the field depends on many circumstances. For example, Amthor (2001) found that higher temperatures or tropospheric ozone levels, as well as insufficient water, could offset the positive effects of CO_2.

Regional Agricultural Production

The effect of climate change on regional crop production will differ considerably. The published literature consistently finds that low-latitude areas tend to have relative decreases in production while high latitude areas tend to have relative increases, assuming that farmers adapt to changing climate conditions. This is because climate change shifts the relative productivity of crops in various regions. The high-latitude versus low latitude differences in crop productivity with climate change also is found because wealthier societies, which tend to be in mid- and higher-latitudes, will have greater capacity to adapt agriculture to climate change than will poorer countries, who tend to be in lower latitudes. At particular risk are dryland regions such as sub-Saharan Africa and South Asia. Such shifts in productivity increase risks of malnutrition; risks that would be exacerbated by a global decline in agricultural productivity and concomitant rise in prices (Parry *et al*., 2004, Box 19.3).

Livestock

The combination of climate change and increased demand for food could put further pressure on grassland ecosystems which support livestock. The carbon fertilization effect alone is estimated to improve grassland productivity. However, grassland species will be affected differently, potentially reducing diversity of grasslands. A combination of factors, such as drier conditions and reduced water supplies can reduce grassland productivity. In contrast, the direct effects of climate change on livestock may tend to be negative. Higher temperatures reduce milk production and grazing time. In addition, diseases affecting livestock could spread. High latitude livestock may need less investment in keeping livestock warm in the winter. Livestock productivity, particularly in low-latitude countries, could decrease as a result of higher temperatures, spread of disease, and reduction in pasture quality.(Chapter 5 ZOD, pp. 27-33)

Fisheries

Freshwater and marine fisheries are very sensitive to changes in climate and will need to migrate to higher latitudes or altitudes to survive. Where migration is not possible because of physical constraints such as closed water bodies or human constraints such as dams, fisheries will be imperiled. Loss of coral reefs and wetlands can also adversely affect fisheries. The level of climate change that will lead to a substantial loss of fisheries is uncertain, though it is very likely vulnerability will vary considerably across different locations and systems (Chapter 5 ZOD, pp 47-49).

19.3.2.4 Forestry

Studies such as Cramer *et al*., (2001) find that net primary productivity of forests can increase up to approximately 1 to 2°C warming above late 20th century climate and then decrease. This implies that the productivity of managed forests could increase until the middle of the 21st century, perhaps into the 22nd century before decreasing. These studies assume a positive effect from carbon fertilization. While CO_2 is projected to enhance plant growth and reduce demand for water, the degree to which it does in the wild is uncertain. Furthermore, studies such as Schlesinger and Lichter (2001) find that the carbon fertilization effect diminishes after a few years. The studies examine forests as a class of vegetation and do not examine the impacts of climate change on individual species. In addition, the work is based on studies, which for the most part do not consider threats to vegetation such as fire, pests, and disease. There is uncertainty about the degree to which carbon fertilization will benefit vegetation in nutrient limited or otherwise stressed environments (e.g., tropospheric ozone can offset positive effects of CO_2). Furthermore, regional dislocations in forests (e.g., in Amazonia, Siberia) are possible. Catastrophic loss of forests in many areas from spread of pests and disease or from fire is also possible, though the uncertainties mentioned suggest that specific projections typically carry no more than medium confidence.

19.3.2.5 Coastal Systems

Coastal systems will be affected by sea level rise, increases in temperature, increases in tropical cyclone intensity, changes in ocean circulation, and changes in freshwater runoff patterns including nutrient loadings and turbidity. The potential vulnerabilities of coral reefs and marine productivity are discussed in the ecosystem section above. Vulnerabilities of coastal settlements and other ecosystems are discussed here.

Large populations of people located either in coastal megacities or in deltas are at risk from sea level rise. Sea level rise will result in either increased expenditures for coastal defences, with residual increases in flood risks, or abandonment of coastal developments and relocation of populations. Risks are particularly high in areas that are subsiding, such as in the Ganges-Brahmaputra delta or the city of Venice, Italy--though the adaptive capacity of the latter for at least modest sea level rises is likely to be much higher than for the former region. A large sea level rise, which may be caused by large-scale deglaciation (see 19.3.1), may result in widespread relocation of coastal populations. Impacts will increase non-linearly with increasing sea-level rise due to overwhelming of existing coastal defences and design/planning setbacks from coast. Backing up in existing drains will increase and saline intrusion will affect building foundations.

Small islands and atoll islands are at particular risk from sea level rise. They face the possibility of loss of freshwater resources, erosion and inundation. The thresholds depend on such factors as the elevation of atolls. In many cases relocation of human populations will be the only feasible adaptation option.

Mangroves, coastal wetlands, freshwater coastal wetlands, and coastal forests are all vulnerable to sea level rise, which causes erosion, submergence, and salt-water intrusion. The loss of mangroves and coastal wetlands is roughly proportional to sea level rise. The loss of freshwater coastal wetlands and coastal forests depends on rate of sea level rise, slope, and geology. Sedimentation and inland migration can offset some losses of mangroves and wetlands where there are no inland barriers. (Coastal ZOD; high confidence)
Estuaries and lagoons are also vulnerable to sea level rise, which results in change in salinity and biota, enlargement of estuaries and lagoons, and inland migration. Impacts on estuaries and lagoons are highly location-specific and have a larger uncertainty associated with them than other impacts of sea level rise.

Coastal systems are also vulnerable to increases in the intensity of tropical cyclones. Knutson and Tuleya (2004) estimate that by 2080, wind speeds in tropical cyclones will increase by 6% and precipitation by 18% within 100 km of the storm center. Emanuel (2005) found that tropical cyclone intensity and storm lifetime has increased significantly in the last 30 years.

19.3.2.6 Health

Climate-sensitive diseases make up a substantial fraction of the total worldwide burden of disease. A standardized approach to estimating the global burden of disease indicates that climate change is already contributing to mortality and morbidity (Campbell-Lendrum, Pruss-Ustun *et al.*, 2003). Temperature and precipitation are key determinants of the distribution of many disease-carrying vectors. For example, malaria is being reported at higher altitudes in several continents (Hay, Guerra *et al.*, 2005; Hay, Shanks *et al.*, 2005). However, whether an increase in potential for disease transmission leads to more frequent occurrence of disease in human populations depends on a range of non-climatic factors. Research reinforces the conclusion that projected changes in climate will increase the pressures on many disease control activities. This will apply particularly in parts of the world that are presently on the margins of transmission for malaria and dengue. Climatic factors have played a part in the emergence of some new infectious diseases, but it is not clear what this means for risks under a future, altered climate (Chua, Bellini *et al.*, 2000; Githeko, Lindsay *et al.*, 2000; Confalonieri 2003).

The increasing number of older adults in developed countries is likely to increase the size of the population at risk from heat (Lutz, Sanderson *et al.*, 2001). The 2003 European heat wave that killed 27-40,000 people is notable because it showed that even developed countries may not be well-prepared to cope with extreme heat (Kovats, Wolf *et al*., 2004). Further, given that anthropogenic climate change likely contributed to a heat wave as severe as this event, suggests that the excess deaths that occurred may be among the first that can be attributed directly to climate change (Stott, Stone *et al*., 2004). Future estimates are difficult as predictive models have not generally been tested for changes in the frequency or intensity of heatwaves, or the capacity of various regions to fashion anticipatory adaptation strategies. There is a lack of information on the effects of high ambient temperature on mortality outside of developed countries.

Due to the very large number of people that may be affected, malnutrition linked to drought and flooding may be one of the most important consequences of climate change, but there are few studies that have systematically linked climate, environment, and nutritional outcomes at the national or local level. Although predictive models suggest global crop yields could increase in some locations with climate change, especially in temperate regions, they also suggest net decreases in yields in hotter and poorer locations (see 19.3.2.2 and Box 19.3). Regardless, expert assessments of the prospects for food security are often pessimistic. New studies from a wider range of countries provide evidence that increases in daily temperature will increase the number of cases of some common forms of food poisoning in temperate regions. Extreme rainfall events test the integrity of water management systems and increase risk of outbreaks of water-borne disease.

The impacts of flooding are particularly severe in areas of environmental degradation, and in communities lacking basic public infrastructure. Climate change is likely to bring deteriorations in outdoor air quality. For instance, concentrations of ground level ozone are projected to increase with rising temperatures, all other considerations unchanged. The changing seasonal pattern of aero-allergens is now well documented, although the implications for population health require further evaluation. Projected climate changes will probably have some health benefits, including reduced cold-related mortality and restricted distribution of diseases where temperatures or rainfall exceed upper thresholds for vectors or parasites. The balance of positive and negative health effects will vary from one location to another, and will alter also over time if temperatures continue to rise or if effective adaptive measures are implemented.

Populations in geographic regions that are particularly vulnerable to the health impacts of climate change include those living in water-stressed regions, in coastal and low-lying areas, in Arctic regions, and slum dwellers and homeless people in large urban areas. Given present health trends, it is unlikely that all health-related Millennium Development targets (see 19.1.4**)** will be met in all countries, and, if so, then health impacts of climate change in some countries might persist and become stronger. Further, population growth will have a major influence on the magnitude of climate change impacts and where these occur. Over the next 50 years approximately 3 billion people will be added to the global population, principally in parts of the world that experience heavy burdens of climate-related disease and injury. In general, economic development is associated with improved capacity to adapt to climate changes. But economic growth does not lead necessarily to reduced vulnerability to the health damaging effects of climate change. Critically important is the manner in which growth occurs, the distribution of the benefits of growth, and trends in other factors such as education that have a strong, independent effect on health status. There are important prerequisites for adaptation that are currently not met in many parts of the world. For instance, access to primary health care and basic education are essential elements of strategies to cope with climate change, but are not available to millions of people. Public awareness, good use of local resources, effective governance arrangements and community participation are all required to mobilize and prepare for climate change. These present particular challenges in resource-poor communities.

19.3.3 Regional Impacts

Many of the sectoral impacts discussed above will be realized within the regions assessed as part of the IPCC 4AR. The chapters discuss the potential regional impacts in detail. Rather than trying to summarize all the key vulnerabilities identified in the regional chapters, this section focuses on a limited set of key vulnerabilities that seem particularly unique to each region, or which could occur with a relatively low level of climate change.

19.3.3.1 Africa

Africa's key vulnerabilities to climate change must be seen in the context of a current climate that is highly variable and difficult to predict. Wider developmental challenges confronting Africa, such as poverty, HIV/AIDs and effective governance are more immediate sources of vulnerability for Africa. Climate change will most likely add to and amplify these existing sources of vulnerability unless there is substantial socio-economic development in the continent leading to a major improvement in adaptive capacity.

The key vulnerabilities for Africa relate to water resources, food security, natural resource productivity, coastal zones, desertification and health impacts through vector and water borne diseases. The impacts of climate change are expected to be particularly severe for African countries, in part because rain-fed agriculture forms a large part of the economies of most African countries in general and for the poorer sections of society within them in particular (Vogel, 2005).

In relation to food security, drier conditions from warming and socio-economic constraints combine to reduce the yield of grain crops (Amthor, 2001). For example, using the Southern African core climate change scenario, simulated yields declined by 36% in the case of maize and 31% for sorghum in the sand veld region by 2050 (TAR, 2001, page 16 ZOD). Based on projections, the combined effect of flooding and reduced rainfall (sometimes in the same year) and shorter growing seasons may well force large regions in Africa out of marginal production (Nyong, 2005; ZOD, p27). Food production in sub-Saharan Africa has been on the decline and has not kept pace with population increases, resulting in a doubling of the number of undernourished people from 1970 -1999 (Nyong, 2005). Given this situation, the challenges to food security posed by climate change can be considered a key vulnerability for the Sub Saharan Africa region (medium confidence). African countries average 21 per cent of GDP from agriculture, with a range from 10-70% (Vogel, 2005, p30). Studies for Egypt report that climate change is expected to substantially decrease national production of many crops (ranging from -11% for rice and -29% for soybeans) by the year 2050 compared to their production under current Egyptian conditions (Eid and El-Marsafawy, 2002). A 2^{o}C warming would substantially reduce areas in Uganda suitable for growing coffee (Africa ZOD, p. 34).

Africa suffers from a number of diseases that are sensitive to temperature and precipitation with disease transmission being worsened by increases in flooding, warming and drought - all of which are predicted to increase with Africa's changing climate (Nyong, 2005, page 12). Africa currently accounts for about 85% of all deaths and diseases associated with malaria worldwide, which is a main cause of morbidity and mortality (1 million deaths and 300-350 million of clinic cases per year) in Africa, in particular among children below 5 years (Nyong, 2005, page 12 citing Lieshout *et al.*, 2004). In South Africa it is estimated that the area suitable for malaria will double and that 7.8 million people will be at risk with 5.2 million of these having never experienced this risk (Nyong, 2005).

Finally in relation to ecosystems, recent assessments of climate change and various flora and fauna species show that substantial extinctions may occur in parts of Africa and elsewhere (Thomas et. al, 2004; Lovejoy and Hannah, 2005) which would have significant impacts on rural livelihoods and tourism (IPCC 2001b). For example, hartebeest, wildebeest and zebra in the Kruger National Park (South Africa), the Okavango Delta (Botswana), and Hwange National Park (Zimbabwe) could be severely threatened by the anticipated 5% drop in rainfall that would affect grazing distribution (WWF 2000). A warming up to 1^{o}C above 1990 puts the South African Succulent Karoo at risk and a warming of 2-3^{o}C risks eliminating the ecosystem and its 2800 endemic species (Food, Fiber Forest, p. 46).

Discussion of specific thresholds at which significant impacts occur is complicated because in Africa and elsewhere it is the complex interplay between existing vulnerabilities and changes in climate on the one hand with complex socio-economic and political issues, on the other hand, operating at a variety of scales, that together combine to produce key vulnerabilities (Vogel, 2005). Although attention has tended to focus on either “extreme” climate events such as heat waves or floods or on “variability” around the norm, the combination of slow climatic changes and an increasing frequency of sudden shocks may as well trigger much larger and frequent harvest collapses than countries can cope with (Vogel, 2005, Devereaux and Edwards, 2004).

19.3.3.2 Asia

Asia’s climate is marked by high climatic variability and frequent natural climate extremes. While Asian societies have built up considerable experience of coping with extreme events, the sheer scale of potential climate change impacts in Asia, particularly on densely populated countries such as Bangladesh, India and Indonesia, pose significant regional risks to the lives and livelihoods of large numbers of people. Climate change, in particular increased temperatures and reduced precipitation, would entail significant consequences for health and Asia’s coastal zones, ecosystems and agriculture systems. Evidence since the TAR points to increases in the intensity, frequency and sometime the geographic scope of extreme events (Ch 10 ZOD, page 14-). For example, droughts, heat waves and floods in India have increased significantly over the past decade (Lal, 2002) as has the geographic area within which they occur.

As the frequency of extremely hot days and multiple day heat wave conditions for India appear to be increasing, the number of fatalities could rise from thousands to tens of thousands per event (Ch 10 ZOD, page 37). Fatalities during the intense heat wave of May 2002 and 2003 in India indicated that poor laborers and rickshaw drivers formed the highest proportion of death (DFID, 2004) supporting the well-established hypothesis that specific vulnerable groups within countries bear the brunt of climatic impacts. The link between higher mortality and higher temperatures is also borne out in other Asian regions with confirmatory studies in Israel and Lebanon (Katz *et al.*, 2000, El-Zein AMe.al, 2004).

The devastation caused by cyclones could also increase in Asia as a result of climate change (Emanuel, 2005). An increase in cyclone intensity of 10-20% given a rise in sea surface temperature of 2-4 degrees C relative to the threshold temperature of 28 degrees C is deemed very likely in the Indian Seas (Ch 10 ZOD, page 29). The Orissa cyclone of October 1999 led to extensive loss of lives (10 000 fatalities), loss of property and livelihoods (3.7 million cattle, 1.6 million hectares of paddy fields and 33000 hectare of other crops and large scale social disruption with over a million people made homeless (Ch 10 ZOD, p.39).

In Central Asia, half of which is arid or desert, many desert species already are near their limits of temperature tolerance, and some may not be able to persist under hotter conditions (Ch 10 ZOD, p15). Vulnerability assessments of semi-desert rangelands in the Aral Sea region indicate that this region is very sensitive to changes in temperature and precipitation: a temperature increase of 0.5°C and reduced precipitation could reduce grassland productivity by 6–32%, and by 40–90% if temperature increase by 2–3°C (Smith *et al*., 1996).

The rate of recession of glaciers in Asia has increased dramatically. Himalayan deglaciation has resulted in flooding of settlements in Nepal, Bhutan, and northern India. It also has significant implications for water security and for agriculture in South Asia as most of the rivers in northern India originate from glaciers and 70 to 80 per cent of their water comes from snow and glacial melts (the remainder is from monsoon rains discussed below).

Finally, recent research concludes that a 2^{o}C increase in mean air temperature over late 20th century temperatures could decrease rice yields in India and China by 5-12% (Lin *et al.*, 2004). Overall, the net cereal production in South Asia is projected to decline at least between 4-10% by the end of this century (Ch 10 ZOD, p30). Asia is predominantly rural (61% of total current population of 3.6 billion), and the majority of the Indian population is dependent on agriculture. These conditions warrant regarding temperature increase and Himalayan deglaciation as key regional vulnerabilities. Such changes would pose significant challenges for food security and for regional conflict over water resources. The risk of regional or even global conflicts resulting from internal and external migration from large, densely populated coastal areas affected by the sea level rise, cyclones and salt water intrusion or regions in proximity to wealthier, climatically more favourable regions is emerging in climate literature (Tanzler, Carius and Oberthur, 2002, Rogers, 2004). This literature draws upon, but expands, research in the early 1990s linking environmental stresses to environmental refugees and natural resource related conflicts (Myers, 1995, Kennedy *et al.,* 1998).

19.3.3.3 Australia and New Zealand

Australia is vulnerable to climate change because it already has extensive arid and semi-arid areas, high rainfall variability from year to year, and increasing pressures on water supplies in many areas. Vulnerability also arises from high fire risk, Australian ecosystems are sensitive to changes in mean climate and to invasion by exotic species introduced by humans. Australia also has a high concentration of population in coastal zones, an economy highly dependent on world commodity prices, tourism dependent on the health of the Great Barrier Reef and other fragile ecosystems, and economically and socially disadvantaged groups of people. Impacts of climate change will be complex and are to some extent uncertain, but Australia has a high capacity to adapt, although possibly at considerable cost (Pittock, 2003).

New Zealand is located further south and has a more moderate climate with considerable rainfall in most areas. It is generally less vulnerable to expected climate changes, although some sectors will still be affected, with a need to adapt. It also has a special relationship with some Pacific Islands, which may be severely affected.

Among the key vulnerabilities in Australia and New Zealand is biodiversity. In particular, there is concern about risks to unique and valuable ecosystems such as the Great Barrier Reef, rainforests, Kakadu wetlands, the south-west of western Australia, and glaciers. High temperatures, drought, fire, and invasive species could act on their own or in combination to threaten many of these ecosystems. A 2^{o}C warming of sea surface temperatures could be critical for such systems as coral reefs (e.g., Hare 2003), while such a warming of air temperatures could reduce the extent of tropical forests in Australia by half (see Food Fiber Forests, p. 46).

Settlements will also be vulnerable to increases in extreme events, particularly extreme heat and high intensity precipitation. There could be increased failure of hydrodams in New Zealand, including glacier-lake outburst floods. There will likely be increasing threat to floodplain settlements lying behind protection systems and urban drainages that would be inadequate in future climates.

In general, Australia and New Zealand are highly developed with a high level of adaptive capacity. Yet, recent events such as fires and floods have demonstrated that there is vulnerability to extreme climate events. In additions, indigenous peoples in both countries may face acute risks from climate change.

19.3.3.4 Europe

There are differences in vulnerability to climate change across Europe because of variability in expected climate change as well as differences in wealth. Many climate models conclude that the climate in southern Europe will become drier, while the climate in northern Europe will become wetter. This pattern would result in significant regional differences in vulnerability. Southern Europe could face a substantial increase in drought, while northern Europe may face increased floods, particularly in the winter. For example, Arnell *et al*., (2004) estimate that runoff in south eastern Europe could be reduced by 40 to 50% by the 2070s. Even in southern Europe, the intensity of precipitation events could increase. Storms are projected to increase in intensity and move further eastward, posing more risk of damage to northern Europe.

Agriculture is likely to fare differently because of the differences in current climate as well as projected changes in temperature and precipitation. Increased yields from a warmer and wetter climate are predicted for Northern Europe, while decreased yields from a hotter and drier climate are predicted for southern Europe. Energy demand is likely to increase in the south because of increased air conditioning and decrease in the north because of reduced heating.

Tourism could shift northward as climate in northern areas becomes more attractive. However, skiing in traditional resort areas such as the Alps is likely to be reduced, and air pollution levels could increase. Assuming no reduction in ozone precursor emissions, most populated areas in Europe are estimated to be exposed to ozone levels above 60 ppb under the A2 scenario by 2080 (about a 1.5 to 3.5^{o}C increase in GMT above 2000; Health ZOD, p. 22).

Europe’s experience with climate variability demonstrates that even well developed countries face significant risks from extreme events. Indeed, Europe is likely to already have experienced the effects of an extreme event related to change in climate. The 2003 heat wave killed an estimated 35,000 people, mostly in France. While individual weather events cannot be attributed to a single cause, Stott *et al*., (2004) find that the likelihood of this extreme event has more than doubled as a result of anthropogenic forcings, compared to the unmodified climate.

In addition, sea level rise will have wide implications in estuarine regions and subsiding coasts, and intensified heat during drought conditions can exacerbate wild fire frequency and intensity. Melting of permafrost in Arctic Europe is beginning, and can have significant impacts on both human settlements and natural systems. Similarly, shorter snow seasons and earlier snowmelt in alpine regions has implications for mountain ecosystems and dwellers, as well as downstream systems.

Finally, if the MOC were to be significantly diminished, north western Europe could be significantly impacted (e.g., Higgins and Schneider, 2005).

19.3.3.5 Latin America

The vulnerabilities to climate change in Latin America are complex. There are differences based on geography, distribution of wealth, and extent of biodiversity. The population in much of Central America and the Andes are poor and quite vulnerable to climate change, while some other countries have achieved a higher level of material welfare. Yet, even the latter face vulnerabilities because of wide disparities of wealth and concentrations of populations in mega-cities. The region contains some of the world’s greatest biodiversity.

Biodiversity and forestry are among the key vulnerabilities for Latin America. This is of particular concern because of the relatively high concentrations of species endemism in many Latin American countries. A combination of higher temperatures and reduced precipitation would lead to more fires and loss of many species. Lovejoy and Hannah, 2005; Thomas *et al*., (2004) and Siqueira e Peterson (2003) have expressed concerns for biodiversity consequences in Latin America, and one of these studies estimates that a quarter of the 138 tree species in central Brazil’s savannas would potentially become extinct with a 2^{o}C warming. Based on Hadley Centre climate change projections, Miles *et al*., (2004) conclude that half of the 69 tree species studied in Amazonia could become extinct by the end of the century. (Latin America ZOD, p.31; Paz 2004; and Jones and Thornton, 2003). However, different simulations with both climatic and ecosystem models often produce very different severities of impacts in Latin American forest regions, suggesting that a risk-management framework (e.g., see Chapter 1, IPCC TAR, WG 2) may be appropriate to examine key ecosystem vulnerabilities to climate change. (Latin America ZOD, pp. 32-34).

Water supply is also a key vulnerability in Latin America. The combination of population growth and drier conditions in some areas could dramatically increase water stress. In addition, melting of Andean glaciers could be a particular problem in Peru. (Latin America ZOD, p. 36)

Currently, 75% of the population in Latin America resides in urban areas and the percentage is projected to increase. Growth in urban areas could increase the vulnerability of the region to sea level rise, increased intensity of coastal storms, floods, and heat waves, as well as increases in air pollution, infectious diseases, and water borne disease. Rates of poverty are very high, particularly in mega-cities such as Sao Paolo and Mexico City.

Agriculture may fare quite differently across Latin America. The magnitude of the impacts for commercial annual crops was highly dependent on the GCM used. For example, yields of many crops in Argentina, Uruguay and Brazil are estimated to decrease under climate change, while others are estimated to increase (de Siqueira *et al*., 2000, Magrin and Travasso 2002) (Latin America ZOD, pp. 32-34). Mexican agriculture may be vulnerable to drier conditions. Furthermore, maize yields were estimated to decrease in many low latitude locations in Latin

America (Jones and Thornton, 2003 as cited in LA ZOD). Because it is a C4 plant and very sensitive to drier conditions, maize is particularly sensitive to climate change (Rosenzweig and Iglesias, 1994).

19.3.3.6 North America

North America is defined here as comprised of Canada and the United States but excluding polar regions, which are considered separately in 19.3.3.7. North America is often assessed to have a relatively high level of adaptive capacity (e.g., IPCC TAR, WG 2). Nonetheless, many systems and regions are vulnerable to climate change. Among the vulnerabilities of this region are ecosystems. While productivity of terrestrial ecosystems may increase in regions where rainfall increases, so too would fire and other disturbances.

A relatively high percentage of the population of the region lives in low lying coastal areas. Increased development and property values have substantially increased exposure to sea level rise and coastal storms (Pielke and Landsea, 1999). Model simulations of hurricane intensity late in this century indicate increases in maximum wind speed and precipitation of 12-26% within a 100 km radius of the centre (Knutson and Tuleya, 2004). Theoretical and, very recently, empirical, work supports this general conclusion as well (Emanuel, 2005). The destruction from current hurricanes increases highly nonlinearly with Saffir-Simpson classification scale or maximum wind speed (Gray, 2003), suggesting the potential for significant increases in damages in the future.

Water resources in some regions in North America may be particularly vulnerable to climate change. The snowpack in western areas, a key source of water supply in western North America, is generally expected to decline. This can increase stress in regions where water supplies are already tight, although adaptations can substantially ameliorate stresses (Lund *et al*., 2003). However, there are large and rapidly growing urban populations in the southwest of the USA, and decreased total water supply would exacerbate increasing urban-rural clashes over water use there. Also, the water system has large reservoirs designed and operated largely for irrigation supply. Decreasing snowpack storage means greater winter-spring runoff, increasing need for management for flood control and thus reducing capacity for irrigation and secure urban water supply. However, since 85-90% of water in the US south west goes to subsidized agriculture, adaptations could certainly be explored in connection with such subsidies. Different adaptive systems are clearly conceivable, but at what price and or change in lifestyles? Such issues are raised by the possibility of climatic changes as typically projected in the region (e.g., Hayhoe, 2004).

Higher temperatures can result in increased levels of air pollution, particularly if emissions of air pollution are not reduced in future years. For example under the A2 scenario by 2050 (a 1 to 2^{o}C increase in regional temperatures), assuming no decrease in air pollution emission, mortality from ozone in New York City could increase by 5%. Most populated areas in North America are estimated to be exposed to ozone levels above 60 ppb under the A2 scenario by 2080 (about a 1.5 to 3.5oC increase in GMT; Health ZOD, p. 22-3).

Increased fire is also a risk in many parts of North America. Although the situation is complicated by widespread fire suppression over the 20th century, climate change could result in a longer fire season and the potential for more frequent and intense fires (North America ZOD p. 3; Lenihan *et al*., 2003). This trend may already be evident as Canada and the United States have witnessed increased fires in the latter half of the 20th Century (North America ZOD, pp. 10, 21).

More problematic is the implications for North America if there were a substantial slowdown in the MOC—particularly for north eastern Canada.

19.3.3.7. Polar Regions

The Polar Regions are already seeing clear signs of climate change, which causes many adverse impacts. One of the most noticeable changes is a reduction in sea ice and glaciers. For example, Nordic sea ice has decreased by almost a third in the last century, while Arctic sea ice has been decreasing about 3% per decade in recent decades. (ACIA, 2004)

Major changes in polar ecosystems are already happening and are expected to continue. Tundra is being displaced by woodier vegetation. Reduction in ice coverage is already affecting many species from krill to penguins in the Southern Hemisphere and polar bears in the Northern Hemisphere. The populations of many migratory birds are also being reduced. For example, more than 80% of populations of Canadian shorebirds are in decline, while only 8% of populations are increasing in abundance (Polar ZOD, p. 21).

Further warming is expected to cause additional ecological problems. Tundra may be displaced by boreal forests in some areas. Polar bears, seals, and lemmings require snow and ice for hunting prey and feeding. Warm winters can lead to starvation among caribou and musk oxen because thaws and refreezing makes plants inaccessible. In addition, a warmer climate may disrupt the timing of food availability for migratory birds. The adaptive capacity of many polar species is low because they have a long life-time and low fecundity (Polar ZOD, p. 5). On the other hand productivity of vegetation in the polar regions could increase with warmer temperatures, particularly if the climate also becomes wetter.

Indigenous human communities in Polar Regions are also highly vulnerable to climate change. Those most at risk include hunting and gathering societies, whose long-standing traditions and ways of life would most likely have to change in response to climate change. In addition, there could be substantial costs of adapting or rebuilding infrastructure to cope with loss of permafrost, not just for indigenous people, but also in larger settlements in northern regions such as Alaska, N. Canada, Scandinavia, Russia. However, there may be economic opportunities as shipping lanes open up, heating costs decrease, (but summer air conditioning may be more widely needed) and access to the region is increased.

19.3.3.8. Small Island States

Small island states (SIS) are particularly vulnerable to climate change because of their small size, the fact that many are low lying, their dependency on limited water supplies, exposure to extreme climate events, and limited adaptive capacity. With globalization, many SIS are increasing their tourist industries. While this can contribute to development, it occurs in a sector that is highly sensitive to climate variability and change.

One of the vulnerabilities that may be witnessed the soonest is a reduction in water supplies. The combination of rising seas, which will squeeze fresh water lenses underlying SIS and decreases in precipitation in some areas could make already tight water supplies even tighter. Freshwater lenses can be as little as 20 cm thick, for example on some islands of Tonga (SIS ZOD, p. 22).A 50 cm sea level rise combined with a 25% decrease in precipitation would reduce the freshwater lens in Tarawa, Kiribati by 65% (SIS ZOD p. 22). Arnell (2004) found that many SIS would be at risk of severe water stress under all the SRES scenarios, but to a greater extent under A2 and

B2 (SIS ZOD p. 22). Drier soils and increased salinization could reduce crop yields.

Sea level rise itself can threaten many settlements on SIS. For example, a 50 cm SLR combined with a 1:50 year storm could result in overtopping, wharf damage, and flooding of hinterland in Suva, Fiji, and Apia, Somoa (SIS ZOD, p24). Adaptations such as sea walls are certainly possible, but can be expensive and damaging to beach access and tourism.

SIS ecosystems are also vulnerable to climate change. In particular, coral reefs are projected to face widespread bleaching with a 1 to 2^{o}C increase in sea surface temperatures. The location of fisheries could shift hundreds of kilometres with warmer oceans and changes in ocean circulation. There is limited capacity for societies to adapt to such changes, and the capacity of natural systems like coral reefs to adapt to the combination of warming temperatures, rising sea levels and acidification of the oceans are questionable (see, for example 19.2.3.1).

19.3.4. Summary of Key Vulnerabilities

A summary of what can be assessed and described as key vulnerabilities is presented in Table 19.1. This table summarizes the information presented in the global, sectoral, and regional categories in Sections 19.3.1, 19.3.2, and 19.3.3, respectively. Each key vulnerability is characterized by the vulnerable system or process (column 1), the potential impacts of climate change on that system or process (column 2), the criteria for selecting this vulnerability as "key" (column 3; see Section 19.2.1), estimates of critical levels and rates of climate change (column 4), further comments on this key vulnerability (column 5), and information about the potential of adaptation policy to reduce the risks associated with this key vulnerability (column 6).

The probability and the magnitude of an impact are still poorly understood in many cases. This means that plausible impacts may in such cases not be well enough understood to attach firm risk estimates. This inevitably leads to subjective assessments guided by expert judgments. Table 19.1 includes a number of less well understood key vulnerabilities. In each case, a level of confidence in the probabilities and consequences is stated in columns 2 and 4 based on the Lead Authors reading of the literature, but rarely if ever can this be done fully for all the subsequent or "downstream" impacts. Some of the key vulnerabilities have been identified in previous IPCC Assessments, but as the science advances, new possible vulnerabilities are emerging and are listed here for the first time in an IPCC Assessment.

Estimates of the potential role of adaptation are expressed in column 6. There is a wide range of views on the effectiveness, costs, and feasibility of adaptation policy. This divergence of opinions is not surprising since the assessment, planning, implementation, and evaluation of adaptations to anthropogenic climate change is an emerging field for scientists, policy analysts and practitioners where very little empirical data on the costs and benefits of specific measures is available. Assessments of "feasible" adaptations and recommendations of "good" adaptations are thus largely based on idealized theoretical frameworks of adaptation or on analogues involving the success and failure of adapting to the current climate, including its variability.

A very optimistic view identifies economically optimal adaptation policies, often assuming perfect information, full cooperation of stakeholders at all levels, absence of cultural and other hurdles to adaptation, low or no transition costs, and absence of adverse side effects of adaptation measures. These studies usually show a large potential for adaptive measures to reduce the adverse impacts of future climate change as well as current climate variability. This oversimplifying perspective has sometimes been dubbed the "clairvoyant farmer" assumption (e.g., Chapter 1 of WG II TAR). A pessimistic view, in contrast, highlights the many barriers to effective adaptation in terms of costs, information, social institutions, political will, etc. as well as the incapability of many societies to adequately cope with current climate hazards. For instance, the infamous Bangladesh Cyclone of 1970 is associated with a death toll of at least 300,000; Hurricane Andrew in 1992 caused monetary damage of US $30 billion, mostly due to destruction in southeast Florida; and the 2004 European summer heatwave lead to about 35,000 premature deaths, most of them in France.

Only recently have climate change assessments attempted to consider the full range of factors that determine which potential adaptations are actually implemented, and how effective they are (Burton *et al*., 2002; Füssel and Klein, 2005). A key concept in this debate is "adaptive capacity", which denotes the generally complex set of resources necessary to implement certain adaptive measures (see Section 17.3 ZOD). Even though a lot of research has investigated the determinants of adaptive capacity at different levels of society, 'there is no well-established set of insights into the determinants of adaptive capacity or of the mechanisms which translate this capacity into action' (Section 17.3.4.1, ZOD). Furthermore, the presence of adaptive capacity alone does not guarantee that effective measures are actually implemented. In the words of Burton *et al.*, (2002), 'the mere existence of [adaptive] capacity is not itself a guarantee that it will be used'. As a result, recent research has increasingly focussed on the motivation of the system (i.e., of potential adaptation actors) to realize its adaptive capacity and to reduce its vulnerability to the effects of climate change (see Section 17.3.2.2, ZOD).

The picture regarding adaptation as a strategy to reduce key vulnerabilities of climate change is necessarily complex. On the one hand, the availability of economic and technical resources to implement specific well-known measures can often be assessed with satisfactory confidence, at least for the near future. On the other hand, assessments of the non-economic determinants of adaptive capacity and the motivations and incentives of relevant stakeholders in the far distant future are highly uncertain, leaving much room for subjective judgements.

In the more favourable view, adaptation potential is deemed considerable on the basis of existing and potential technology. Many adaptations are considered technically feasible now and more will become so as technology advances. There may be substantial costs constraints, especially in developing countries, but the costs are largely unknown and/or unmeasured. In the less favourable view, it is asserted that many systems (e.g., vulnerable ecosystems, coastal communities, etc.) cannot feasibly adapt to climate changes, particularly if warming exceeds 1-2°C above current levels. Currently, neither the "adaptation optimists" can prove that their favourable views are warranted nor can the "pessimists" prove that getting action in the future will always be as difficult as in the past, even after consciousness of climate damages motivates resources and attention to the problem. For this reason, assessments of adaptive capacity for specific key vulnerabilities were categorized as partly subjective in Section 19.2.1. Despite the large uncertainties and subjective elements, Column 6 attempts to synthesize the diverse views on the "realistic" potential of adaptation to reduce key vulnerabilities of climate change.

TABLE 19.1

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Slowdown or cessation of meridional overturning circulation(MOC) (MOC also widely known as THC) (Ch. 19.3.1.3, WGI Chs. 5 & 8, WGII Chs. 6 & 12)	High-latitude cooling in North Atlantic region, southern hemisphere warming, equatorial drying. Reduced oxygen levels and carbon uptake in deep ocean. Extent of impacts depends on rate of warming and hydrological sensitivity. Models & paleo-analogs indicate likely slowdown (moderate confidence). The extent to which any such slowdown recovers is highly uncertain.	Impacts widespread, possibly severe, uneven, possibly irreversible, although details highly uncertain. Timing uncertain but significant slowdown during 21st century likely if warming is rapid.	Some evidence of slowdown already, but may be natural variability. Simplified, high-sensitivity models show complete shutdown for warming >3ºC/100yr. AOGCMs show shutdown and re-start, but very limited studies. Some preliminary probability distributions are available. (low to moderate confidence in specific quantitative results)	Imperfect paleo-analogs suggest widespread impacts. Some results come from AOGCM imposed Northern Hemisphere high latitude freshwater increases rather than realistic anthropogenic forcing experiments. Little work done on potential impacts such as changes in storminess or teleconnections to other regions—like drying in northeastern Brazil or enhanced warming in Alaska, that some models find.	The potential for society and natural ecosystems to adapt to such a large-scale change in climate as MOC has received little attention in the literature and is largely unknown. Such rapid and large changes in climate will most likely result in disruptions to sectors of society sensitive to climate, imposition of large costs, and substantial losses to some populations and regions because the capacity to adapt to such a change appears to be limited. MOC slowdown is expected to be associated with a “roller-coaster” change in temperature in many affected region, where an initial warming period is followed by significant cooling. Such non-monotonic changes in temperature make adaptation particularly difficult. Developed countries will generally be in a better position to adapt to MOC than developing countries because of their higher adaptive capacity, particularly in the Southern Hemisphere, which is more distant

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as "key"	Critical levels and their timing (confidence)	Comments	Adaptation potential
					from any local cooling in the North Atlantic. However, Southern Hemisphere developing countries may be better able to adapt than developed countries directly affected by North Atlantic cooling. Nonetheless, adaptation costs and residual damages are expected to be substantial even in developed countries.
Melting of Greenland Ice Sheet (GIS) & disintegration of West Antarctic Ice Sheet (WAIS) Ch. 19.3.1.2, WGI Chs. 4, 5 & 10, WGII Chs.6, 7 & 15)	Rapid and irreversible global sea- level rise of several metres over several centuries, threatening major coastal cities and settlements and hundreds of millions of people. Massive relocations needed. Eventual GIS deglaciation at large (>3°C) warming very likely (high confidence), and moderate confidence of GIS deglaciation for warming as low as 1-2°C above current levels.	Large impacts on a global scale. Eventual sea level rise up to 7m from GIS, ~5m from WAIS on multi-century timescale Effectively irreversible once process is triggered, though may take most of a millennium to play out.	Local warming ~3°C Greenland ice surface, ~10 °C WAIS surface, cause slow deglaciation in models. Observed fast processes and paleo-analogs suggest that deglaciation is possible on multi-century timescales for WAIS with global warming > 2-4°C. Possible commitment but little deglaciation in 21st C. (moderate confidence)	Recent disintegration of Larsen Ice shelf and acceleration of contributory glaciers heightens interest. Fast processes still controversial, but risk is present. Meltwater could contribute to changes in ocean circulation (above).	The potential to adapt to a large rise in sea level appears to be limited. Current technology is insufficient to prevent very significant loss of land if sea level rises by several meters as a consequence of major ice sheet loss. Adaptation would thus require substantial internal and/or international migration, which might create or aggravate internal or international conflicts. Protection of some coastal areas may be possible, but feasibility and sustainability is uncertain. The capacity of developing countries to adapt is currently very limited. A key uncertain factor for adaptation is the pace at which ice sheets disintegrate. Faster rates of sea level rise will make adaptation more costly and lead to more damages.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Accelerated warming due to positive feedbacks of climate change on carbon dynamics (Ch. 19.3.1.1, WGI Chs. 7 & 10, WGII Chs. 1, 4 & 15)	Warming reduces carbon uptake by oceans and eventually turns terrestrial biosphere into a source (moderate confidence). Conversion of tundra ecosystems may enhance either carbon uptake or emission. Destabilization of marine gas hydrate reservoirs possible on multi-century time scales (low confidence). Overall, switch of global terrestrial carbon reservoir from sink to source likely in late 21st century (moderate confidence).	Global impact. May significantly accelerate warming by effectively increasing climate sensitivity. Irreversible on time scale of centuries. Tundra thawing already observed.	Coupled models indicate that terrestrial ecosystems switch from a net sink to a net source of carbon to the atmosphere around middle of this century. Gas hydrates in tundra and oceans may destabilise episodically with uncertain timing. If biosphere becomes significant source of carbon, this would substantially increase the probability of climate sensitivity being in upper end of current uncertainty range.	Large variations in carbon uptake or release from oceans occur now due to ENSO. Accelerated warming would increase chance of reaching critical and/or unexpected thresholds for rapid or discontinuous change (moderate confidence).	An increase in the magnitude or rate of warming will make adaptation far more challenging. As with other large-scale changes in climate, the costs, effectiveness, and feasibility of adaptation to accelerated warming has received little attention in the literature. It is reasonable that such changes will result in widespread damages and high adaptation costs. In relative terms, the largest damages and costs are expected to be borne by developing countries.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Water bodies Especially closed lakes e.g., Aral and Caspian Seas, Lakes Balkash (Kazakhstan), Chad (Africa), Titicaca (South America), Great Salt Lake (USA), several Great Lakes in USA and Africa. (WGII, Chs. 3, 6 & regional)	Sensitive balance between inflow and evaporation in closed seas and lakes, and in others with large areas and small outflows. Lower water levels and warming will impact fishery, biodiversity, and local climates. Widespread occurrence of these impacts likely (high confidence).	Multiple examples of such water bodies exist on most continents. Climate change likely to exacerbate existing stresses. Impacts on many people and ecosystems.	Decreasing water levels are observed now in many water bodies. In some cases warming of 1 or 2ºC above 2000 levels may be critical for aquatic ecosystems. Migration of affected species often not possible.	Synergistic effects from water withdrawals for irrigation and growing population. Such withdrawals may dominate present water body shrinkages (e.g., Aral Sea) but increase vulnerability to climate change.	Adaptations include projects to adjust in or outflow from lakes, more efficient irrigation systems, drought resistant crops etc. Very large changes will likely require retreat from areas where lakes expand or abandonment of activities like fishing where significant lake contraction occurs.Adaptation in resource-limited developing countries appears more difficult than in developed countries.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Glaciers and small ice sheets shrinkage and disappearance (WGI Ch. 4, WGII Chs.3, 4, 7 and regional)	Tropical glaciers are most sensitive but many glaciers will disappear,. Impacts include glacial lake outbursts, declines in water storage and supply, threats to groundwater, ecosystems, and loss of revenues from tourism. Contribution to sea level rise. Widespread occurrence already (high confidence of significant effects for all SRES scenarios)	Widespread on most continents, affecting large populations in some cities and irrigated farms. Some effects happening now and will increase rapidly as warming proceeds.	The vast majority of the world’s glaciers are shrinking now. Warming of >2ºC is sufficient to eventually eliminate most glaciers. Melting Alaskan glaciers and Patagonian Ice sheet currently add 3 mm and 1 mm per decade to global sea level, respectively. High confidence that rates of melting will accelerate.	A small fraction of glaciers are advancing due to increased snowfall, but this is likely to reverse as warming continues.	The potential of adaptation varies across the different impacts caused by glacier shrinkage. Adaptations for water supplies are possible in some locations, but at a cost. Technological research and development may increase adaptation potential. Lifestyle changes may be necessary in developed countries. Adaptation for water supplies is more difficult in developing countries. Warning systems are possible for glacial lake outbursts, but the feasibility of their implementation is questionable. Adaptation may be very difficult for communities dependent on tourism that is linked to the existence of glaciers.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Ecosystems e.g., montane ecosystems, coastal wetlands, tundra, coral reefs, mangroves, and fire-prone ecosystems. (Ch. 19.3.2.2, WGI, Ch. 3?, WGII Chs.1, 4 and regional)	Ecosystems bound by altitude, coasts or human land use are very vulnerable. Loss of species and ecosystem functions and services. Large impacts on food supplies, tourism, World Heritage Areas, biodiversity hotspots, national parks, genetic resources. Some impacts are already occurring now; they are likely to become more widespread as climate change intensifies (high confidence).	Very widespread impacts, including extinction of many species over time, particularly for warming >2°C. Vulnerability is increased by other stresses such as land use change, which is already happening and is expected to increase.	Many species are already responding to the 0.7°C warming since 1900, and some extinctions are already claimed. Threshold for sustained coral bleaching and extensive reef mortality is 1-2°C warming; many other systems are threatened at similar warming levels. Widespread ecosystem changes and losses with limited adaptive capacity at 1-2°C	Climate impacts on ecosystems are highly synergistic with other stresses, especially local pollution and habitat fragmentation.	There is limited potential for adaptation of natural ecosystems via migration corridors, increased reserve areas, human intervention to relocate or breed species and reductions of other stresses. Corals may have some adaptation potential for modest rate of warming. Loss of ecosystem services would require human adaptation or development of alternative services at costs unaffordable in some developing countries. There is substantially higher adaptation potential in managed ecosystems. Some ecosystem goods and services could be substituted, but at a cost. Adaptation requires far-sighted investment in technology research and development. Substitutions may conflict with environmental values.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Coastal cities, low-lying islands, and densely populated deltas (Ch. 19.3.2.5, WG II, Chs. 6, 7 & regional).	Sea level rise and more intense tropical storms may cause flooding, erosion, wave damage, and salinisation of groundwater, which would displace many people and disrupt economic activities. Sea level rises and intensification of tropical cyclones already observed. Widespread occurrence very likely with increased warming (high confidence).	Very widespread, affecting hundreds of millions of people by 2100. Very large infrastructure and heritage values at risk. Adaptation costly, withdrawal required in some areas. Displaced people may cause internal or cross-border conflicts.	Numbers affected rise rapidly with greater sea level rise. Probability of a 0.5 m sea level rise by 2100 is not negligible, even for low SRES scenarios. Storm surge damage will be episodic; many populations are ill-prepared.	All impacts would be greatly increased if disintegration of GIS and/or WAIS occurred, leading to much larger sea-level rise (see above), though such occurrences would take many centuries to fully play out.	There is substantial potential to protect developed coastal areas from a 1-meter sea level rise, but costs could be substantial. It may not be feasible or affordable to protect all developed coastal areas, particularly in developing countries or some small island states. In those cases, retreat and relocation may be the only feasible adaptations. Substantial loss of coastal wetlands and mangroves is likely, as is inundation of undeveloped or otherwise low value coastal areas. Proper planning for sea level rise can reduce adaptation costs and damages.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Indigenous communities (WG II, Chs. 8, 11, 14, 15)	Traditional hunting and food gathering becomes threatened. Reduced water supplies, coastal flooding, erosion and health problems. These impacts are already occurring in Arctic and some island communities, and for some indigenous communities in Andes where glaciers are disappearing. High confidence the stresses will build if warming accelerates as typically projected.	Equity issue affecting disadvantaged minorities in several developed and developing countries. Survival of unique cultures at risk.	Some island, high mountain and Arctic communities are already affected. Critical levels of climate change are regionally specific and difficult to generalize.	Synergistic effects due to land-use change and population growth.	The livelihoods and the cultural identity of indigenous communities are generally closely tied to climate-sensitive environmental characteristics. Adaptation may thus require fundamental changes in lifestyle and depend on outside help. Economic development can reduce vulnerability to climate change, but at the risk of diminishing cultural identity. Abandonment and migration may be required for some islands, at the risk of losing cultural identity.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Crops and food supply (Ch. 19.3.2,3, WGII Ch.5)	Net decreased yields (i.e., more losses than gains) in low-latitude developing countries, even for small warming levels and in developed countries for larger warming levels. Sensitive to the highly uncertain CO_2 fertilization effect (moderate confidence).	Widespread impacts, worse in developing countries, are likely to exacerbate international inequities. Increase in malnutrition is possible.	Even 1-2ºC warming reduces yields at low latitudes (likely over the next several decades). Above several ºC warming, yields also decrease at some higher latitudes (late 21st century). Effects would be more negative globally if CO_2 fertilization effects less than typically assumed, as some recent field studies suggest (moderate confidence).	Yield increases with higher ambient CO_2, but effectiveness may be limited. This benefit would be counteracted by large warming levels, decrease in soil moisture, and other stresses (e.g., ozone pollution, nutrient stress). Drought and heat stress are critical.	There is a high potential for adaptation to the effects of climate change on agriculture, especially at the lower end of the warming range, assuming a gradual rate of change. A moderate degree of warming could be of benefit to agriculture in some developed high-latitude regions. Adaptations by genetically improved varieties or other technological improvements are possible but uncertain. Increases in climate variability, extreme events, spread of pests and diseases, which can happen with a moderate amount of warming, can make adaptation more difficult. The potential for adaptation is more limited with faster rates or higher magnitudes of warming. Adaptation is also more limited for perennial crops (e.g., viticulture, olive trees). At the higher end of warming projections, adaptation could be quite limited in currently hot climates. Adaptation in developing countries is more limited (severely limited in some cases) due to lack of access to technology, cost constraints, and low adaptive capacity. Risks are greatest for subsistence farmers in developing countries.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as "key"	Critical levels and their timing (confidence)	Comments	Adaptation potential
Forests (Ch. 19.3.2.4, WG II Ch.5)	Higher temperatures, drier conditions, more fires, pests and diseases, would decrease yields and carbon storage in many tropical and mid-latitude forests (moderate confidence). Carbon fertilization and longer growing seasons can increase yields, but are more effective for smaller warming levels. (moderate confidence). For large warming (>3°C) negative effects likely to be widespread.	Widespread impacts affecting wood supplies, biodiversity and carbon storage. C-cycle feedback (see entry above) exacerbates impacts..	2-3ºC likely to lead to widespread impacts (moderate to high confidence).	igher ambient CO_2 may initially increase productivity, but may be counteracted by warming, water and nutrient stress, drought, and fire. Northward movement of Arctic tree line can co-occur with loss at southern boundary of boreal forests Net effects unclear.	The potential for adaptation in forests is more limited by the long term nature of investments and slower turnover of tree crops of forest species. Adaptation generally has greater potential in plantations than in natural forest because of the higher level of management. Potential increases in forest fires, diseases, and pests can limit adaptation. There is a high potential for substitutions for commercial timber products. Adaptation in developing countries may be limited (severely limited in some cases) by lack of access to technology, cost constraints, and low adaptive capacity.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Water supply (Ch. 19.3.2.1, WG II, Ch. 3)	Increased water shortages for many people, especially in arid and semi-arid regions very likely (high confidence). Effects will be highly heterogeneous, depending on regional climatic changes and local hydrological situation.	For those regions experiencing negative impacts, this would affects health and possibly survival of many millions of people, exacerbating existing problem of water stress and competition.	Regional water shortages already evident in both developed and developing countries partly due to increasing demand, some exacerbated by prolonged drought and warming trends. Reliability of local water supply systems defines critical levels.	Precipitation changes vary regionally but even small increases in temperature can result in increased demand and reduced supply. Loss of glacier storage adds to regional problems, as does salinisation of groundwater in coastal regions affected by sea-level rise.	There is substantial potential for societies to adapt to changes in water supplies and quality through improved efficiency of water consumption, water recycling, reforms of water pricing and allocation, and desalinisation. However, these adaptations are costly and in some cases may be infeasible, especially in developing countries. In addition, adaptations may involve the loss of some services (such as water supplies to certain user groups and hydropower), and they may cause damage to aquatic ecosystems.
Infrastructure (WG II, Ch.7)	More intense tropical storms and precipitation events, earlier snowmelt, higher extreme temperatures, greater extreme winds in some places are very likely to increase stresses on infrastructure, especially in coastal areas & flood plains (high confidence).	Widespread damage, with potentially large costs. Damages and costs increase non-linearly with greater warming (high confidence).	Extreme climate events (e.g., floods, tropical cyclone intensities) are already damaging. Climate change will be superimposed on natural climate variability. Local damage thresholds exist related to wind speed, flood levels, engineering design standards, zoning, etc.	Rapid population and economic growth in exposed areas exacerbates the climatic trend to higher exposure to risk, though more resources from effective development activities can increase adaptation potential.	There are many potential adaptations for infrastructure, including setbacks, zoning laws, stringent design rules, insurance, flood plain management, and abandonment. Yet, many of these adaptations are expensive and have their limits, particularly for a rapid climate change or increased frequency and/or intensity of extreme events. Developing countries generally have less capacity to adapt, although they may have more opportunity to incorporate climate change in the design of new infrastructure and other development activities. Designing infrastructure to anticipate uncertain regional changes in climate is a challenge.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as "key"	Critical levels and their timing (confidence)	Comments	Adaptation potential
Health (Ch. 19.3.2.6, WG II, Ch. 8)	The incidence of malnutrition, malaria, dengue fever, diarrhoeal diseases, injuries due to storms and floods, and morbidity from air pollution is likely to increase unless strong counter-measures are taken (high confidence).	Many people are likely affected, especially in low-income communities and developing countries (high confidence).	Current burden of all these problems is high, indicating inadequate counter measures, regardless of the levels of climate change. Any exacerbation of conditions from climate change will almost certainly increase morbidity and mortality unless public health infrastructure and service delivery is substantially improved.	Higher temperature, water stress, reduced crop yields, more extreme weather events, possibly worse air pollution all contribute to increase in health risks. Improved delivery of health services has already been identified as a global development priority, that would also reduce climate impacts on health.	There is a high potential for adaptation in developed countries if public health infrastructure is maintained or improved. There is a low potential for adaptation at current levels of development in many other countries because of inadequate public health infrastructure. Should economic development result in improved public health infrastructure, vulnerability to health effects of climate change will likely be substantially lower than at present. Such development is, however, uncertain.

Vulnerable system or process (AR4 cross-references)	Impacts (confidence)	Criteria for inclusion as “key”	Critical levels and their timing (confidence)	Comments	Adaptation potential
Cross-border issues These arise from uneven impacts on different countries and climate change-induced situations leading to increased tensions between groups or countries.	Changes in trade patterns (e.g., agricultural goods) are likely as a result of unequal changes in supply and demand. Infrastructure damages, competition for resources (e.g., water), disaster relief, economic impacts, and displaced populations cause migration pressures (moderate confidence).	Potential widespread changes to local economies and livelihoods, leading to possible exacerbation of regional tensions and political instability. Raises environmental security issues.	Many resource-based tensions could be exacerbated by climate change, but the assessment when they become critical is highly subjective and dependent on pre-existing social and political tensions. Not just restricted to cross-border scale, but such stresses can be induces within countries, across watersheds etc. Only low confidence in specific conclusions, as the literature on such conflicts is sparse.	Increased migration from developing countries and Small Island States affected by sea level rise is one example. Larger climatic impacts falling on those with less adaptive capacity--who also produced a small fraction of the emissions that created these impacts--could exacerbate existing international tensions.	The potential role for adaptation for cross-border issues is difficult to assess as the literature on this topic is very limited. Adaptation could include strong aid and development policies, international conflict resolution, public education, and accommodation of migration. How effective such policies would be if climate change led to large scale migration is uncertain.

19.3.5. Update of Information about the five Reasons for Concern identified in the TAR

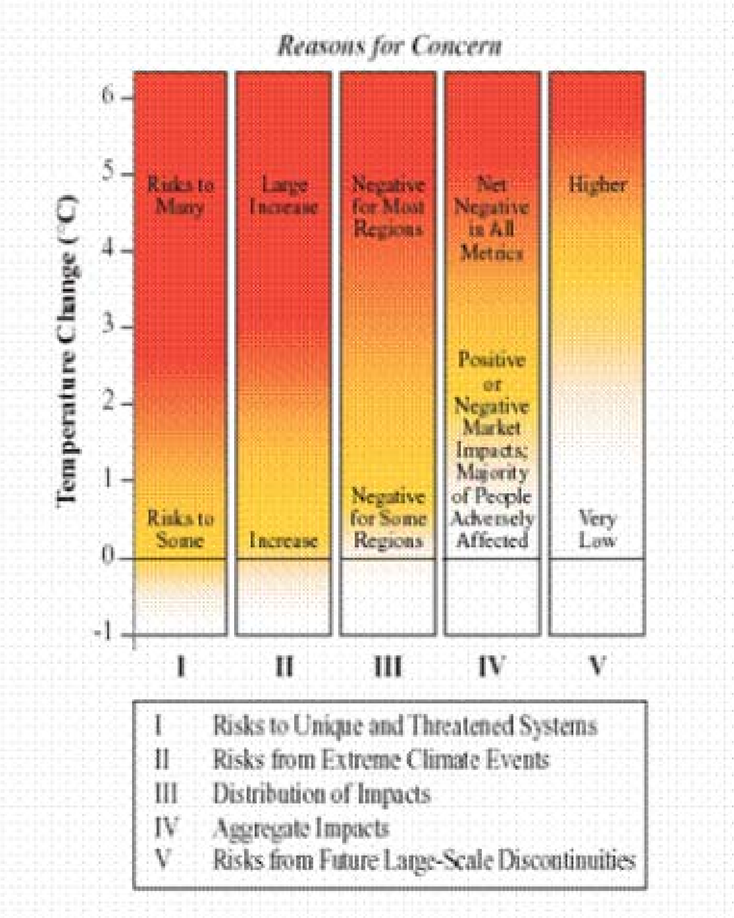

Figure 19.2: Five reasons for concern. Source: Watson and the Core Writing Team (2001)

The IPCC Third Assessment Report (TAR; Smith *et al*., 2001; Watson and the Core Writing Team, 2001)) identified five "reasons for concern" about climate change. Figure 19.2 shows the relationship between global mean temperature change (above 1990 levels) and the risks or impacts for each reason for concern identified in the TAR. In this section, we present results from research done since the TAR that can be used to update this information.

The TAR drew the following conclusions about the amount of increase in global mean temperature above 1990 levels that would exceed the thresholds defined above:

1 *Unique and Threatened Systems*. The TAR concluded that there is medium confidence that an increase in global mean temperature of 2^{o}C above 1990 levels or less would harm several such systems, in particular coral reefs and glaciers.

Since the TAR, there is new and much stronger evidence of observed impacts of climate change on unique and vulnerable systems (Parmesan and Yohe, 2003; Root *et al*., 2003), many of which are described as already adversely affected by climate change to date. This is particularly evident in polar ecosystems (e.g., ACIA, 2004) and mountain-top ecosystems (Pounds *et al*., 2005). Furthermore, confidence has increased that a 1 to 2^{o}C increase in global mean temperature above current levels will pose significant risks to many unique and vulnerable systems, including many biodiversity hotspots (Hare, 2003).

A qualitative review by Corfee-Morlot and Höhne (2003) results in a threshold target for overall risks to unique and threatened species of 1ºC-2ºC global mean temperature warming above 1990 levels. In summary, there is now high confidence that a warming of 1-2^{o}C would have adverse impacts on many unique and vulnerable systems.

2 *Extreme Events*. The TAR concluded that there is high confidence that the frequency and magnitude of many extreme climate-related events (e.g., heat waves, tropical cyclone intensities) will increase with temperature increase of less than 2°C above 1990 levels, and that this increase will become greater at higher temperatures. There was also high confidence that increases in extreme events will cause rapidly increasing damage to many human and natural systems, especially for magnitudes of climate change above 2°C.

Recent extreme climate events have demonstrated that such events can cause significant loss of life and property damage in developing as well as developed countries (Schär *et al*., 2004). While individual events cannot be attributed solely to anthropogenic climate change, recent research has shown that human influence has already significantly increased the risk of certain extreme events (e.g., heat waves: Stott *et al*., 2004, tropical cyclone intensity increases: Emanuel, 2005) (more than 90% ;very likely)

3 *Distribution of Impacts*. The TAR concluded that there is high confidence that developing countries will be more vulnerable to climate change than developed countries. There was medium confidence that a warming of less than 2^{o}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. There was high confidence that above 2°C, net positive impacts would start to decline, eventually turning negative, and initial negative impacts would become more negative.

There is still high confidence that the distribution 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. For instance, indigenous populations in high-latitude areas are already faced with significant adverse impacts from climate change to date, and coastal dwellers are facing increasing risks.

4 *Aggregate Impacts*. The TAR concluded that there is medium confidence that with an increase in global mean temperature of up to 2^{o}C above 1990 levels, aggregate *market* sector impacts would be plus or minus a few percent of global product, but most people in the world would be negatively affected. Most studies of aggregate economic impacts found net damages beyond 2 to 3^{o}C, 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 temperature increases, and an overly simplistic representation of adaptation. 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. Hence, the current generation of aggregate estimates in the literature could well understate the actual costs of climate change. However, current studies also may overlook some positive impacts of climate change or underestimate the potential of adaptation to reduced damages from climate change. In summary, there is now lower confidence in most assessments of aggregate effects than in the TAR, in particular there is greater uncertainty in estimates that show aggregated benefits from climate change below a few degrees of warming.

5 *Large-Scale Singularities.* The TAR concluded that there is low to medium confidence that a rapid warming over 3^{o}C would trigger large-scale singularities in the climate system, such as 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 indicates that thresholds for at least one of these events, deglaciation of West Antarctica, may be lower than reported in the TAR. While there is no consensus yet, some studies (Oppenheimer and Alley, 2004, 2005) indicate that a 2 to 4^{o}C global warming above current levels could begin WAIS deglaciation (low to medium confidence). Recent observations also suggest that the Greenland ice sheet is losing mass at its periphery faster than previously thought, and that rapid deglaciation could be triggered by GMT increases of about 1^{o}C above current levels (Hansen 2005). The literature on thresholds for triggering a slowdown of MOC or net biogenic feedbacks is consistent with the TAR, but still is not reporting high confidence conclusions.

19.4. Assessment of Response Strategies to Avoid Key Vulnerabilities

In Section 19.3, we identified global, sectoral, and regional key vulnerabilities associated with different levels of climate change. This section reviews the literature addressing the linkages between key vulnerabilities and response strategies to avoid them. The principal response strategies to the risks posed by anthropogenic climate change are mitigation of climate change and adaptation to climate change. These two strategies have largely different foci in terms of their characteristic spatial and temporal scales (see Figure 19.3). As discussed in Section 19.2, the relative lack of feasible adaptations to many key vulnerabilities has been an important criterion for the selection of what is called a “key” vulnerability in the first place.

The two response strategies—mitigation and adaptation—are often portrayed as having largely different foci in terms of their characteristic spatial and temporal scales (see Figure 19.2). However, there is debate over the extent to which benefits from adaptation can be considered local and benefits from mitigation global (see WG II AR4, Chapter 17). On the other hand, actions involving adaptation are more likely to be local whereas actions to achieve mitigation require a global-scale effort, as most GHGs globalize well before they are chemically or biologically removed. This debate is not resolved in the literature, and thus no position in this context could remotely be labelled as well-established. However, since Chapter 17 deals specifically with adaptation in considerable detail, this section focuses on the avoidance of key vulnerabilities or DAI through mitigation of climate change, assessing the literature which addresses this strategy explicitly—though a brief assessment of the potential for adaptation is included in the discussion of key vulnerabilities on Table 19.1).

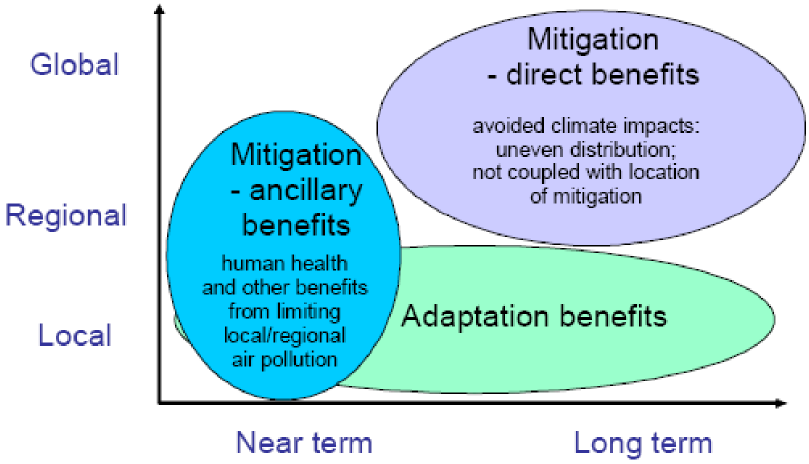

Figure 19.3: *Mitigation and adaptation policy benefits over space and time. Source: Corfee-Morlot and Agrawala (2004)*

As discussed earlier, the UNFCCC is ambiguous about which specific impacts to consider and whether to weigh adaptation potential and costs of mitigation in determining what is “dangerous”. Article 2 and its negotiation history offer limited—and controversial—guidance as to how to operationalize the ultimate objective of the UNFCCC (Oppenheimer and Petsonk, 2004, 2005). Studies that have attempted to link DAI with specific levels of GHG concentrations or global temperature change therefore had to combine scientific analysis and normative judgements in deciding how to operationalize DAI. Furthermore, most model analyses reviewed here have to make some assumptions about the socio-economic system, which are discussed in more detail by WG III.

This section is structured as follows. Section 19.4.1 briefly discusses the treatment of uncertainties in the context of this chapter, and Section 19.4.2 presents four basic methodological approaches applied to determine and assess linkages between DAI, key vulnerabilities, and response strategies. A more extensive review of the literature on methods for characterizing future emissions pathways and climate change scenarios is given in Chapter 2. Section 19.4.3 – 19.4.6 review the literature for each assessment approach, and Section 19.4.7 summarizes the key lessons from these studies.

19.4.1. Uncertainties in the assessment of response strategies

Climate change assessments and the development of response strategies are hampered by multiple uncertainties and unknowns (see Chapter 2.2.2). The most relevant sources of uncertainty in this context are:

1 Natural randomness
2 Lack of scientific knowledge
3 Value diversity
4 Social choice

Some sources of uncertainty can be represented by probabilities whereas others cannot. The natural randomness in the climate system can be characterized by frequentist (or objective) probabilities, which describe the *likelihood* of a repeatable event under known circumstances. The reliability of knowledge about uncertain aspects of the world (such as the "true" value of climate sensitivity) can only be represented by Bayesian (or subjective) probabilities, which refe r to the *degree of belief* in a particular statement. Bayesian probabilities may be elicited through expert surveys (e.g. Morgan & Keith, 1995), constraining uncertain model parameters with observations (e.g. Andronova & Schlesinger, 2001), or a combination of these methods (e.g. Forest *et al.*, 2001). Whether probabilities can be applied to describe future social choice, in particular uncertainties in future greenhouse gas emissions, has been the subject of considerable scientific debate (e.g., Schneider, 2001; Grubler and Nakicenovic, 2001; Pittock *et al.*, 2001; Lempert and Schlesinger, 2001; Allen *et al.*, 2001; Reilly *et al.*, 2001; Schneider, 2002). Value diversity (such as different attitudes towards risk or equity) cannot be meaningfully described probabilistically and is often assessed through sensitivity analysis or scenario analysis, in which different value systems are explicitly represented and contrasted.

The probabilistic analyses of DAI reported in this section draw substantially on (subjective) Bayesian probabilities to describe key uncertainties in the natural system, such as the rate of oceanic heat uptake, the magnitude of current radiative forcing, the magnitude of indirect aerosol forcings, the value for climate sensitivity, and uncertainties in other climate system parameters (see WG I for a more detailed discussion). While these uncertainties prevent the establishment of a one-to-one linkage between atmospheric greenhouse gas concentrations and global mean temperature increase, probabilistic analyses can determine the likelihood of exceeding certain temperature thresholds for given emission scenarios or concentration targets.

19.4.2. Methodological approaches to the assessment of response strategies

A variety of methods are used to identify response strategies that would avoid key vulnerabilities or thresholds of DAI by analyzing the linkages between key vulnerabilities, global mean temperature increase, and atmospheric GHG concentrations. These methods can be characterized according to several dimensions:

- *Static vs. dynamic.* Static approaches link stabilization levels for atmospheric GHG concentrations to equilibrium levels of global temperature change or to thresholds for DAI, thus helping to define the stabilization "level" that would prevent DAI, as called for by Article 2 UNFCCC. Dynamic analyses include information about the trajectories of GHG emissions, concentrations, and climate change, thereby providing information about the "time-frame" of GHG stabilization required to meet the objective of Article 2 UNFCCC.
- *Non-targeted vs. targeted.* In the context of this section, targeted approaches refer to the determination of policy strategies that attempt to avoid exceeding pre-defined targets for climate change, key vulnerabilities, or DAI thresholds, whereas non-targeted approaches determine the implications for climate change, 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 vs. probabilistic vs. hybrid:* Probabilistic analyses consider key uncertainties by describing one or more parameters of the coupled socio-natural system in terms of probability distributions whereas deterministic analyses are based on best-guess estimates for uncertain parameters or a selected number of possible values to conduct a sensitivity

analysis. Sometimes, hybrid analyses are performed (e.g., a 10th, 50th and 90th percentile estimate of some important process or outcome).

- *Non-optimizing vs. optimizing vs. adaptive:* Optimizing analyses select specific emission scenarios based on a pre-defined objective, such as cost minimization, whereas non-optimizing analyses do not require the specification of such an objective function. Adaptive analyses are a subcategory of probabilistic optimizing analyses that include assumptions about the resolution of key uncertainties in the future.

Table 19.2 characterizes the main methods applied in the relevant literature based on two of the dimensions defined above. These categories are used to structure the review of the literature in the rest of this section.

***Table 19.2**. Methods to identify climate policies to avoid DAI*

Method	Description	Optimizing strategy?	Based on pre-defined targets?
Scenario analysis, analysis of stabilization targets	Analyze the implications for temperature increase or DAI of specific concentration stabilization levels, concentration pathways, or emission scenarios.	No	No
“Guardrail” analysis	Derive ranges of emissions that are compatible with predefined constraints on temperature increase, intolerable climate impacts, and/or mitigation costs.	No	Yes
Integrated assessment of key vulnerabilities and DAI	Include representations of key vulnerabilities or DAI in a cost-optimizing integrated assessment framework.	Yes	No or partly
Cost-effectiveness analysis	Identify cost-minimizing emission pathways that are consistent with pre-defined constraints for GHG concentrations, climate change, or climate impacts.	Yes	Yes

19.4.3. Scenario analysis and analysis of stabilization targets

Scenario analysis describes studies that analyze the implications of specified emissions pathways or concentration profiles for future climate change (e.g., magnitude and rate of temperature increase or sea level rise, or changes to specific processes or systems) dynamically. In this section, we also consider static analyses that examine the relationship between stabilization targets for GHG concentrations and equilibrium values for climate parameters. Some of these studies treat the uncertainty in future GHG emissions and climate change by analyzing a discrete range of scenarios (hybrid methods) whereas others quantify uncertainty using probability distributions for one or more parameter of the coupled social-natural system.

The carbon available for fossil fuel combustion is comparatively small versus the size of the marine carbon reservoir (Putilov, 2003, pp. 61-65; Semenov, 2004, p. 113). Employing a very long term perspective (i.e., many millennia or longer), CO_2 concentrations, may thus return to values close to pre-industrial levels through natural processes such as dissolution of marine carbonates and geologic weathering (Brovkin *et al*., 2002, p. 86-89). Therefore, a climate change scenario may be associated with DAI even if stabilizes at a low level of GHG concentrations in the very long-term. In order to avoid this complication, the discussion of CO_2 stabilization in this chapter always refers to the shorter time scales (up to several centuries) that are more relevant for the avoidance of DAI.

Concentration stabilization scenarios that consider processes operating on these timescales have proven useful in examining the constraints on emissions that would follow from consideration of key vulnerabilities. First generation concentration trajectories generally were designed as monotonically increasing curves starting from current CO_2 concentrations and ending at a certain final asymptotic level (Enting *et al.*, 1994; Schimel *et al.*, 1996; Wigley *et al.*, 1996). An extended approach allowing temporary exceedance of the final concentration level on multi-decadal timescales ("overshoot trajectories") has been developed recently (Kheshgi., 2004; O'Neill and Oppenheimer, 2004; Izrael and Semenov, 2005; Kheshgi *et al*., 2005; Meinshausen *et al*., 2005). In another approach, stabilization scenarios were developed associated with a program of reduction of global CO_2 emissions having a certain starting year beyond which global emissions are reduced by a given percentage related to the previous year (Izrael and Semenov 2005). Some stabilization scenarios adopt existing emission scenarios for a limited time and extend them further into the future to reach stabilization of CO_2 concentrations. Stabilization scenarios that have been derived in this manner are usually tied to SRES during the 21st century and achieve stabilization of CO2 concentrations at levels between 450 and 750 ppm during the 22nd century (Swart *et al.*, 2002).

Several recent studies have specifically focused on the analysis of stabilization scenarios to thresholds for specific key vulnerabilities or thresholds for DAI. O'Neill and Oppenheimer (2002) related several stabilization scenarios approaching 450, 550, and 650 ppm atmospheric CO_2 concentrations to targets for temperature increase associated with specific key vulnerabilities. They concluded that none of these scenarios will prevent widespread coral reef bleaching in 2100 (assumed to occur for 1°C increase above current levels); only the 450 ppm CO_2 stabilization scenario is "likely" to avoid MOC collapse (assumed to occur for 3°C increase in global mean temperatures in 100 years) and may also avert deglaciation of West Antarctica. A consistent, and intuitively obvious, conclusion from these studies is that the risk of exceeding thresholds for specific key vulnerabilities or DAI increases with higher stabilization levels for GHG concentrations (very high confidence).

To quantify this conclusion, some studies present a probabilistic approach to assessing the risk of exceeding temperature thresholds for DAI under various stabilization scenarios, including overshoot scenarios (Hare and Meinshausen, 2005; Schneider and Mastrandrea, 2005, Knutti *et al*., 2005). These studies generate probability distributions for future global mean temperature increase based on probabilistic quantifications of the uncertainty in climate sensitivity and other climate parameters. Figure 19.4, for instance, depicts the risk of exceeding a temperature threshold of 2°C above preindustrial levels based on a range of published probability distributions for climate sensitivity. We present a threshold of 2ºC above preindustrial levels here as exemplary of the choice of many authors for their analysis of DAI, though as found in the literature and demonstrated in this chapter, there are many other possible levels that have been or may be chosen. To render eventual exceedence of this exemplary threshold "unlikely" (<33% chance) for all climate sensitivity distributions considered, the CO_2-equivalent stabilization level must be less than 470 ppm. To make exceedence "very unlikely" (<10% chance), the level must be below 420 ppm.

Wigley (2004) combines probability distributions for climate sensitivity and non-CO_2 forcing with a probabilistic definition for DAI to construct probability distributions for the CO_2 stabilization level required to avoid DAI. As demonstrated in his study, these probability distributions reflect only one set of assumptions possible in such an analysis, and other assumptions could significantly affect the results. Under this assumption set, the median stabilization level for atmospheric CO_2 concentrations is 536 ppm, and there is a 17% chance that the stabilization level necessary to avoid DAI is below current atmospheric CO_2 levels (it must be kept in mind that current GHG concentrations in the atmosphere, even if held fixed indefinitely, have not yet had their eventual equilibrium climate changes fully realized.

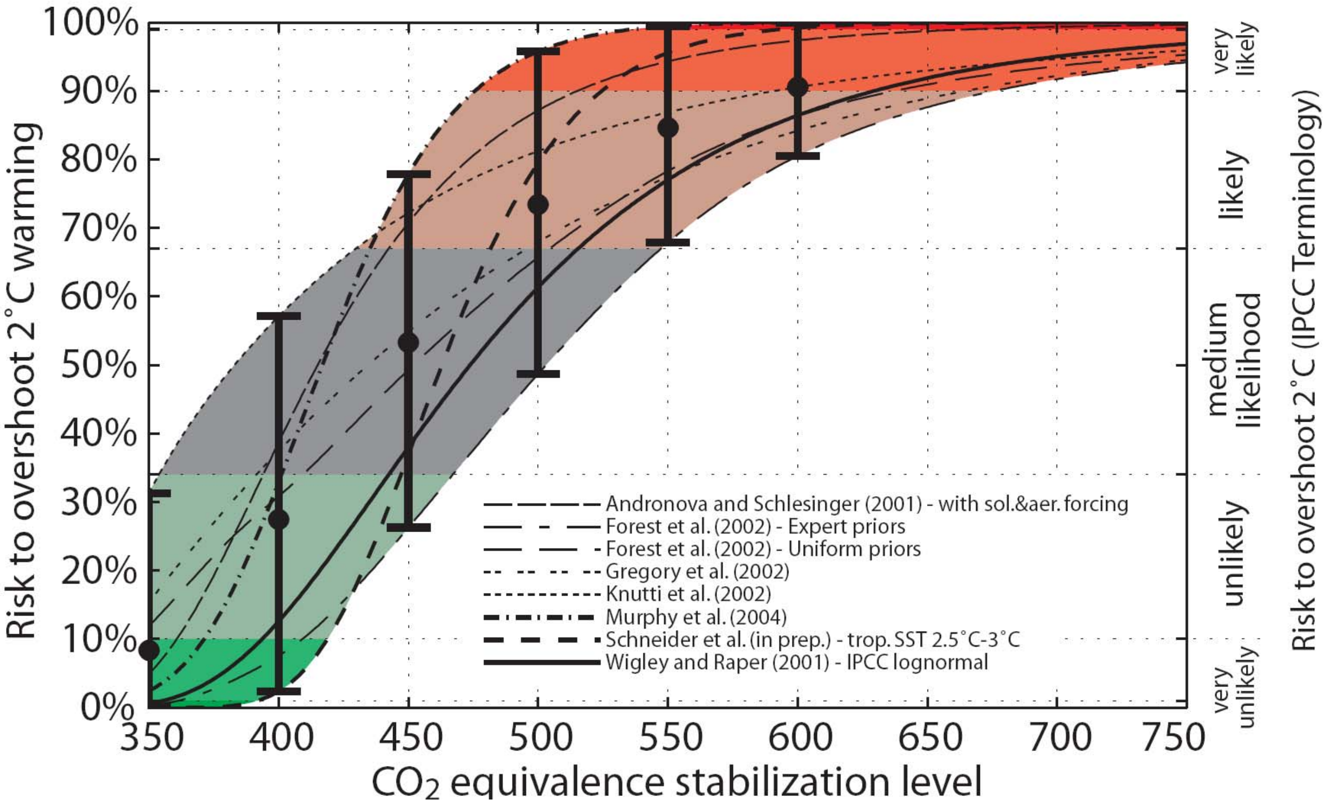

***Figure 19.4**: Risk of exceeding a global warming of 2°C above preindustrial (corresponding to 1.4°C above 2000 levels). Source: Hare and Meinshausen (2005).*

Significant differences in environmental impacts are anticipated between GHG concentration stabilization trajectories that allow overshoot of the stabilization concentration versus those that do not, as well as those with a fast versus slow approach to stabilization, even when they lead to the same final concentration. Schneider and Mastrandrea (2005) compared the probability distributions of temperature change induced by specific overshoot and non-overshoot scenarios stabilizing at 500 ppm CO_2 equivalent, based on published probability distributions representing uncertainty in climate sensitivity. They found that, from 2000-2200, the overshoot scenario increased the probability of temporary or sustained exceedence of a 2ºC above preindustrial threshold by 70% (from 45% to 77%), as shown in Figure 19.5a. They also defined two metrics, Maximum Exceedence Amplitude (MEA) and Degree Years (DY) to characterize emissions pathways and their associated temperature profiles by the maximum and cumulative magnitude of overshoot of any given temperature threshold, as shown for an illustrative scenario in Figure 19.5b. Their numerical estimates using a simple modeling framework can best be interpreted by comparing the relative magnitude of results rather than the model-dependent specific quantities.

However, studies addressing this complexity consistently find that, compared to non-overshoot stabilization scenarios, scenarios overshooting the final target before stabilization induce higher transient temperature increases, which increase the risk of temporary or permanent exceedence of thresholds for key vulnerabilities or DAI (high confidence) (Hammit 1999; O'Neill and Oppenheimer, 2004; Hare and Meinshausen, 2005; Schneider and Mastrandrea, 2005). This result suggests that the use of an equilibrium stabilization concentration alone is an insufficient indicator by which to evaluate exceedence of thresholds for specific key vulnerabilities or DAI, and that dynamic approach should be part of the analysis tool kit.

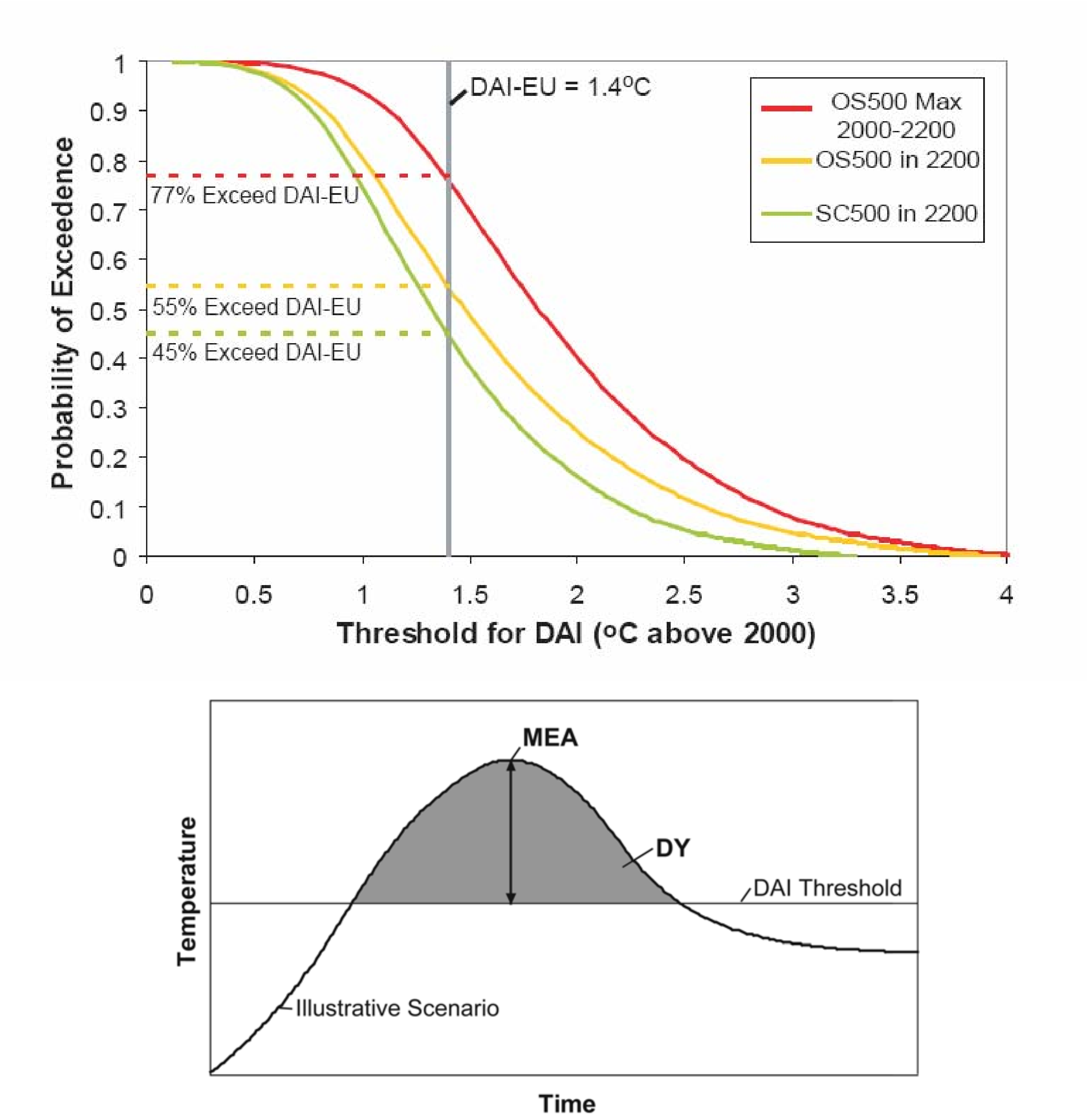

Figure 19.5*: a) Probability of exceedence of 1.4ºC above current levels (labelled DAI-EU, as the European Union has endorsed this level of climate change as their climate policy target) for overshoot (OS500) and non-overshoot (SC500) scenarios. b) Visualization of Maximum Exceedence Amplitude (MEA) and Degree Years (DY) for an illustrative overshoot temperature profile. Source: Schneider and Mastrandrea (2005).*

19.4.4. 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 approach (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 range of permissible greenhouse gas emissions. It has been applied to several normative thresholds for climate impacts, which are analyzed together with socio-economic constraints that aim at excluding unacceptable mitigation policies. Toth *et al*., (2002) analyze 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*., (2003a) 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% shall be avoided. This result, however, is contingent on the regional climate change projection of the specific GCM applied in this analysis (HadCM2). Thus, the specific numerical results, while plausible, are clearly assumption-bound and model-dependent, but the framework of this type of analysis is more general. In general, the consideration of regional and local climate impacts in inverse analyses raises challenges as to the treatment of the significant uncertainties associated with them. If the relationship between GHG emissions and the impact to be avoided is very uncertain, probabilistic assessments are more appropriate to guide climate policy then deterministic assessments based solely on “best guess” values.

The tolerable windows approach has also been applied in analyses of the stability of the thermohaline circulation (THC, or alternatively, MOC). Rahmstorf and Zickfeld (2005) conclude that the SRES A2 emission scenario leaves the range of emissions corresponding to a 5% and 10% risk of a THC shutdown around 2035 and 2065, respectively. A 2% risk of THC shutdown can no longer be avoided even with very stringent emission reductions, given the assumptions in their models.

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 stabilization. This analysis draws largely on the IPCC TAR but includes also more recent literature. They argue that any CO_2 stabilization target above 450 ppm is associated with a “very significant” probability of triggering a large-scale singularity, which in turn would affect, and very likely dominate, all other reasons for concern. An inverse analysis of the implications of reaching CO_2 stabilization at 450 ppm concludes that more than half of the SRES emission scenarios leave that stabilization target virtually out of reach as of 2020.

19.4.5. Integrated assessment of key vulnerabilities and DAI

The broad integrated assessment literature has increasingly addressed climate impacts relevant to assessment of DAI and determination of key vulnerabilities. Most early integrated assessments of climate change assume that climate change will be a gradual and smooth process. Recognizing the over-simplicity of this assumption, an extensive literature has developed examining integrated assessment and decision-making in the context of Article 2 (Jones, 2003) with a particular emphasis on abrupt change at global (Alley *et al.*, 2003; Azar and Lindgren, 2001, 2003; Wright and Erickson, 2003; Schneider and Azar, 2001; Higgins *et al.*, 2002; Baranzini at al, 2003) and regional scales (Rial *et al.*, 2004).

Several papers have focused on incorporating damages from large-scale climate instabilities into integrated assessment models, specifically on a climate change-induced shutdown of the MOC (Keller *et al.*, 2000; Mastrandrea and Schneider, 2001; Keller *et al.*, 2004; Link and Tol, 2004b). Quantifying market-based damages associated with MOC changes is a difficult task and current analyses might be best interpreted as order-of-magnitude estimates. These preliminary analyses suggest that significant reductions in anthropogenic greenhouse gas emissions may be an economically efficient investment given even small damages (less than 1% of gross world product) associated with a MOC collapse. However, model results are very dependent on assumptions about climate sensitivity, the damage functions for smooth and abrupt climate change, and time discounting.

Mastrandrea and Schneider (2004) implemented a probabilistic integrated assessment, generating probability distributions for future climate change based on uncertainty in key social and natural model parameters. They investigated the risk of exceeding probabilistic thresholds for DAI based on the IPCC “reasons for concern,” and developed relationships between the level of mitigation efforts and probability of exceeding thresholds for DAI. This analysis demonstrated that the establishment of climate mitigation policies can significantly reduce the probability of exceeding DAI thresholds (high confidence), although the authors caution against taking the model-dependent numerical results literally.

19.4.6. Cost-effectiveness analysis

Cost-effectiveness analysis involves determining cost-minimizing policy strategies that are compatible with pre-defined constraints on future climate change or its impacts. Such scenarios have proven to be valuable for exploring the tradeoffs between climate change impacts and the cost of emissions mitigation needed to achieve stabilization (Wigley *et al.*, 1996). Probabilistic analyses of this type derive pathways that reduce the risk of crossing climate or climate impact thresholds. This method has been applied to limit the risk of potentially abrupt changes such as an MOC collapse (Keller *et al.*, 2000, Keller *et al.*, 2004). The reductions in greenhouse gas emissions determined by cost-effectiveness analyses are much larger than the ones typically suggested by cost-benefit analyses neglecting such constraints, though cost-benefit analyses with large assumed damages from climate change also arrive at significant “optimal” abatement levels.

Some cost-effectiveness 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. Whether sequential decision strategies call for higher or lower near-term emission reductions than corresponding analyses without learning depends on the specific assumptions about the current uncertainties in key model parameters and their resolution in the future. The quantitative results of these analyses cannot carry high confide4nce 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). However, there is a general consensus that “moderate” abatement of

GHG emissions in the near term is a robust strategy across a wide range of possible stabilization targets that prevents substantial adjustment costs later (e.g., Yohe *et al*., 2004). Hence, these authors argue that the scientific uncertainty cannot by itself used as a justification for doing nothing today to mitigate potential climate damages.

19.4.7. Synthesis

The studies reviewed in this section diverge widely in their methodological approach, in the sophistication with which uncertainties are considered in physical, biological and social systems, and in how closely they approach an explicit examination of key vulnerabilities or DAI. The level of model sophistication varies from simple carbon cycle and climate models to highly aggregated integrated assessment models to comprehensive integrated assessment frameworks incorporating 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. Nor can conclusions from the literature for individual “reasons for concern” be equated with a single threshold for DAI. The following conclusions from literature since the TAR, however, are more robust:

1 Uncertainty prevails in analyses of response strategies to avoid key vulnerabilities or DAI. Therefore, deterministic studies alone may not provide sufficient information for the design of response strategies, as they cannot cover the full range of plausible outcomes that some policy makers may wish to be aware of. Probabilistic approaches motivated by risk management frameworks, since these cover a wider range of imaginable outcomes and some estimation of their relative likelihood, may thus be more useful for drawing policy-relevant conclusions, despite the large uncertainties they explicitly reveal (e.g., as anticipated in WG 2 TAR, Chapter 1 and demonstrated in more recent literature cited in this section).

2 Some large-scale singularities (e.g., abrupt or essentially irreversible changes) of the climate system can no longer be avoided with high confidence. Given historical climate change and the inertia of the climate system (Wigley, 2005), a small probability (of the order of several percent) of triggering such events remains even for stringent emission reductions (Rahmstorf and Zickfeld, 2005; Wigley, 2004).

3 Despite all the uncertainties and the many definitions of DAI, it is a robust finding across recent integrated assessments (see citations in this section) that any reduction in GHG emissions will reduce the risk of DAI. Postponement of emissions reductions, in contrast, increases the risk of DAI and, depending on the rate of learning that brings down costs of low-GHG emitting technologies, makes achievement of the lower range of stabilization targets (e.g., less than 500ppm CO2-equivalent) increasingly expensive or infeasible (except via overshoot scenarios).

4 Research results using different analytical methods indicate a high confidence that CO2 stabilization levels above 450 ppm eventually (in equilibrium) are likely to produce global mean warming in excess of 1°C-2°C above 1990 levels (O’Neill and Oppenheimer, 2002; Corfee- Morlot and Höhne, 2003; O’Neill and Oppenheimer, 2004; Hare and Meinshausen, 2005; Schneider and Mastrandrea, 2005). This level would likely be associated with wide-spread disruptions in many ecosystems (Hare, 2003); it could also induce significant shrinkage of the major ice sheets (Hansen, 2005; Oppenheimer and Alley, 2004, 2005).

19.5. Priorities for Research

[Not available in this FOD]

19.6. Conclusions

[Not available in this FOD]

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