IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review

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

Coordinating Lead Authors:
A. Patwardhan (India), S. Semenov (Russia), S. Schnieder (USA)

Lead Authors:
I. Burton (Canada), C. Magadza (Zimbabwe), M. Oppenheimer (USA), B.Pittock (Australia), A. Rahman (Bangladesh), J. Smith (USA), A. Suarez (Cuba), F. Yamin (UK)

Contributing Authors:
J. Corfee-Morlot (France), A. Finkel (USA), M. Fuessel (Germany), K. Keller (Germany), Dena MacMynowski (USA), M. Mastrandrea (USA), A Todorov (Bulgaria)

Review Editors:
R. Sukumar (India), J. Zillman (Australia)

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Executive Summary

Key vulnerabilities to climate change are risks from climate change that merit particular attention by policy-makers. The identification of key vulnerabilities is intended to provide guidance for identifying levels and rates of climate change that, in the terminology of UNFCCC Article 2, 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 informed by the state of scientific knowledge. No single metric can adequately describe the diversity of key vulnerabilities, nor determine their ranking.

The purpose of this chapter is to apply the concept of "key vulnerabilities" in the context of risks from climate change, and to provide an assessment of:

- interpretations of the concept in the literature, and criteria for identifying key vulnerabilities;
- specific risks related to climate-sensitive physical, biological, and social systems (as reported in WGI and WGII Chapters 3-16) that could be identified as key vulnerabilities; and
- adaptation and mitigation response strategies aimed at avoiding key vulnerabilities.

This chapter identifies seven criteria for assessing and defining key vulnerabilities:

- magnitude
- timing
- persistence and reversibility
- likelihood and confidence
- potential for adaptation
- distribution
- "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. Other key vulnerabilities are associated with "normative thresholds" that are related to smoothly-varying impacts of climate change deemed unacceptable by certain decision-makers. Key vulnerabilities are found in many climate-sensitive systems, including food production, health, water resources, coastal systems, global biogeochemical cycles, ice sheets, modes of oceanic and atmospheric circulation, ecosystems and biodiversity.

General conclusions include:

- Observed climate change to 2006 has been associated with some impacts that can be considered key vulnerabilities. Among these are increases in human mortality, loss of glaciers, and increases in extreme events such as intense tropical cyclones.
- Global mean temperature changes of up to 2ºC above ~1990 will exacerbate current key vulnerabilities and trigger others (high confidence), such as reduced food security in many low-latitude nations (medium confidence).
- Global mean temperature changes of 2 to 4 C above ~1990 will result in an increasing number of key vulnerabilities at all scales (high confidence), such as widespread loss of biodiversity and triggering of widespread deglaciation of major ice sheets.
- Global mean temperature changes greater than 4ºC above ~1990 will lead to major increases in vulnerability (very high confidence), exceeding the adaptive capacity of many systems.
- 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 due to projected increases in the magnitude and frequency of already-damaging extreme events.

Planned adaptation can significantly reduce many potentially dangerous impacts of climate change and reduce the risk from many key vulnerabilities. However, the technical, financial, and institutional capacity and the political motivation necessary for planning and implementing effective adaptations are currently quite limited in many regions. In addition, the risk-reducing potential of planned adaptation is either very limited or very costly for some key vulnerabilities, such as loss of biodiversity, melting of mountain glaciers 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 may be much higher.

The literature presents a wide range of views on the potential for adaptation to reduce the risks from climate change. However, it is consistent in suggesting that it will be much more difficult for both human and natural systems to adapt to larger magnitudes of global mean temperature change than to smaller ones, and that adaptation will be more difficult and/or costly for faster warming rates than for a slower warming.

Several decision-analytical approaches have been applied to assess the complex relationship between mitigation strategies and key vulnerabilities. Approaches that are prominent in the literature include: scenario analysis and analysis of stabilization targets, “guardrail” analysis, (probabilistic) cost-benefit analysis, and cost-effectiveness analysis. Though these categories encompass a very diverse set of studies, several conclusions are robust across most of the literature:

- Given the uncertainties in factors such as climate sensitivity, regional climate change, and vulnerability to climate change, a risk management framework is generally the most appropriate approach to address key vulnerabilities. However, the assignment of probabilities to specific key vulnerabilities is often very difficult due to 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 CO_2-equivalent) increasingly expensive or infeasible (except via overshoot scenarios).
- Some large-scale events (e.g., deglaciation of major ice sheets) can no longer be avoided with high confidence due to historical climate change and the inertia of the climate system. The probability of triggering such events (currently of the order of at least several percent in much of the literature) will continue to increase as long as greenhouse gas concentrations continue to increase.
- There is a high confidence that equilibrium CO_2 stabilization levels above 450 ppm could cause an increase in global mean temperature in excess of 2ºC above current levels, though the likelihood of this exceedence depends on the specific probability distribution assumed for climate sensitivity.

The “reasons for concern” identified in the TAR remain a viable framework to consider DAI issues. The literature 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, coastally bounded and mountain-top ecosystems. Furthermore, confidence has increased that a 1 to 2C increase in global mean temperature above current levels will pose significant risks to many unique and vulnerable systems, including many biodiversity hotspots.

2 Extreme Events. Recent extreme climate events (heat waves in Europe and South Asia, several very intense tropical cyclones, severe floods in many regions) have caused significant loss of life and property damage in developed as well as developing countries. While individual events cannot be attributed to anthropogenic climate change alone, recent research has shown that it is likely that human interference with the climate system has already significantly increased the risk of some highly damaging extreme events.

3 Distribution of Impacts. There is still high confidence that the distribution of climate impacts will be uneven and that low-latitude less-developed areas that have historically contributed little to anthropogenic climate change are generally at greatest risk. 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, 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 a preliminary representation of adaptation. Recent studies have included some of these previously neglected 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 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 reduce 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 for low levels of climate change.

5 Large-Scale Singularities. Recent studies indicate that the thresholds for triggering at least one large-scale singularity, deglaciation of the West Antarctica Ice Sheet (WAIS), may be lower than reported in the TAR. While there is no clear consensus yet, some studies indicate that a 1-2^{o}C global warming above current levels could trigger partial deglaciation of both WAIS and the Greenland ice sheets with rates of sea level rise up to 1m/century. The literature on thresholds for triggering a slowdown of the meridional overturning circulation (MOC) and net biogenic feedbacks on the carbon cycle is largely consistent with the TAR, and contains very few high confidence conclusions.

19.1 Introduction

19.1.1 Purpose, Scope and Structure of Chapter

Since the TAR, policymakers and the scientific community have increasingly turned their attention to which impacts might be considered “dangerous”, whether these are related to critical thresholds or levels of climate change that can be identified, and what response strategies may avoid such impacts. The identification of “key vulnerabilities” here is intended to provide guidance for identifying levels and rates of climate change that, in the terminology of UNFCCC Article 2 (see Box 19.1), may be considered “dangerous” by relevant decision-makers. Ultimately, the definition of “dangerous anthropogenic interference with the climate system” must incorporate value judgments concerning the unacceptability of a range of risks through a political process that is informed by scientific knowledge.

The purpose of this chapter is two-fold. First, it synthesizes information from Working Group I and Chapters 3-16 of this Report to assist policymakers in evaluating the risks inherent from varying levels of climate change. Accordingly, the analytic emphasis of this chapter is on people and systems that may be *adversely* affected by climate change, particularly where these impacts could have serious and/or irreversible consequences. Since a detailed description of climate impacts in all sectors and regions is beyond the scope of this chapter, readers are encouraged to turn to the executive summaries of the sectoral and regional chapter of this Report for a fuller accounting. Moreover, IPCC Plenary determined the remit of this chapter be focused on shedding light on key vulnerabilities and climate change risks, rather than assessing the literature for all the positive and negative impacts generated by climate change or attempting a normative trade-off analysis among and between human and natural systems. (The term “normative” is used in this chapter to refer to a process or statement that inherently involves subjective value judgements or beliefs.) Weighing the benefits of avoiding such climate-induced risks versus the costs of mitigation or adaptation, as well as the distribution of such costs and benefits (i.e., equity implications of such trade-offs), is beyond the charge to and scope of this chapter. However, the integrated assessment literature briefly summarized at the end does move toward that normative framework, though many more examples of that literature can be obtained in this Report in Chapter 20 and in Working Group III AR4. Furthermore, our focus is not to compare the value of marginal effects of climate change to the value of overall socio-economic developments paths, but rather we expect that individual decision makers will decide for themselves the extent to which they see merit in comparing marginal climatic costs or benefits to the scale of overall economic development pathways.

Second, the chapter provides an assessment of literature bearing on the contributions that various response strategies, such as stabilisation and mitigation/adaptation options, could make to avoiding or reducing risks. Finally, the chapter identifies research priorities for addressing current knowledge gaps.

The remainder of Section 19.1 presents the conceptual framework and the criteria used in this chapter to identify and assess key vulnerabilities from climate change. Section 19.3 presents selected vulnerabilities that could be considered “key” based on these criteria. As far as possible, key vulnerabilities are linked to specific levels of global mean temperature increase (above 1990-2000 levels; see Box 19.2). The link between key vulnerabilities and global mean temperatures is germane to assessing what can be considered “dangerous” climate change under Article 2 of the UNFCCC. Due to space limitations, Section 19.2 cannot provide an exhaustive list of key vulnerabilities. Those selected here represent the authors’ collective judgements, based on the criteria presented in Section 19.2, from a vast array of possible candidates suggested in the literature. Section 19.4 draws on the literature addressing the linkages between key vulnerabilities and strategies to avoid them by adaptation (Section 19.4.1) and mitigation (Section 19.4.2). Section 19.5 suggests research priorities for the natural and social sciences that may help provide relevant knowledge for assessing key vulnerabilities of climate change.

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."

Box 19:.2 Reference for Temperature Thresholds

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 1990-2000 levels, and perhaps only 1.3^{o}C above 2006 levels. Climate impact studies often assess changes in response to regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (see WGI Chapter 11) Unless specified otherwise, this chapter refers to global mean temperature change above 1990-2000 "current" levels, which reflects the most common metric used in the literature on key vulnerabilities.

19.1.2 Conceptual Framework for the Identification and Assessment of Key Vulnerabilities

19.1.2.1 Meaning of "key vulnerability"

The various research communities involved in climate change research conceptualize the term "vulnerability" in many different ways (Füssel, 2005; WGII Chapter 17). 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). Other scholars use the term "vulnerability" more specifically to describe properties of a system or community that make them susceptible to a range of hazards.

In accordance with the pertinent literature, the term "key vulnerability" is used here broadly in the context of potentially severe impacts of climate change that merit particular attention by policy makers because they endanger the lives or well-being of people or other valued attributes of climate-sensitive systems. The term "key vulnerability" may refer to the vulnerable system itself (e.g., low-lying islands or coastal cities), the impact to this system (e.g., flooding of coastal cities and agricultural lands or forced migration), or the mechanism causing these impacts (e.g., disintegration of West Antarctic Ice Sheet). Key vulnerabilities are found in many social, economic, biological and geophysical systems.

Studies of the risks from climate change have provided 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).

19.1.2.2 Scientific Assessment and Value Judgements

The assessment of key vulnerabilities involves substantial scientific uncertainties as well as value judgements. It requires consideration of important non-climatic developments that affect adaptive capacity, of the response of biophysical and socio-economic systems to changes in climatic and non-climatic conditions over time, of the potential for effective adaptation across regions, sectors and social groupings, and of value judgments about the acceptability of potential risks as well as of potential adaptation and mitigation measures. Therefore, scientists and analysts need to provide a "traceable account" (Moss and Schneider, 2000) of all relevant assumptions.
Scientific analysis can inform policy processes but choices about which vulnerabilities are "key" and preferences for policies appropriate for addressing them necessarily involve value judgements. The IPCC has repeatedly emphasized this point, for instance in the Synthesis Report of its Third Assessment Report: "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). While value judgements are necessarily subjective, they may be informed by ethical, moral, or religious arguments (e.g., MacIntyre, 1981; Forum on Religion and Ecology, 2004).

19.1.2.3 Article 2 UNFCCC

Article 2 of the UNFCCC leaves the definition of "dangerous" flexible, thereby allowing different interpretations and reinterpretations of what is dangerous (Oppenheimer, 2005; Leiserowitz, 2005). The question of which impacts might constitute "dangerous anthropogenic interference with the climate system" (DAI) in terms of Article 2 has attracted much attention only recently, and the literature still remains relatively sparse (Oppenheimer and Petsonk 2005)**.** Operationalising Article 2 requires, first, a scientific analysis of what impacts are expected for different level of greenhouse gas concentrations or climate change. Second, it requires a normative evaluation of which impacts are significant enough to constitute, individually or in combination, DAI. This assessment is informed by the magnitude of climate impacts as well as by their distribution across regions, sectors, population groups, and time (e.g., Mastrandrea and Schneider, 2005; Yamin *et al.*, 2005; Corfee-Morlot *et al.*, 2005). 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). The specific references in Article 2 to natural ecosystems, food production, and sustainable development provide some guidance as to which impacts may be considered in the definition of DAI.

Operationalisation of Article 2 is necessarily a dynamic process because the establishment of a specific level of greenhouse gas concentrations as "dangerous" may be modified based on changes in scientific knowledge, social values, and political priorities. One target that has received considerable attention in the literature is to limit global mean temperature increase to 2°C over pre-industrial levels (about 1.3^{o}C above 2006 levels). This goal was first adopted by the Council of the European

Union (1939th Council meeting, Luxembourg, 25 June 1996) and confirmed by the European Union Heads of Government in March 2005. Arguments for higher and lower suggested levels for a DAI GMT threshold are also available in recent literature.

19.1.2.4 Distribution and aggregation of impacts

Vulnerability to climate change differs considerably across socio-economic groups, thus raising important questions about equity. Most studies in the context of key vulnerabilities and Article 2 have focused 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). Vulnerability research in developed countries has often focused on groups of people, such as those living in coastal or flood prone regions (UKCIP, 2004) or socially vulnerable groups, like the elderly.

Many policy decisions require detailed information about who, where, and when will be hit hardest by climate change. Nevertheless, aggregation of impacts across different regions, sectors, and population groups can provide a concise "snapshot" of the expected consequences of climate change. This aggregation requires an understanding of (or assumptions about) the relative importance of impacts in different regions, sectors, and population groups. Consideration of fairness, justice, or equity adds a value-laden aspect to the assessment of the magnitude of impacts (Jamieson, 1992; Gardiner, 2004). 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 (Section 4.4 of Schneider, 2004; Jacoby, 2004).

19.1.2.5 Critical Levels and Thresholds

Article 2 of the UNFCCC defines international policy efforts in terms of avoidance of a level of greenhouse gas concentrations beyond which the effects of climate change would be considered to be "dangerous". Discussions about "dangerous interference with the climate system" and "key vulnerabilities" are also often framed around thresholds or critical limits (Patwardhan *et al.*, 2003; Izrael, 2004). Key vulnerabilities may be linked to systemic thresholds where nonlinear processes cause a system to shift from one major state to another (such as a sudden change in the Asian monsoon or the disintegration of the West Antarctic Ice Sheet). An obvious example of such a nonlinear process is the melting 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, and tourism, to name a few.

Smooth responses to climatic changes may also lead to damages that are considered 'unacceptable' after a certain point. For instance, even a gradual and smooth increase of sea-level rise will eventually reach a level that certain stakeholders would consider unacceptable, Such normative impact thresholds have been defined on the global level (e.g., Toth *et al.*, 2002 for natural ecosystems) and on the regional level (e.g., Jones, 2001 for irrigation in Australia).

19.2 Criteria for Selecting" Key" Vulnerabilities

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" dimensions of risk, respectively (Patwardhan *et al.*, 2003; Dessai *et al.*, 2004, Pittini and Rahman, 2004). More objective, or factual, criteria include the scale, magnitude, timing and persistence of the harmful impact, and the confidence in the climate change-impact relationship (Parry *et al.*, 1996; Kenny *et al.*, 2000; 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 influenced by the perception of different risks, which depend on the cultural and social context (e.g. Slovic, 2000). Different decision makers are thus likely to perceive different vulnerabilities as "key".

The criteria that gave rise to the selection of key vulnerabilities in this chapter are explained below. Similar criteria have been proposed by Goklany (2002).

Magnitude

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

Various aggregate metrics are used to describe the magnitude of climate impacts. The most widely used quantitative measures for climate impacts are monetary units such as income or revenue losses (e.g. Nordhaus and Boyer, 2000), costs of anticipating and adapting to certain biophysical impacts such as a large sea level rise (e.g. Nicholls, 2004), and estimates of people's willingness to pay to avoid (or accept as compensation for) certain climate 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; Füssel *et al.*, 2003; Parry *et al.*, 2004) and species extinction numbers or rates (AR4 WGII Ch.4; Thomas *et al.*, 2004). For some impacts, qualitative rankings of magnitude are more appropriate than quantitative ones. Qualitative methods have been applied to reflect social preferences related to the potential loss of cultural or national identity, loss of cultural heritage sites, and loss of biodiversity (Schneider *et al.*, 2000).

Timing

A harmful impact is more likely to be considered "key" if it is expected to happen soon rather than in the distant future (Bazerman 2005; Weber 2005). Impacts occurring further in the future, which are caused by near-term events or forcings, may also be considered "key." An often cited example of such "delayed irreversibility" is the disintegration of the West Antarctic Ice Sheet, where an irreversible dynamic collapse may be triggered before significant observable effects occur. Debates over an "appropriate" rate of time preference for such events (i.e., discounting) are widespread in the integrated assessment literature, and can influence the extent to which a decision maker might label such possibilities as "key". Another important aspect of timing is the rate at which impacts occur. In general, adverse impacts occurring suddenly (and surprisingly) are perceived as more dangerous than the same impacts occurring gradually, as they limit the potential for adaptation for both human and 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 (Niemeyer *et al.*2005). Climate change in the 20th century has already lead to numerous impacts on natural and social systems (see WG II Chapter 1), some of which may be considered "key".

Persistence and reversibility

A harmful impact is more likely to be considered "key" if it is persistent, or even irreversible. Examples of impacts that could 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), certain land cover changes (Cowling *et al.*, 2004), and the loss of unique cultures (Barnett and Adger, 2003). Examples of loss of unique cultures 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.

Likelihood and confidence

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 aggregate economic impacts (Nordhaus, 1994), of uncertain parameters of the climate system (Morgan and Keith, 1995; Morgan *et al.*, 2006) or of certain large-scale climate events (Arnell *et al.*, 2005), the likelihood can be framed as the central value of the probability distribution, whereas the confidence is reflected primarily by its spread (the lesser the spread, the higher the confidence). An impact with a high likelihood is more apt to be seen as "key" than an impact of similar magnitude but with a lower likelihood of occurrence. Other things being equal, the more risk-averse a stakeholder is, the more attention will be given to impacts whose likelihood can only be determined with low confidence compared to similar impacts with high confidence in the likelihood estimates, since low confidence implies a less well-bounded characterization of potentially severe risks. On the other hand, 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, societies and nature to adapt to or ameliorate adverse impacts must be considered (see Section 19.3.1 and WGII Chapter 17). The lower the availability and feasibility of effective adaptations, the more likely such impacts would be characterized as "key vulnerabilities". The potential for adaptation to ameliorate the impacts of climate change differs between and within regions and sectors (e.g., O'Brien *et al.*, 2004). While there is often considerable scope for adaptation in agriculture and in some other highly managed sectors, there is much less scope for adaptation to some impacts of sea-level rise, and there are no realistic options for preserving endemic species in areas that become climatically unsuitable (see Chapter 17). Adaptation assessments need to consider not only the technical feasibility of certain adaptations but also the availability of required resources, 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.

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

Distribution

The distribution of climate impacts across regions and population groups raises important equity issues (see Section 19.1.2.3). In particular, the adverse impacts of current and future climate change and the benefits from past and current greenhouse gas emissions are very unequally distributed (Müller, 2002). Based on fairness arguments, decision-makers may therefore be more likely to consider impacts as “key” if they affect regions or population groups whose past and current contribution to anthropogenic climate change was small compared to groups with a more greenhouse gas-intense lifestyle, particularly if the relative severity of potential impacts, and ability to adapt to them, were greater for those who contributed less to the problem.

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 many endemic species or contains endangered charismatic species. If the livelihoods of people depend crucially on the functioning of a natural system, this system may be regarded as more important than a similar system 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 those with more anthropocentric views may judge importance primarily based on their provision of goods and services to humans. Moreover, aggregating various metrics to measure the value of such goods and services involves a normative analysis.

19.3 Identification and Assessment of Key Vulnerabilities

This section discusses what the authors have identified as possible key vulnerabilities based on the criteria specified in the Introduction and Section 19.2, and on the literature on impacts that may be considered potentially “dangerous” in the sense of Article 2. The key vulnerabilities identified in this section are, as noted earlier, meant to be an illustrative, not comprehensive list. Section 19.3.1 introduces key vulnerabilities, organizing them by reasons for concern as well as by type of system, i.e., market, social, ecological, or geophysical. The following sections discuss some of the key vulnerabilities by type of system.

19.3.1. Introduction to Tables 19.1 and 19.2

Tables 19.1 and 19.2 give short summaries of some vulnerabilities, which in the judgement of the authors of this chapter, in the light of earlier chapters of Working Groups 1 and 2, may be considered “key” according to the criteria set out above in 19.2. Some candidates for key vulnerabilities are set out in Table 19.1 under the classification of the five “reasons for concern” presented in the Third Assessment Report, WG2, Chapter 19. These key vulnerabilities are listed with cross-references to earlier chapters. The main criteria for listing the particular impacted sectors, systems or regions as key vulnerabilities are given in column 2, while column 3 briefly discusses, where known, critical levels of global warming the timing of impacts and the confidence in statements. The table is not a complete list, and some entries could be sub-divided on a more regional or specific basis.

In Table 19.2 a more detailed list of key vulnerabilities is given, with an attempt to describe, as quantitatively as possible from the literature, how the impacts vary by global mean temperature increase above 1990 levels (with the author's confidence estimates attached). This mainly refers to the long-term increase in temperature. Where known, the table presents information regarding dependence of effects on rates of warming, duration of the changes, exposure to the stresses and adaptation taking into account uncertainties regarding socio-economic development. However, only in a few cases does the literature address duration of warming and its consequences.

As entries in both tables are necessarily short, reference should be made to relevant chapters and to the accompanying text in this chapter for more detailed information, including additional caveats where applicable

Table 19.1: *A list of candidate key vulnerabilities, classified according to the TAR reasons for concern. See text and cross-references to other chapters in AR4 for more details than is possible in this condensed table. Note that all criteria for inclusion are not listed and that this table is not quantitative. It is an illustrative reflection of the scientific judgement of the authors, taking account of critical comments received. Temperatures are increases in global mean temperature above 1990.*

Key Vulnerability (Cross-references)	Criteria for "key"	Remarks on critical level, timings and confidence
Risks to unique and threatened systems		
Glaciers and small ice sheets (WGI Ch.4, WGII Ch.3)	Widespread melting with adverse consequences for many ecosystems and communities	Already occurring, very likely many would disappear at several ºC warming this century
Terrestrial ecosystems (Ch.4)	Bounded ecosystems such as coastal, mountain and remnant already threatened	Many ecosystems already being affected and widespread disruption at at 1-2ºC or more (high confidence)
Forests threatened by drought and fire (Ch.5)	Large areas such as in Mediterranean climates and boreal regions vulnerable.	Increased drought and fire frequency evident at warmings <2ºC (medium to high confidence)
Ocean ecosystems (Ch.4)	Vulnerable to increased acidification, warming and decreased vertical mixing, notably coral reefs	Coral reefs threatened at 1ºC warming (high confidence). Effects of acidification complex and poorly understood
Closed lakes (Ch.3 and regional chapters)	Widespread, multiple stresses exacerbated by climate change, valuable fisheries and ecosystems.	Many already stressed, widely distributed (medium to high confidence)
Risks from extreme events		
Coastal communities (Ch.6)	Sea-level rise (SLR) and increased storm surge threatens infrastructure, protective barrier dunes, mangroves and levees.	Vulnerability under present climate variability will increase non-linearly as design criteria exceeded (high confidence). Population and economic growth will increase exposure, but vulnerability can be partially reduced through adaptation.
Infrastructure Ch.7)	Non-linear impacts due to design criteria being exceeded by increased intensity and/or frequency of extreme events.	Rapidly increasing damages (high confidence), though much can be reduced by more stringent zoning, design criteria and retrofitting.
Distribution of impacts		
Indigenous, poor or isolated communities (Ch.7, 8 and regional chapters)	Water supply, health and infrastructure vulnerable to extreme events, disease, sea-level rise, etc., with low adaptive capacity.	Some communities already affected (e.g., Arctic, low-lying islands) (high confidence). Thresholds are site-specific.

Key Vulnerability (Cross-references)	**Criteria for "key"**	**Remarks on critical level, timings and confidence**
Cross-border issues (Chs. 7, 17?)	Potential dislocation of large populations due to climate change and SLR, increasing economic inequities. Risk of exacerbating disputes over water management in multi-national river basins.	Regional migrations already occur with climate a contributing factor. Future socioeconomic conditions are highly uncertain making prediction difficult, although SLR will displace many people. (low confidence)
Regional Systems (Chs. 15, 9 and 12)	Many Arctic systems vulnerable to permafrost melting, sea –ice retreat etc. Africa vulnerable to decreased food production and extreme events. Europe vulnerable to increased drought in south and floods in north. Low-lying islands and coasts highly vulnerable.	Varying regional vulnerability likely to increase inequities and cause pressures for internal and external migration, external aid etc. Implementation of adaptive potential for Arctic and particularly Africa are uncertain.
Aggregate impacts		
Economic production/welfare (Ch.7, 20)	Widely used economic measure (however results vary with weighting schemes, treatment of non-market goods and extreme events)	Low confidence over extent to which aggregate GDP increases or decreases below approximately 2^o warming whereas GDP decreases are typically projected above 3^oC.
Crops and food supplies (Ch.5 and regional chapters)	Vital welfare measure. Large regional differences in impacts. Welfare outcome depends on aid and trade capacity.	Initial negative impacts at small warmings in warm regions and positive impacts in cool regions, wider negative impacts at large warmings (low confidence). High adaptive capacity in many regions; tends to be lower in poorer regions.
Health (Ch.8)	Climate change is already affecting health, and is projected to increase morbidity and mortality due to malnutrition, diarrheal diseases, certain vector-borne diseases, water-borne diseases, air pollution, heat waves, and other extreme events.	Aggregate health impacts likely to increase incrementally with increasing climate change. Thresholds will appear at local scales due to unique characteristics of population vulnerability, disease transmission, and other factors. Adaptive capacity high, but actual responses will vary widely according to income and resources etc.
Water supply (Ch.3)	Vital welfare measure. Large regional variations with more runoff at high latitudes but less especially in Mediterranean type climates. Reduced snow and ice storage reduces reliability.	Critical levels will vary with location. Some regions already stressed. Strong interplay with other stresses and socio-economic change. Marginal change due to climate change vital in some locations. (varying levels of confidence)
Risks from large-scale discontinuities and irreversible changes		
MOC/THC (WGI, Ch.x)	Slowdown may be observed already, cessation possible, widespread impacts possible. May be irreversible.	Slowdown this century (medium confidence). Cessation possible next century (medium confidence). Societal consequences mostly uncertain.
Greenland Ice Sheet, West	Triggering of partial deglaciation possible at 1-2	Much debate about rapidity of onset. Ongoing Greenland melting

Key Vulnerability (Cross-references)	**Criteria for “key”**	**Remarks on critical level, timings and confidence**
Antarctic Ice Sheet (WGI, Ch.10)	ºC. Potential for ten or more metres SLR over several centuries to millennium above 2.5-5 º C.	likely this century. WAIS disintegration more uncertain, with models of new mechanisms not yet available. Because of long time frame, adaptation potential uncertain, but may require massive relocation of coastal populations and loss of coastal ecosystems.
Biospheric positive feedbacks (WGI, Ch.7, 10 and WGII Ch.4)	Climate change reduces the efficiency of the Earth system to absorb anthropogenic carbon dioxide due to a reduction of land carbon uptake, leading to accelerated global warming.	Some observations suggest process may be starting now, e.g., permafrost melting, and observed biospheric sources of CO_2 under drought and fire conditions.
Methane stores destabilised (WGI, Ch.?, WGII Ch.4).)	Large stores of methane could be released by permafrost melting or destabilisation of hydrates on sea floor, leading to accelerated global warming.	Permafrost already melting. Sea floor hydrates destabilised by warming at ocean depth but stabilised by SLR. Which effect dominates may vary by region. Magnitude and timing highly uncertain.

Table 19.2: *Table of selected key vulnerabilities for which there are reasonable estimates of magnitude of impacts triggered at specified levels of global mean warming. This list is not ordered by priority or severity but by category of system either affected or which causes vulnerability. The categories range from economic systems, for which adaptation potential is greatest, to geophysical systems, which typically have least adaptive capacity. Extreme events are a class of causes of vulnerability, and for these adaptation applies to the affected systems, which are largely socio-economic. Entries are necessarily brief to limit the size of the table, so further details, caveats and supporting evidence should be sought in the accompanying text, cross-references and in the primary scientific studies referenced in this and other chapters of the AR4. In many cases climate change impacts are marginal or synergistic on top of other existing and often increasing stresses.*

Selected KVs:	<2ºC above 1990 (confidence)	2-4ºC above 1990 (confidence)	>4ºC above 1990 (confidence)	Remarks: [rate information, duration, exposure]
Market Systems				
Food Supply	Reduced low-latitude production (low confidence). Potential for increased global production (low confidence)	Global production peaks and begins to decline (low confidence)	Further declines in global production (low to medium confidence)	High adaptive potential, unevenly distributed, realization of potential uncertain.
Infrastructure	Some increased damages likely	Rapidly increasing damages as design criteria are exceeded (high confidence)	Further rapid increases in damages (high confidence)	Adaptation generally possible with anticipation, but retrofitting particularly expensive. Adaptation costs include increased energy demand. Faster rates of change can greatly increase costs.
Net Market Impacts	Net market impacts plus or minus a few percent of GDP (low confidence). Developing countries likely to have greater percent losses	Net market impacts could peak or continue to decline with increasing losses in developing countries (low confidence)	Projected to be net losses with increasing losses at higher temperatures (medium confidence)	It is difficult to account for all market sector costs, the consequences of development, and actual implementation of adaptation.
Social Systems				
Water Supply	Many regions already stressed, especially in Mediterranean type climates, reach critical levels (high confidence)	Many regions presently only mildly stressed experience increased stress (high confidence). Those regions include areas fed by snow or glacier melt that lose	Many regions are severely stressed, requiring extreme adaptations such as out migration. (medium confidence)	Many adaptations available in low stressed regions such as improved water use efficiency and use of water pricing. More costly adaptations include irrigation and desalinization. These have environmental and energy costs.

Selected KVs:	**<2ºC above 1990 (confidence)**	**2-4ºC above 1990 (confidence)**	**>4ºC above 1990 (confidence)**	**Remarks: [rate information, duration, exposure]**
		storage capacity.		
Coastal Resources	Storm surge, wave erosion and salinisation affect many low-lying communities but many of them can adapt (high confidence).	Adverse effects increase and adaptation becomes more expensive and less satisfactory (e.g., need for retreat or abandonment)	Many communities become too expensive to protect, with out migration necessary (medium to high confidence).	Adaptation requires foresight, large expenditures of money and energy, and can include losses of amenity and natural ecosystems. For large sea level rises (~metres) large populations will need to move.
Health	Climate change increasing morbidity and mortality due to malnutrition, diarrhoeal diseases, malaria, heat waves, and floods. (low to medium confidence)	Increasing health risks, resulting from such factors as malnutrition, infectious diseases, air pollution, and weather disasters, unless effective adaptation measures are implemented (medium confidence).	Further increased health risks in many regions (medium confidence).	Aggregate health impacts likely to increase incrementally with increasing climate change. Thresholds will appear at local scales due to unique characteristics of population vulnerability, disease transmission, and other factors. Climate change will increase the pressures on disease control activities. Status of public health infrastructure and disease control activities are critical. (Medium-high confidence).
High-Mountain Communities	Glacial melt is causing flooding in some areas, shifts in ecosystems and water security problems due to decreased storage.	Further loss of glaciers and shifts in ecosystems; increased flooding e.g., in Himalayas (medium to confidence)	Widespread impacts on most communities (high confidence). Many areas will lose their mountain glaciers.	Loss of glacier storage will reduce ability to even out seasonal flows and droughts, leading to water supply insecurity. Glacier lake outburst floods are an increasing issue (see Asia chapter)
Indigenous, poor or isolated communities	Many of these communities are already stressed. Climate change and sea level rise adds significantly to other stresses (medium confidence).	Communities in low-lying coastal and arid areas are especially threatened (high confidence)	Many of these communities may need to be abandoned (medium confidence).	Adaptation is difficult in these communities without large outside support.
Cross-Border Issues	It is possible, but speculative, that extreme events such as droughts and floods, inundation of	Higher magnitudes of climate change more likely to contribute to cross-border	Higher magnitudes of climate change even more likely to contribute	It is very difficult to project cross-border crises such as migration. Many factors such as governance, development and adaptation, will play a critical role. Climate change is likely to increase the potential for

Selected KVs:	**<2ºC above 1990 (confidence)**	**2-4ºC above 1990 (confidence)**	**>4ºC above 1990 (confidence)**	**Remarks: [rate information, duration, exposure]**
	low-lying areas can trigger migrations or exacerbate regional tensions. Difficult to associate with specific thresholds.	issues.	to cross-border issues.	problems, perhaps by exacerbating existing resource constraints and tensions.
Biological Systems				
Ocean Systems	Widespread bleaching of coral reefs*. 5-18% of coastal wetlands lost with a 40-cm SLR	Repeated intense bleaching and death of coral reefs (high confidence). Up to 38% loss of coastal wetlands with a 75-cm SLR	Potential regional extinction of coral reefs.	Limited adaptation possible for low rates of warming. Acidification of oceans and more intense storms will exacerbate problems.
Biodiversity	Many species in bounded ecosystems are already affected, with effects increasing rapidly. Loss of up to a quarter of species (medium confidence). Almost half of ecosystems cannot adapt (medium confidence.)	Loss of one-third of species. About two thirds of ecosystems cannot adapt (medium confidence).	Extinctions are widespread with additional effects on dependent species and ecosystem services (high confidence).	Rapid warming or rainfall changes will exceed natural rates of adaptation. Loss of species is irreversible.
Forests	Widespread impacts, notably during droughts and from more frequent and extensive fire. Increased productivity possible (medium confidence).	Large areas of forest are threatened with fire, disease, and change to savannah or grassland (medium confidence). Productivity of vegetation will peak. (medium confidence).	Large shifts in most natural and managed forests (high confidence). Loss of biomass in temperate and boreal forests amplifying global warming. (medium confidence)	While there can be beneficial impacts from longer growing season in higher latitudes and carbon fertilization, increased stress from higher temperatures, drought, fires, insects, and disease likely in the long run reduce forest productivity, and highly likely to change ecosystem types.
Rivers and Closed	Closed lakes are especially vulnerable	Many closed lakes dry (low to medium confidence).	Further adverse ecological impacts (high	Changes in runoff, flow, lake levels, as well as chemical changes to water bodies are likely to

Selected KVs:	**<2ºC above 1990 (confidence)**	**2-4ºC above 1990 (confidence)**	**>4ºC above 1990 (confidence)**	**Remarks: [rate information, duration, exposure]**
Lakes	(medium to high confidence). Higher flows in many northern rivers increase flooding and bank erosion (medium confidence).	Low flow, stratification, and eutrophication events greatly increase. Biological productivity decreases (high confidence). Increased floods occur in many regions (medium to high confidence).	confidence).	adversely affect freshwater biodiversity and could reduce productivity. Changes in food chains likely to lead to collapse of pelagic inland fisheries in low latitude lakes. Adaptations may be expensive and have ecological consequences.
Geophysical Systems				
MOC	Some weakening* (medium confidence)	Considerable weakening (high confidence), triggering shutdown (low confidence)	Considerable weakening (very high confidence), shutdown occurs (low to medium confidence)	Simplified models show shutdown for warming above ~3ºC by 2100. The shutdown likelihood increases with the rate of warming and the stabilization level. The recovery time after a shutdown would be several centuries.
WAIS	Localized grounding line retreat* (high confidence)	Widespread deglaciation triggered (medium confidence)	Complete deglaciation triggered above 4-5 C (medium confidence). Several centuries to millennia for ~5m sea level rise (medium to high confidence)	Complete deglaciation is effectively irreversible. The WAIS contribution to sea level rise may be up to 1m/century (medium confidence).
Greenland IS	Localized deglaciation* (high confidence)	Widespread to complete deglaciation triggered (high confidence)	Complete deglaciation triggered (medium to high confidence). Commitment to ~7m sea level rise (high confidence)	Rate of deglaciation increases with regional warming. Full deglaciation takes several centuries to millennia.
Arctic		?	?	
Extreme Events				
Tropical Cyclone Intensity	Considerable increase in Cat. 4-5 storms* (medium to high	Further increase in tropical cyclone intensity (high confidence.)	Even greater increase in storm intensity (high confidence.)	Change in frequency, location, and duration of tropical cyclone season still speculative—WG1 3.8). Regional shifts appear likely due to regional changes in sea

Selected KVs:	**<2ºC above 1990 (confidence)**	**2-4ºC above 1990 (confidence)**	**>4ºC above 1990 (confidence)**	**Remarks: [rate information, duration, exposure]**
	confidence)			surface temperatures and ocean circulation (Anthes *et al.*, BAMS in press)
Flooding	Increases in flash flooding occur in many regions due to increased rainfall intensity*[WG1 3.8], particularly in large basins in mid and high latitudes (medium confidence).	Increased flooding in many regions due to greater increase in winter rainfall exacerbated by loss of winter snow storage. Greater risk of dam burst in glacial mountain lakes (high confidence).	Large river flooding in northern North America and Eurasia becomes frequent, especially in winter (high confidence).	Flooding may be exacerbated by loss of forest cover from episodic drought and fire, with changes in river characteristics due to large sediment loadings and bank erosion. Adaptation capacity varies, but will involve costs. Impacts could involve much damage and dislocation, especially if the rate of change is large.
Heat	Increased heat stress and heat waves, especially in continental areas (very high confidence)	Frequency of heat waves (according to current classification) will increase rapidly, causing increased mortality (high confidence).	Frequency of hot days will be much greater, with many locations untenable without changes in infrastructure and other adaptations .	Most mortality from heat waves can be substantially avoided by adaptation. However, adaptation via early warning systems, provision of cooling offset infrastructure, and other measures will impose costs and increase energy demand.
Drought	Increasing frequency and intensity of drought in mid-latitude continental areas[*WG 1 3.3] (high confidence)	Intensity of droughts will continue to increase (high confidence).	Conditions expected to be more extreme (high confidence)	Droughts are already increasing and expected to increase in severity and frequency with additional warming. Loss of winter snow and glacier storage will exacerbate problem. Thresholds and adaptive capacity vary widely.
Fire	Increased fire frequency and intensity in many areas, particularly arid and semi-arid areas (high confidence).	Frequency and intensity likely to be greater (high confidence)	Conditions expected to be more extreme (high confidence)	Decreased precipitation will likely increase frequency of fires. In arid climates, fire frequency can increase even with increased precipitation with large enough warming. In particular, it can increase biomass, thus resulting in larger fires. Fire fighting capacity can be stepped up, but extreme conditions can overwhelm most fire-fighting efforts.

*Some observational evidence, see WG-1

**Marginal changes on top of baseline changes

19.3.2 Market Systems

Market systems are those by which interactions are primarily, but not exclusively, economic. They often involve provision and sale of goods and services in formal or informal markets. They are often considered to be an important component of sustainable development.

19.3.2.1 Agriculture

Agricultural impacts are probably the largest among all market system impacts from climate change. Ensuring that food production is not threatened is an explicit criterion of UNFCCC Article 2. Chapter 5 notes with high confidence that agricultural systems will be affected differently depending on location and type of crop. In general, low-latitude areas are most at risk because of potential reductions in grain yields combined with fewer financial and technological resources to adapt to climate change (see Chapter 5). In spite of this, there is low confidence that global agricultural production could increase up to 2.5 to 3.5^{o}C of warming (approximately above 1990). Beyond 2^{o}C, yields of many crops in temperate regions are projected to decline (low confidence). So, beyond that level of warming, marginal global production may decline because of climate change. With higher increases in GMT, the marginal decline continues. Part of the reason there is low confidence in this finding is that most studies on global agriculture have not yet incorporated a number of critical factors, including changes in extreme events or spread of pests and disease (Climate Risk Management Limited, 2005; Rosenzweig *et al.,* 2002; Hallegate *et al.*, forthcoming). In addition, they have not considered development of specific practices or technologies to aid adaptation. Adaptation at the farm level and through market adjustments could play a significant role to limit the adverse impacts of climate change (Callaway, 2004).

19.3.2.2 Other Sectors

Other market systems could also be affected by climate change. These include livestock, forestry, and fisheries industries, which could be directly affected as climate affects the quality and extent of rangeland for animals, soil and other growing conditions for trees, and freshwater aquatic and marine ecosystems for fish. Other sectors are also sensitive to climate change. These include energy, construction, insurance, tourism and recreation. The aggregate effect of climate change on many of these sectors has received little attention in the literature and remains highly uncertain. Some may see shifts in expenditures, some may see contraction, and some could see net expansions. Yet, for some sectors, such as insurance, the impacts of climate change may well be negative [see Chapter 7]. The major reinsurance companies are at risk from very large claims from catastrophic losses in events such as Hurricane Katrina, which has been the most costly event (both natural and human induced) for the insurance industry ever (Munich Re 2006). The adaptive response of the industry is likely to be a reduction in the share of risk they will accept (primary insurance companies will be able to pass on less risk to reinsurers), and the raising of premiums (Mills, 2005).

Other sectors such as tourism and recreation may also see substantial shifts (e.g., reduction in ski season, loss of some ski areas, shifts in tourism because of changes in climate and extreme events). Global net energy demand is likely to change (Tol, 2002b) eventually increase as air conditioning demand increases sufficiently to eventually overcome the energy savings from lower heating demands (low confidence). What global average temperature is associated with minimum energy demand (and thus above it would have a net increase in energy demand) is uncertain (Hitz and Smith, 2004).

19.3.2.3 Aggregate Market Impacts

Estimating total economic impacts from climate change is highly uncertain. Total economic impacts may be in the range of a few percent of global product (see Chapter 20). While it is possible that gross world product could increase up to about 2°C warming, largely because of estimated direct CO_2 effects on agriculture, whether global world product increases or decreases is highly uncertain. Above this level of warming, most studies indicate that gross world product could decrease. For example, Tol (2002a) estimates net positive global market impacts at 1°C when weighting by economic output, but finds net negative impacts when weighting by population. Nordhaus (2006) uses geographical weighted output and finds more negative economic impacts than previous studies, although still in the range of a few percent of gross world product. How to value impacts in various metrics other than market systems (e.g., losses in human life, species lost, distributional inequity, etc.) is deeply normative and limits the confidence that can be assessed for analyses of aggregate impacts (see 19.1.2).

19.3.2.4 Distribution of Impacts

The global figures mask substantial variation at the national or local scale. Even if gross world product were to change just a few percent, national economies could be reduced by relatively larger amounts. All studies with regional detail show Africa, for example, with climate damages on the order of several percent of GDP at 2°C increase in GMT or even lower levels of warming. (see Chapter 7).

19.3.3. Societal Systems

Societal systems exist to secure the health and well-being of humans and society by meeting fundamental needs such as the provision food and water as well as essential services such as education, housing and health care. The type and level of such goods and services a person or group receives varies from society to society depending on the level of resources available and the effectiveness of legal and political systems. Formal institutions such as states and regulated markets tend to underpin provision of basic goods and social services in the developed world, informal social institutions, such as families and community groups, tend to dominate or may be the only service providers in much of the developing world, particularly in rural areas or areas subject to conflict.

The resulting differences in type and level of provisions of basic goods and social services means there is no single threshold beyond which it is clear that most or all societal systems are vulnerable to climate change. There are, instead, a myriad of thresholds, specific to particular groups, systems at specific timeframes beyond which they can be vulnerable to variability and to climate change. These differences in vulnerability are a function of a number of factors. Exposure is one key factor. For example, communities in low lying areas are more exposed to sea level rise or storm surges.

A second key factor affecting vulnerability is the capacity of social systems to adapt to their environment, including coping with the threats it may pose and taking advantage of beneficial changes. Smit *et al.* (2001) identified a number of determinants of adaptive capacity, including such factors as wealth, societal organization, and access to technology (see also Yohe and Tol, 2002). These attributes differentiate vulnerability to climate change across societies facing similar exposure. For example, Nicholls (2004) and Nicholls and Tol (in press) find that level of development and population growth are very important factors affecting vulnerability to sea level rise. However, comparisons across countries or continents can mask differentiation of vulnerability at finer scales. For example, the specific vulnerabilities of communities with climate related risks, such as the elderly and the poor, are typically much higher than for the population as a whole.

Human health and water resources are key societal systems where there are many vulnerabilities at different scales. It is estimated that a global mean temperature increase of 2 to 3°C above 1990 will place an additional 80-125 million people (±10 million) at risk of hunger by the 2080s (Parry *et al.*, 1999). Hundreds of millions of people are estimated to live in areas that will face increased risk of malaria with a global mean temperature increase of 1 to 2°C. Further increases in temperature could increase the number of people at risk, while decreasing risk in some areas. Development and adaptation are key factors affecting human health risk (see Chapter 8).

Vulnerability associated with water resources are complex because vulnerability is quite region specific. In addition, the level of development and adaptation are very important factors in determining vulnerability of water supplies. Studies differ as to whether climate change will increase or decrease the number of people living in water stressed areas (e.g., Parry *et al.*, 1999; Arnell, 2004; Alcamo, 2005; Hitz and Smith, 2004). Hundreds of millions of people can be affected by changes in water quantity and quality.

19.3.3.1 Regional vulnerabilities

Many of the societal impacts discussed above will be realized within the regions assessed as part of the IPCC 4AR. Vulnerabilities that appear to be key for particular regions are incorporated into Table 19.1. Other chapters in this volume address vulnerabilities at the regional or local scale and some brief examples are given below.

In relation to the criteria for key set out in section 19.2, one of the most salient key vulnerabilities for Africa is greater risks of food insecurity from recurrent drought and land degradation, particularly for communities and countries already on the margins of food production. About three-fourths of the people estimated to be at increased risk of hunger from climate change are projected to be African (Parry *et al.*, 1999; see Chapter 9 for additional discussion).

Human settlements in polar regions are already being adversely affected by reduction in ice coverage and coastal erosion (see Chapters 6, 7, and 15). Future climate change may result in additional disruption of traditional cultures and loss of communities. For example, warming of freshwater sources may pose risks to human health because of transmission of disease (Martin *et al.*, 2005). Shifts in ecosystems will most likely alter traditional use of natural resources, and hence, lifestyles.

Many islands are already experiencing some negative effects of climate change. The long-term sustainability of societies of small islands is at great risk from climate change with sea level rise and extreme events posing special challenges on account of the limited size, proneness to natural hazards and external shocks combing with limited adaptive capacity and high costs relative to GDP. Subsistence and commercial agriculture on small islands will be further impacted by climate change and sea-level rise, as a result of inundation, seawater intrusion into freshwater lenses, soil salinization, decline in water supply and deterioration of water quality. A group of low islands such as Tarawa, Kiribati, could face average annual damages of more than 8 million to 16 million USD a year (equivalent to 17-18 percent of Kiribati's GDP in 2002; see Chapter 16).

Even in developed countries, there can be many vulnerabilities. Impacts to human settlements in the Arctic is one example of such vulnerabilities. Arnell (2004) estimated there will be a 40 to 50% reduction in runoff in southern Europe by the 2080s (associated with a 2 to 3°C increase in global mean temperature). Fires could increase in arid and semi-arid areas such as in Australia and the western U.S. Climate change is likely to increase the frequency and intensity of extreme heat events, as well as concentrations of air pollutants, such as ozone, which increase mortality and morbidity in urban areas (see Chapters 8, 11, 12, and 14).

19.3.4 Ecosystems and Biodiversity

Climate change is expected to result in substantial disruption of many ecosystems and loss of biodiversity. The loss of diversity is expected to include extinction of many species and reduction in the diversity of ecosystems. Vulnerability of ecosystems and species is partly a function of the expected rapid rate of climate change relative to the resilience of many such systems. 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.

Climate change is already affecting species and ecosystems around the world (Root *et al.*, 2003; Parmesan and Yohe, 2003) and may be adversely affecting many species and ecosystems. For example, the extent and diversity of polar and tundra ecosystems is in decline. Pests and disease have been spreading to higher latitudes and altitudes. While attribution is complex and the changes may be the result of many factors, climate change appears likely to be a contributing factor. Indeed, impacts on ecosystems appear to be happening more rapidly than scientists thought would happen (Chapter 4).

Further warming is likely to cause additional adverse impacts to ecosystems and biodiversity. Each additional degree of warming increases disruption of ecosystems and loss of species. Individual species and ecosystems may have specific thresholds of change in temperature, precipitation or other variables, beyond which they are at risk of disruption or extinction. Looking across the many ecosystems and thousands of species at risk of climate change, there appears to be a continuum of increasing risk of loss of ecosystems and species as the magnitude of climate change increases, though individual confidence levels will be hard to assess.

- A few tenths of a degree of additional warming can cause harm to such ecosystems as coral reefs and the South African Karoo.
- A warming of 1°C above 1990 levels could result in bleaching of four-fifths of coral reefs and 10% of global ecosystems losing area. Thomas *et al.* (2004) estimate that almost one-fifth of species could become extinct.
- A warming of 2°C above 1990 levels is estimated to result in bleaching of 97% of coral reefs, one-sixth of global ecosystems losing area (Leemans and Eickhout, 2003), and one-quarter of species becoming extinct. For example, many Arctic species such as polar bears and walrus, could be at risk of extinction, the South African Karoo would lose four-fifths of its area. Net ecosystem productivity could peak by this amount of warming (Cramer *et al.*, 2001).
- An additional degree of warming, to 3°C would result in over one-fifth of ecosystems losing area (Leemans and Eikhout, 2003) and a third of species becoming extinct (Thomas *et al.*,2004). Two-thirds of the world's tundra could be lost . Such stresses as fire and pests would increase substantially. (See Chapter 4 for more detailed discussion of these and other impacts.)

Additional warming would most likely cause further disruption of ecosystems and extinction of species. However, few studies have examined the effects of climate change beyond 3 to 4°C temperature rise by 2100 over late 20th century climate levels. So, quantitative estimates of the level of loss are limited.

19.3.5 Geophysical Systems

A number of Earth system changes may be classified as key vulnerabilities.

19.3.5.1. Global biogeochemical cycles

The sensitivity of the carbon cycle to increased CO_2 concentrations and climate change, is a key vulnerability (AR4 WGI section 7.1.4) because it may lead to positive feedbacks that act to increase atmospheric CO_2 concentrations, driven by a combination of reduced Net Primary Productivity and increased CO_2 soil respiration under a warmer climate (AR4 WGI section 7.2.2.1.4; Matthews *et al.,* 2005; White *et al.*1999; Cramer *et al.*, 2001). An intercomparison of ten climate models with a representation of the land and ocean carbon cycle (see WG1 Chapter 7; WG1 Ch.10.4.1) show that by the end of the 21st century, additional CO_2 varies between 20 ppm and 200 ppm for the two extreme models, with most of the models projecting additional CO2 between 50 and 100 ppm (Friedlingstein *et al.*, 2006). This additional CO_2 leads to radiative forcing ranging between 0.1 and 1.3 W m^{-2} and hence an additional warming ranging between 0.1 and 1.5°C. A similar range results from estimating the effect including forcing from aerosol and non-CO2 GHGs. These feedbacks would significantly *decrease* the cumulative emissions corresponding to a given CO2 stabilization level.

At the regional level (see AR4 WGII ChX), important aspects include the role of fire in transient response and possible abrupt land cover transitions from forest to grassland or grassland to semi-arid conditions (Claussen *et al.*1999; Eastman *et al.*, 2001; Rial *et al.*2004; Cowling *et al.,* 2004). A larger warming, particularly beyond 3^oC, would cause more adverse impacts.

Warming of permafrost and marine sediments may destabilize methane gas hydrates in some regions (AR 4 WGI section 7.2.2.2.8), as may have occurred during the Paleocene thermal maximum (Dickens, 2001, Archer and Buffet 2005). A rising eustatic (global) contribution to sea level would tend to stabilise hydrates. One study (Harvey and Huang, JGR 1995) reports that methane releases may increase very long-term future temperature by 10-25% over a range of scenarios. Most studies also point to increased methane emissions from wetlands in a warmer, wetter climate (WGI 7.4.1.2).

Increasing ocean acidity due to increasing atmospheric concentrations of CO_2 (AR4 WGI section 7.2.2.2.3; Sabine *et al.*2004; Royal Society 2005) may reduce biocalcification of marine organisms such as corals (Hughes *et al.*, 2003; Feely *et al.*2004). Reduction in $CaCO_3$ production could result in shifts in species composition and major ecological impacts (e.g., Turley *et al.,* 2006 DEFRA). Destruction of wide areas of bottom and sediment fauna and indirect effects on the marine food chain (Liu and Millero, 2002) also may result.

19.3.5.2 Deglaciation of West Antarctic and Greenland ice sheets

The potential for partial or complete deglaciation of the Greenland and the West Antarctic ice sheets (WAIS) and associated sea level rise (Alley *et al.,* 2005; Vaughan, 2006), have been analyzed specifically in the context of key vulnerabilities and Article 2 (Oppenheimer and Alley 2005; O'Neill and Oppenheimer 2002; Hansen, 2005) and scenarios for future warming (Huybrechts and de Wolde, 1999; Gregory *et al.,* 2004; Gregory and Huybrechts 2006). Deglaciation is a key vulnerability because eventual sea level rise could reach 7m and ~5m from Greenland and WAIS, respectively (for a total of ~12m if both completely disintegrated), with wide-ranging consequences (Schneider and Chen, 1980; Revelle, 1983, Atlantis, 2005; Vaughan 2006) and would not be reversible except on very long timescales if at all (WGI AR4 10.7.4.3 and 10.7.4.4). The ability to adapt would depend crucially on the rate of deglaciation. Estimates of this rate range from rapid (several centuries, sea level rise up to 1m/century) to slow (a few millennia; see also AR4 IPCC WGI sections 4.7.4, 6.4.3.3, 10.7.4.3, 10.7.4.4, Vaughan and Spouge, 2002). Deglaciation may be triggered centuries before the resulting sea level rise becomes comparable to that from other sources (Oppenheimer, 1998).

The threshold for deglaciation is estimated at 4.5+/-1.8 °C local warming relative to preindustrial (2.3+/-1.6°C global warming above present day) for Greenland (WGI AR4 Ch.10.7.4.3). Models indicate that warming would initially cause the Antarctic ice sheet as a whole to gain mass owing to increased accumulation of snowfall. Scenarios of deglaciation suppose that this effect would be outweighed by accelerated dynamical discharge of ice following weakening or collapse of ice shelves and melting at the base of the ice where it enters the ocean. Recent observation of unpredicted, rapid local acceleration and consequent loss of mass from both ice sheets (Alley *et al.*2005) underscores the inadequacy of existing models of the relevant processes, particularly for WAIS (AR4 WGI section 4.7.4; AR4 WGI 10.6.4.2, 10.7.4.4; Payne and Vieli, 2005). Based on output of one AOGCM and using surface ablation of ice shelves as an indicator of ice sheet vulnerability, a global warming limit of 4 °C has been proposed beyond which WAIS may experience large scale deglaciation (Oppenheimer and Alley, 2004, 2005). Consideration of a wider range of models indicates ice shelves are unlikely to become vulnerable for less than 5°C (WGIAR4 ch. 10..7.4.4) global warming. However, paleoclimatic evidence (AR4WGI.Ch.6.X) suggests 1-2°C global warming as a limit beyond which both ice sheets may be vulnerable to at least partial deglaciation causing sea level rise of at least 4-6 meters.(IPCC AR4 WGI Ch. 6.4.3; Overpeck *et al.,* 2006; Otto-Bliesner *et al.*2006; Hansen, 2005; Oppenheimer and Alley, 2004, 2005).

19.3.5.3 Possible Changes in North Atlantic Meridional Overturning Circulation (MOC)

The sensitivity of the North Atlantic meridional overturning circulation (*cf.* WGICh10 for a discussion of the relationship to the thermohaline circulation) is regarded as a key vulnerability due to the potential for large and abrupt regional impacts (Alley *et al.* 2003; O'Neill and Oppenheimer 2002; Mastrandrea and Schneider, 2002; Rahmstorf and Zickfeld 2005; Tol, 1998, Keller *et al.*, 2000, Rahmstorf *et al.*, 2003, Higgins and Schneider, 2005). Potential impacts associated with MOC changes include reduced warming or absolute cooling of northern high latitude areas near Greenland and NW Europe, a warming of southern hemisphere high latitudes, tropical drying (Vellinga and Wood 2002, Wood *et al.*, 2003), as well as changes in marine ecosystems productivity (Schmittner, 2005), terrestrial vegetation (Higgins and Vellinga 2004), oceanic CO_2 uptake (Sarmiento and Le Quéré 1996), oceanic oxygen concentrations (Matear and Hirst 2003), and shifts in fisheries (Keller *et al.,* 2000, Link and Tol 2003). Paleo-analogues and model simulations (AR 4 WGI chapter 10) suggest that the MOC might react abruptly and with an irreversible hysteresis response, once a certain forcing threshold is crossed. Estimates of the forcing threshold that would trigger large-scale and persistent changes in the North Atlantic MOC are speculative. Published estimates range from approximately 2 °C to more than 5 oC (cf. Rahmstorf and Zickfeld, 2005, Keller *et al.,* 2006, WG1Ch10.X). Adaptation to MOC related impacts would be difficult if the impacts occur abruptly (*e.g.*, on a decadal time scale). Overall, there is moderate confidence in predictions of a MOC slowdown during the 21st century, but less confidence in the scale of climate change that would cause full shutdown.

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

Sensitivity of modes of climate is a key vulnerability because such modes dominate years-to-decades regional climate variability, and adaptation to variability remains challenging in many regions (AR4WGIIChs X,Y, WG1Ch10). For example, anthropogenic greenhouse gas emissions may have already affected El Niño Southern Oscillation (ENSO) properties (AR4 WGI section 10.x, Timmermann *et al.* 1999; Fedorov and Philander 2000). ENSO shifts would affect agriculture (Cane *et al.*, 1994, Legler *et al.*O'Brien 1999), infectious diseases (Rodo *et al.* 2002), water supply, flooding, and droughts (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 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) level of warming when triggered.

The North Atlantic Oscillation (NAO) and the Annular Mode in both the northern and southern hemispheres (aka 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) may be affected by greenhouse forcing and ozone depletion. Such changes would affect 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. Implications are potentially severe for water resources and storminess in Australia, New Zealand, Southern Africa, Argentina and Chile, southern Europe and possibly parts of the US, where Mediterranean-type climates prevail. Relation of current forcing to observed changes in these modes is uncertain; such trends have been simulated in models without forcing (Cai *et al.*, in press). Summer monsoons would be expected to intensify and winter monsoons weaken in this century due to relative warming of land versus sea surface (AR4WGII ChX) but other factors may alter this pattern. 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. Asian summer monsoon may have already intensified (Anderson *et al.*2002). Confidence of projections of specific monsoonal changes is only low to medium.

19.3.6 Extreme events

As discussed in WGI Chapter x, various extreme events are expected to change in magnitude and/or frequency and location with global warming. In some cases significant trends have been observed in recent decades.

The most likely changes are an increase in the number hot days, or in days exceeding various threshold temperatures, and decreases in the number of cold days including particularly frosts. These will affect human comfort and health, and natural ecosystems and crops. Extended warmer periods will also increase water demand and evaporative losses, increasing the intensity and duration of droughts, assuming no increases in precipitation.

Precipitation is generally predicted in climate models to increase in high latitudes and to decrease in some mid-latitude regions (see model agreement maps in WGI, Chapter x). These changes, together with a general intensification of rainfall events, are expected to increase the frequency of flash floods and large-area floods in many regions, especially at high latitudes. This will be exacerbated, or at least seasonally modified in some locations, by earlier melting of snowpacks and melting of glaciers. Regions of constant or reduced precipitation will experience more frequent and intense droughts, notably in Mediterranean type climates and in mid-latitude continental interiors.

The increased frequency and intensity of droughts in fuel-rich areas is projected to lead to increases in wild fire frequency and intensity, with impacts on natural ecosystems and human settlements. This may lead to overall releases of stored carbon from the biosphere.

Tropical cyclones (including hurricanes and typhoons), are also expected to become more intense with sea surface temperature increases, with model simulations predicting increases by mid-century. However, some data reanalyses suggest that tropical cyclone intensities have increased far more rapidly. (see WG Ch X, Emanuel 2005, and Webster *et al.*2005).

The combination of rising sea level and more intense coastal storms, especially tropical cyclones, are expected to cause more frequent and intense storm surges, possible exacerbated in their effects by more intense rainfall and winds.

Many adaptation measures exist which can reduce vulnerability to such hazard events. (Burton, Kates and White 1993). Among them are dams to provide flood protection and water supply, dykes for protection against coastal surges, improved construction standards to better cope with extreme events, land use planning to reduce exposure, improved evacuation procedures and broader availability of insurance and emergency relief (Burton, 2005-6). However, despite considerable advances in knowledge of weather extremes the relevant adaptation measures are underused, partly for reasons of cost. (White, Kates, and Burton 2001).

19.3.7. Update on Reasons for Concern

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 and showed schematically how their seriousness would increase with global mean temperature change (Figure 19.1 In this section, we update the "reasons for concern".

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 (AR4, WG 2, Chapter 1; 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). Furthermore, confidence has increased that an up to 2^{o}C increase in global mean temperature above 1990 will pose significant risks to many unique and vulnerable systems, including many biodiversity hotspots (Hare, 2003; Leemans and Eikhout, 2004). In summary, there is now high confidence that a warming of up to 2^{o}C would have significant impacts on many unique and vulnerable systems, and is likely to increase the endangered status of many threatened species.

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)

   Recent extreme climate events have demonstrated that such events can cause significant loss of life and property damage in both developing and developed countries (e.g., Schär *et al.*, 2004). While individual events cannot be attributed solely to anthropogenic climate change, recent research indicates that human influence has increased the risk of certain extreme events such as heat waves an intense tropical cyclones. (Stott *et al.*, 2004, Emanuel, 2005; Webster *et al.*, 2005; see also Work Group I chapters 3 and 5; medium confidence)

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; 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; and high confidence that above 2°C to 3°C, there would be net negative impacts in many developed countries and additional negative impacts in many developing countries.

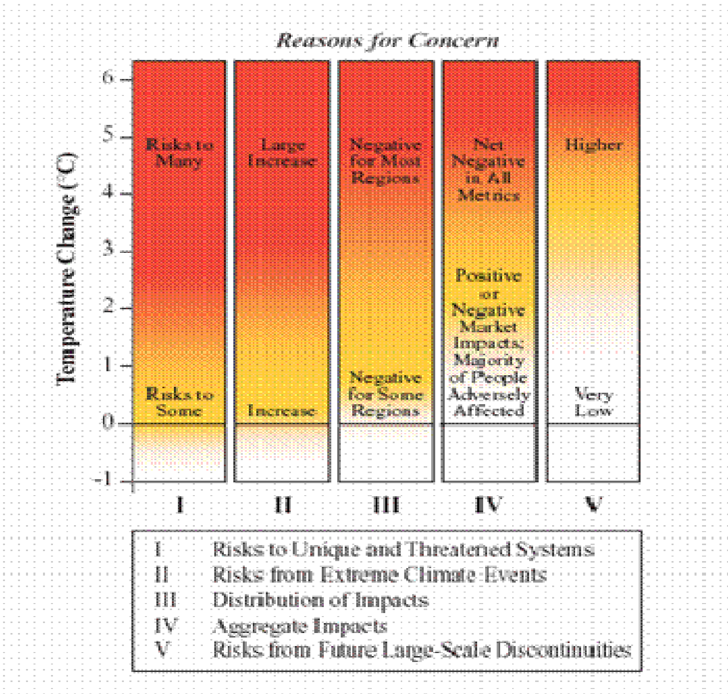

***Figure 19.1:**. Five reasons for concern. Source: Watson and the Core Writing Team (2001) will increase with temperature increase of less than 2°C above 1990 levels; and that this increase and damages will become greater at higher temperatures.*

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 to even a warming of less than 2^{o}C. For instance, indigenous populations in high-latitude areas are already faced with significant adverse impacts from climate change to date, and the increasing number of coastal dwellers, particularly in areas subject to tropical cycles, 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 mean temperature increases, and a preliminary representation of adaptation and development. Recent studies have included some of these previously unaccounted for aspects, such as flood damage to agriculture (Rosenzweig *et al.*, 2002) and damages from increased cyclone intensity (Climate Risk Management Limited, 2005). These studies imply that the physical impacts and costs associated with these neglected aspects of climate change may be very significant. Different analytic techniques (e.g., Nordhaus, 2006; Kemfert and Schumacher, 2005) can result in estimates of higher net damages. Also, long term costs from even a few degrees of warming, such as eventual rise in sea level (e.g., Overpeck *et al.*, 2006), are not accounted for in aggregate damage estimates. In addition, current literature is limited in accounting for economic opportunities that can be created by climate change. On balance, the current generation of aggregate estimates in the literature could understate the actual costs of 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.

The literature also includes analysis of aggregate impacts of climate change other than monetary effects. Parry *et al.* (1999) found that climate change could adversely affect hundreds of millions of people through increased risk of coastal flooding, reduction in water supplies, increased risk of malnutrition, and increased risk of exposure to disease. All of these impacts would directly affect human health. The "Global Burden of Disease study" estimated that the climate change that has occurred since 1990 has increased mortality, and projected climate change will increase future disease burdens even with adaptation (McMichael *et al.*, 2004)

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 changes in climate variability (e.g., ENSO changes), breakdown of the thermohaline circulation (THC—or equivalently, meridional overturning circulation, MOC), deglaciation of the WAIS, and climate-biosphere-carbon cycle feedbacks. However, determining the trigger points and timing of large-scale singularities was seen as difficult because of the many complex interactions of the climate system.

   Since the TAR, the literature indicates that thresholds for deglaciation of West Antarctica may be lower. Partial deglaciation of both WAIS and the Greenland ice sheet leading to global sea level rise of ~4-6m could begin with global warming of ~1-2C above 1990 levels (WGI Ch 6.X, Ch 10.7.4.4). While there is no consensus yet, some studies (Oppenheimer and Alley, 2004, 2005; WG1 Ch.10.7.4.4) indicate that a 2 to 4-5^{o}C global warming above current levels could lead to large scale WAIS deglaciation (medium confidence). As a result, rates of sea level rise up to 1m/century may occur (WGI Ch6.4.3.3; 10.7.4.4; Overpeck *et al.*2006). 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

Section 19.3 identified global, sectoral, and regional key vulnerabilities associated with different levels of global or regional 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 are often portrayed as having largely different foci in terms of their characteristic spatial and temporal scales.

This section is structured as follows. Section 19.4.1 briefly reviews the literature on the role of adaptation to avoid key vulnerabilities. This section complements the assessment of the potential for adaptation included in the discussion of key vulnerabilities in Table 19.1. As discussed in Section 19.2, the relative lack of feasible adaptations has been an important criterion for the selection in the selection of key vulnerabilities in the first place. Section 19.4.2 this reviews the literature that specifically addresses the avoidance of key vulnerabilities or DAI through mitigation of climate change. Section 19.4.3 synthesizes the knowledge about avoiding key vulnerabilities of climate change.

Given the integrating nature of this section at the interface between climate change impacts and vulnerabilities, mitigation, and adaptation, there are important links with other chapters of the IPCC AR4. Most importantly, WG II Ch. 17 discusses the role of adaptation to climate change; WG II Ch. 18 and WG III Ch. 2.6.3 and Ch. 3.5 discuss the links between mitigation and adaptation; WG III Ch. 1.5 and Ch. 2.3 discuss the characteristics of the challenge and the decision-making problem around responding to global climate change, respectively; WG II Ch. 2.2.3 and WG III Ch. 2.4 discuss methods to address uncertainties in this context; WG III Ch. 3.3 and Ch 3.6 discuss climate change mitigation from a long-term and a short-term perspective, respectively; and WG II Ch 2.3.4 discusses methods of evaluating impacts associated with mitigation scenarios.

19.4.1. Adaptation

19.4.1.1 Adaptation as a Response Strategy.

How much can be achieved by (proactive) adaptation? As evidence of the current impacts of climate change mounts (Chapter 1), and at the current rate of progress towards the stabilization of the atmospheric concentrations of greenhouse gasses (Working Group III), it is becoming more vital to understand the potential and limitations of adaptation to reduce impacts and to prevent the emergence of more key vulnerabilities.

In some instances there are claims on the optimistic side that much can be achieved by adaptation (Goklany, 2003, Ausubel (no date)). In other cases the prospects seem much worse, (Pittock 2006). The scientific literature on these questions is still relatively small compared with mitigation, and the conclusions are necessarily speculative in many cases. It is clear, however, that there is no simple comprehensive response to the adaptation question, and that the answer is very nuanced and is likely to become more so as new research results come in.

In agriculture, for example, previous IPCC assessments have generally concluded that in the near to medium term aggregate world food production is not threatened (IPCC 1996, IPCC 2001). However considerable regional variation in impacts and adaptive capacity suggests that severe impacts and food scarcities could occur in some regions especially in low latitudes and may already be evident as seen in recurrent drought and food shortages in Africa. (World Food Programme 200x). In global terms agriculture has been extremely resilient and world food production has expanded rapidly to keep pace with world population growth. Even where shortages have occurred the reasons are rarely to be found in an absolute lack of food but are more due to lack of purchasing power and failures of the distribution system (Sen 1981). Attention to adaptation in agriculture has tended to focus on specific measures at the farm level, and some progress in being made in the incorporation of climate risks into agricultural practices. On the other hand the processes of globalization and technological change are placing adaptation more in the hands of agri-business, national policy makers, and the international political economy including such factors as prices, tariffs and subsidies, and the terms of international trade. (Apuuli *et al.* 2002; Burton and Lim 2005).

The record of past success in agriculture is mirrored in other sectors, and in many regions it is evident that climate variability falls largely within the coping range (Jones 2001). One possible exception is in the case of extreme events where losses (both insurance and uninsured (Munich Re. 2006) have been rising sharply. In such cases adaptation has not been so successful despite major improvements in understanding the risks and in forecasts and warnings. (White, Burton and Kates 2001). One reason is the decline in local concern and thus reduced propensity to adopt proactive adaptation measures as the memory of specific disaster events fades. Related to this lack of appreciation of possible risks is that governments and communities can still be taken by surprise when extreme events occur even though scientific evidence of their potential occurrence is widely available. Hurricane Katrina of 2005, the European heat wave of 2003, and many other similar events have caused more damage and loss of life due to a lack of sufficient adaptation. So while the overall record of adaptation to climate change and variability in the recent past (200 years) has been successful overall, there is evidence of an adaptation deficit, especially in relation to extreme events. (Burton 2004, Burton and May 2004; Hallegate *et al.* 2006).

It is clear that in the future there is considerable capacity and potential for adaptation provided that existing and developing scientific understandings and technology and know-how can be effectively applied. It might be expected that the slower the rate of climate change the more likely adaptation is to be successful. For example, even a major rise in sea level might be accommodated and adjusted to by human societies if it happens very slowly over many centuries (Nicholls *et al.* forthcoming). On the other hand slow incremental change might still involve considerable costs and people might not be strongly enough motivated to take precautionary action and bear the costs without some more dramatic stimulus. It sometimes takes a disaster or a near-disaster to get people moving (cite: PRUDENCE, UK Foresight studies). Paradoxically therefore the full array of human adaptation potential is not likely to be brought to bear if one takes into account the market and institutional barriers to adaptation.

In terms of the key vulnerabilities identified in Tables 19.1 and 19.2 it is clear that adaptation potential is greater the more the system is under human management and control. Thus major geophysical vulnerabilities leave little room for adaptation. Fortunately these vulnerabilities are likely to unfold relatively slowly. There is somewhat greater adaptive capacity in biological systems but it is still very limited. Biodiversity and ecosystems are likely to be impacted at a much faster rate than geophysical systems without a commensurately larger adaptive capacity. It seems likely therefore that the greatest impacts than cannot be effectively adapted to in the near to medium terms will be in biological systems. As we move into human social systems and market systems adaptive capacity at the technical level increases dramatically. However the understanding of impacts, adaptive capacity, and the costs of adaptation is weaker and the uncertainties higher. This is especially the case for synergistic or cross cutting impacts. Considered in isolation the prospects for agricultural adaptation may appear to be good. When related impacts in water regimes, droughts and floods, pests infestations and plant diseases, human health, the reliability of infrastructure, as well as other non-climate related stresses are taken into account the picture is less clear.

The bottom line on the basis of the rudimentary levels of present understanding is that for market and social systems there is considerable adaptation potential at least in theory, but the costs are potentially large and largely unknown and unequally distributed, as is also our adaptation potential. For biological and geophysical systems the adaptation potential is much less and because impacts on the biological systems are on a more rapid time scale the growth new key vulnerabilities is more likely to occur in biological systems. This does not mean that social and market systems are immune. They too depend on biological systems even if less directly and as the world of ecosystems is impacted by mounting stress from climate change then follow-on (second order) effects on human health, safety, livelihoods and prosperity could be considerable.

19.4.2. Mitigation

19.4.2.1 Uncertainties in the assessment of response strategies

Climate change assessments and the development of response strategies are hampered by multiple uncertainties and unknowns (see WG II Ch. 2.2.3 and WG III Ch. 2.4). The most relevant sources of uncertainty in this context are:

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

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. There are, however, limitations to the frequentist description given that the climate system is non-stationary at a range of scales or that past forcing factors cannot be perfectly known. The reliability of *knowledge* about uncertain aspects of the world (such as the "true" value of climate sensitivity) cannot be represented by frequentist probabilities. "Pseudo-frequentist" probability distributions of climate sensitivity that look like frequency representation can be meaningfully constructed, though they will have substantial elements of subjectivity embedded. Making subjective elements transparent is an essential obligation of those using such an approach.

One method for characterizing uncertainty due to lack of scientific knowledge is by Bayesian (or subjective) probabilities, which refer to the *degree of belief* of experts in a particular statement, considering the available data. Another approach is imprecise probabilities and non-probabilistic representations of epistemic uncertainty (Helton and Overkamp, 2004; Hall *et al.*, in review). 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). In situations of social choice, value diversity (such as different attitudes towards risk or equity and how they might change with time) cannot be meaningfully addressed through an objective probabilistic description. It is often assessed through sensitivity analysis or scenario analysis, in which different value systems are explicitly represented and 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 assign a subjective likelihood of exceeding certain temperature thresholds for given emission scenarios or concentration targets.

19.4.2.2 Methodological approaches to the assessment of response strategies

concentrations or global temperature change therefore have to combine scientific analysis and normative judgements in deciding how to operationalise DAI. 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 (see also WG II Ch. 2.3.4 and Ch. 2.3.5). These methods can be characterized according to the following 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 and development pathways), 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. discrete vs. probabilistic:

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 or range bounding estimates for uncertain parameters. Uncertainty can also be treated discretely by set-based methods that select a number of possible values (which may or may not have been derived from explicit probability distributions).

- Non-optimizing vs. optimizing vs. adaptive:

Optimizing analyses select a specific mitigation target (e.g. stabilisation target or emission scenario) 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 19.3 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.

19.4.2.3 Scenario analysis and analysis of stabilization targets

Scenario analyses examine 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. Related static analyses 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 whereas others quantify uncertainty using probability distributions for one or more parameters of the coupled social-natural system. Note that the term "GHG stabilization" is used here with a time horizon of up to several centuries, which is most relevant for the avoidance of DAI. We thus neglect that over many millennia CO_2 concentrations may return to values close to pre-industrial levels through natural processes such as dissolution of marine carbonates and geologic weathering (Putilov, 2003, Brovkin *et al.*, 2002, Semenov, 2004). Similarly, a few centuries is too short a time frame to analyze the very long term responses of deep oceans or large glaciers to human induced forcings over the next few generations, and such studies would likely underestimate some impacts such as long term sea-level rise.

The methods for designing such scenarios differ across studies with regard to their scope of specified emissions (time frame and consideration of non-CO2 gases) and their shape. Scenario shape (or the distribution of emissions across time) is of particular relevance to the consideration of key vulnerabilities, as it influences transient temperature change (see e.g., Schneider and Mastrandrea, 2005; Meinshausen, 2005; O'Neill and Oppenheimer, 2004). Some studies focus on the key radiative forcing agent CO_2, while others include additional gases and aerosols in their analysis. Two main categories can be distinguished in regard to shape: (a) stabilization scenarios, which imply monotonically increasing concentrations from current levels up to a final asymptotic stabilization concentration (e.g., Enting *et al.*, 1994; Schimel *et al.*, 1996; Wigley *et al.*, 1996; Morita *et al.*, 2000; Swart *et al.*, 2002; O'Neill and Oppenheimer, 2004). (b) peaking scenarios, which imply a peaking concentration with subsequent lowering of concentrations. While such a peaking is a necessity for the exploration of stabilization levels close to or below current concentration levels (see e.g., Enting *et al.* 1994; Wigley *et al.* 1996), a number of studies also design scenarios with a temporary exceedance of higher stabilization levels on multi decadal timescales with so-called "overshoot trajectories" (Kheshgi., 2004; O'Neill and Oppenheimer, 2004; Wigley, 2004; Izrael and Semenov, 2005; Kheshgi *et al.*, 2005; Meinshausen *et al.*, 2005).

Table 19.3: *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 unacceptable mitigation costs.	No	Yes
Cost-benefit analysis including 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

Several recent studies have specifically focused on the analysis of stabilization scenarios and 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 based on temperature projections from the TAR. 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 likelihood 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 and peaking 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. The relationship between stabilization concentration and equilibrium temperature increase is dependent on the climate sensitivity. Figure 19.2, for instance, depicts the likelihood of exceeding an equilibrium temperature threshold of 2°C above preindustrial levels based on a range of published probability distributions for climate sensitivity. A threshold of 2ºC above preindustrial levels is exemplary of the choice of many authors for their analysis of DAI (see WG III Ch. 1.2.2). To render eventual exceedence of this exemplary threshold "unlikely" (<33% chance), the CO_2-equivalent stabilization level must be below 400ppm for the majority of considered climate sensitivity uncertainty distributions (range 350 and 470ppm). To make exceedence "very unlikely" in equilibrium (<10% chance), the level must be even lower given the current knowledge on the uncertainty of climate sensitivity.

Wigley (2004) combines probability distributions for climate sensitivity (solid line in Figure 19.2) and non-CO_2 forcing with a definition for DAI (3^o C) 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, as the system is not currently in equilibrium. Of course, different assumptions would change these results.

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 19.3a. 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 19.3b. Their numerical estimates using a simple modelling 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 approaches that properly incorporate sources of uncertainty in the climate system should be part of the analysis tool kit.

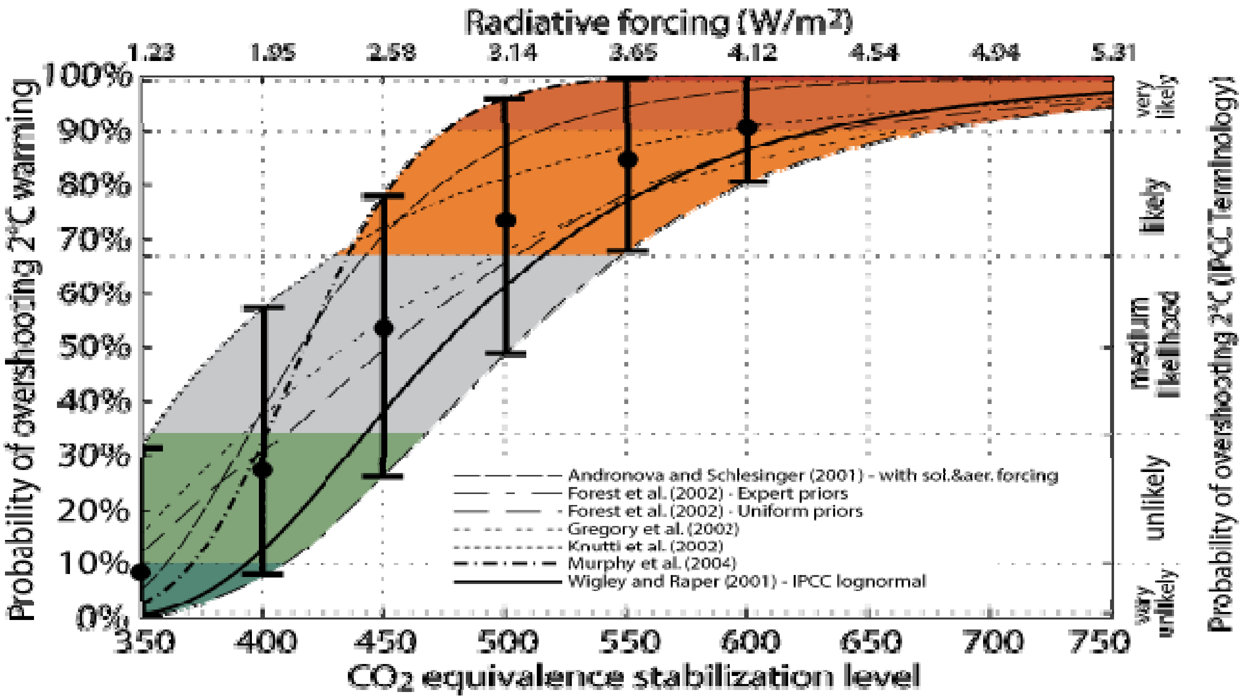

Figure 19.2: *Probability of exceeding an equilibrium global warming of 2°C above preindustrial (corresponding to 1.4°C above 1990 levels). Source: Hare and Meinshausen (2005)*

A family of simple stabilization scenarios was proposed in (Semenov, 2004). Each scenario was characterized by the starting date for the implementation of emission reduction program and specific reduction rate, i.e. a factor by which the global CO_2 emission should be cut each year. The trade-off for the date and the rate preventing GMT increase above the pre-industrial level by 3°C on average over 2000-3000 was considered (later dates required higher rates); the minimal reduction rate was estimated at 0.3% to be applied since 2012.

A controversial alternative approach to stabilizing the Earth's climate is “geoengineering”, in which deliberate modification to the Earth’s radiative budget would be undertaken to offset greenhouse gas forcing. For example, Izrael (2005) suggested that 1-2°C cooling can be achieved via injection of sulphate aerosols into the lower stratosphere, echoing similar suggestions published since 1974. Nearly all such proposals are usually described by their authors as researchable topics, with very few adherents in the literature favouring near-term implementation of any such schemes, given the uncertain side effects and potentially divisive nature of any deliberate climate system intervention undertaken by a limited number of parties (National Academy of Sciences, 1991).

19.4.2.4 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 initially 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

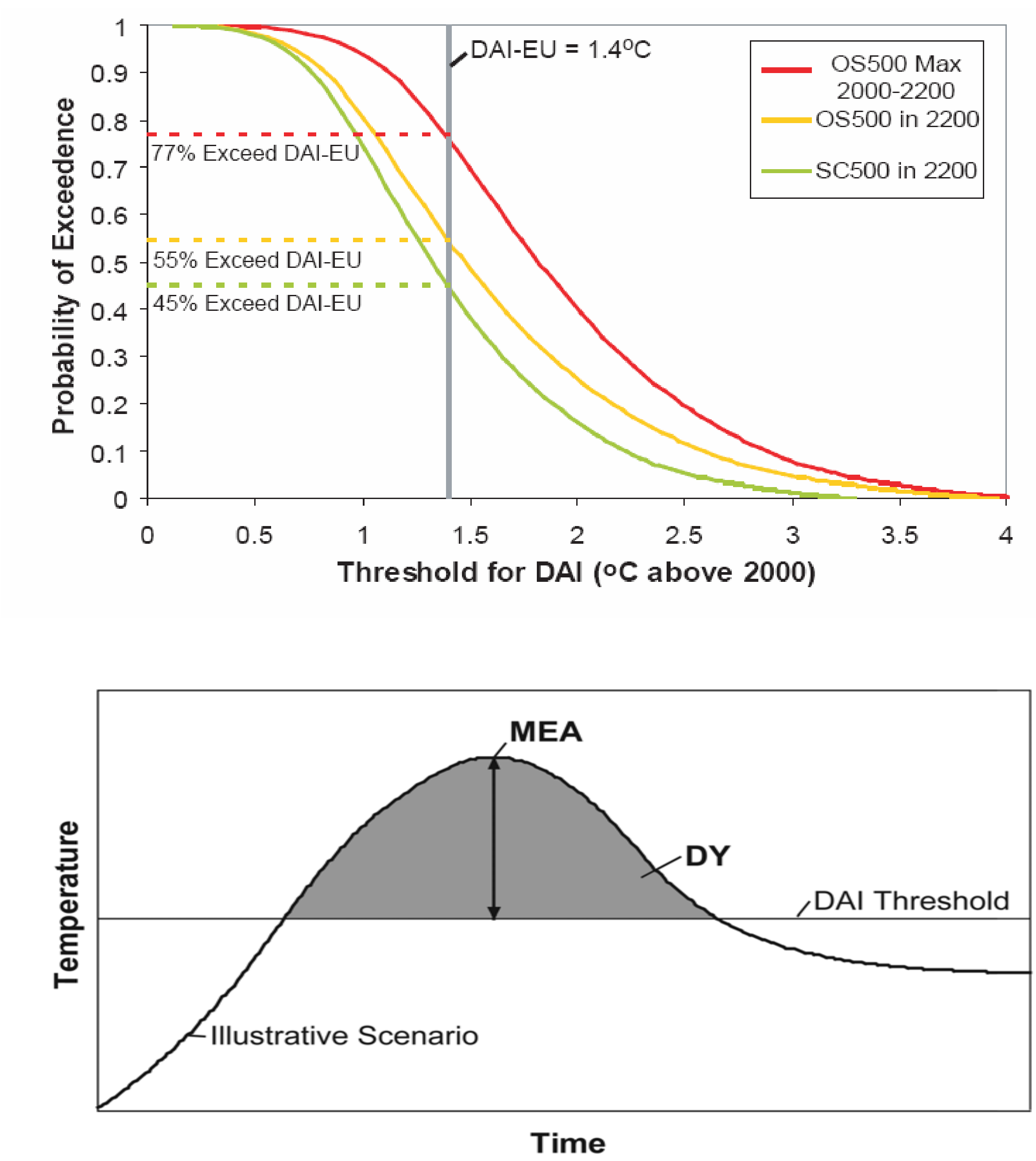

Figure 19.3: *a) Probability of exceedence of 1.4°C above current levels (labelled DAI-EU, as the European Union has endorsed this level of climate change as their climate policy target) for overshoot (OS500) and non-overshoot (SC500) scenarios. OS 500 Max is derived from the maximum overshoot temperature which occurs at some point during the transient response but before 2200, the latter of which is represented by OS 500 2200. b) Visualization of Maximum Exceedence Amplitude (MEA) and Degree Years (DY) for an illustrative overshoot temperature profile. The study authors caution that the model-dependent quantities on the figures are not to be taken literally, and that the point of the analysis is to demonstrate the utility of a probabilistic framework for DAI studies. Source: Schneider and Mastrandrea (2005).*

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, similar to the caveat in the caption to Figure 19.3, the specific numerical results, while plausible, are clearly assumption-bound and model-dependent, but a framework of this type of analysis is more 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 than deterministic assessments based solely on "best guess" values.

The tolerable windows approach has also been applied in connection with systematic climate thresholds, predominantly for probabilistic analyses of the stability of the thermohaline circulation (THC, or alternatively, MOC) (Zickfeld and Bruckner, 2003; Bruckner and Zickfeld, 2004; Rahmstorf and Zickfeld, 2005). Rahmstorf and Zickfeld (2005) conclude that the SRES A2 emission scenario exceeds the range of emissions corresponding to a 5% and 10% likelihood of inducing a commitment to 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 significant probability of triggering a large-scale singularity and that keeping open the option to achieve such a stabilisation target would be a cautious way to guide near-term policy. 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.

19.4.2.5 Cost-benefit analysis

Most early cost-benefit analyses of climate change have assumed that climate change will be a gradual and smooth process. This assumption has prevented these analyses from determining an optimal policy solution (Hall and Behl, in press). Recognizing the restrictions of this assumption, an extensive literature has developed extending cost-benefit analyses and related decision-making in the context of Article 2 (Jones, 2004) 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 identified as key vulnerabilities, such as climate change-induced slowing or 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, none carrying high confidence. These preliminary analyses suggest that significant reductions in anthropogenic greenhouse gas emissions may be an economically efficient investment even given damages less than 1% of gross world product associated with a MOC slowing or 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 using a very reduced form coupled climate-economy model, investigating the likelihood of exceeding probabilistic thresholds for DAI based on the IPCC "reasons for concern." Since these "reasons" include non-market metrics, this analysis mitigates to some extent the concerns about market system only aggregations discussed in Section 19.3. They developed relationships between the level of mitigation efforts and the probability of exceeding thresholds for DAI, and demonstrated with this simple cost-benefit model that the establishment of climate mitigation policies can significantly reduce the probability of exceeding DAI thresholds (high confidence) unless high discount rates are used. As in other such simple modelling studies, the authors again caution against taking the model-dependent numerical results literally. Other researchers have also implemented probabilistic treatments of uncertainty in integrated assessment modelling (e.g., Hope, 2005).

19.4.2.6 Cost-effectiveness analysis

Cost-effectiveness analysis involves determining cost-minimizing policy strategies that are compatible with pre-defined probabilistic or deterministic 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 (e.g., Wigley *et al.*, 1996; Azar, 1998), although the cost-effective balance is of course dependent on assumptions about such factors as technological development and time discounting. 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 incorporating such constraints are much larger than the ones typically suggested by many earlier cost-benefit analyses. One reason is that most early cost-benefit analyses do not consider the key vulnerabilites underlying such constraints in their damage functions. In addition, cost-benefit analysis assumes perfect substitutability between all costs and benefits of a policy strategy whereas the hard constraints in a cost-effectiveness analysis can be interpreted as infinite costs or no substitutability from the perspective of cost-benefit analysis.

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. The quantitative results of these analyses cannot carry high confidence as most studies represent uncertain parameters by two to three discrete values only and/or employ rather arbitrary assumptions about learning (e.g., Hammitt *et al.*, 1992; Keller *et al.*, 2004, Yohe *et al.*, 2004). 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 be used as a justification for doing nothing today to mitigate potential climate damages.

19.4.3. Synthesis

The studies reviewed in this section diverge widely in their methodological approach, in the sophistication with which uncertainties are considered in 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. Response strategies considered in literature aim at preventing climate change-caused damage to particular key elements and processes in the Earth's system and socio-economic system. "Key" means (see Section 19.2) that they are sensitive to climate change, have limited adaptation potential, and could be used by policy-makers in designing DAI-preventing policy (the latter property involves a value judgement).

2. A constant long-term increase in equilibrium global mean surface temperature above the pre-industrial equilibrium (recalculated to an increase above 1990 levels, as needed) is considered in the literature in a majority of cases, whereas the transient temperature changes are much less frequently considered in literature. Many studies provided global mean temperature thresholds which would lead sooner or later to a specific key vulnerability, i.e. to disruption/shutdown of a vulnerable process. Such thresholds are not known precisely, and are characterized in literature by a range of values (or occasionally by probability functions).

3. Assessments of whether emission pathways/GHG concentration profiles exceed given temperature thresholds are characterized by high uncertainty. Therefore, deterministic studies alone cannot provide sufficient information for a full analysis of response strategies, and probabilistic approaches should be considered. Risk analyses suggest that some large-scale singularities can no longer be avoided with high confidence, given historical climate change and the inertia of the climate system (Wigley, 2004; Wigley, 2005; Rahmstorf and Zickfeld, 2005).

4. Computer modelling using different analytical methods and PDFs for equilibrium climate sensitivity indicates a high confidence that CO_2 stabilization levels above 450 ppm could produce global mean warming in excess of 2ºC above 1990 levels, though the likelihood of this exceedence depends on the assumed probability distribution for climate sensitivity (WG1 CHX; O’Neill and Oppenheimer, 2002; O’Neill and Oppenheimer, 2004; Hare and Meinshausen, 2005; Schneider and Mastrandrea, 2005).

5. A stabilization program for emission reduction implemented in the near term has been shown in the literature to have a significant effect on the concentration and temperature profiles over the decades ahead. Later initialization of stabilization efforts has been shown to require higher rates of reduction if they are to avoid given levels of DAI (Semenov, 2004). Substantial delay (several decades or more) makes achievement of the lower range of stabilization targets (e.g., 500ppm CO2-equivalent and lower) infeasible, except via overshoot scenarios.

19.4.4 Priorities for Research

As noted throughout this chapter, there many uncertainties in virtually all phases of the analyses reported in the literature. This implies the necessity of a vigorous research agenda on many aspects of the key vulnerabilities questions.

In brief, research efforts are needed on:

- identifying various thresholds in the socio-natural system, so that various DAI levels can be better characterized for various sectors and regions,
- exploring which vulnerabilities imply irreversible effects (e.g., species extinction, large

glacier/ice sheet collapses)

- searching for examples of successful adaptation and exploring if these can serve as models for adaptive capacity for climate change scenarios of various degrees of warming,
- examining the gap between adaptive potential and actual implementation of adaptive actions, and how to narrow that gap,
- determination of pdfs and cdfs for various system thresholds, and implementing these in various decision analytic tools to examine the DAI implications of alternative policy choices,
- assessing attitudes of both lay and expert communities towards risk that might help in the valuation of various metrics of impacts, and their clear communication to decision makers,
- examining how different groups might perceive systemic thresholds versus social determinations of what constitutes “unacceptable” impacts,
- studying the potential for and risks of various geoengineering proposals, exploring attitudes about the relative valuations of different metrics of impacts, and their relationships to sustainable development.

References

Aaheim, H. A. & C. Bretteville, Decision-making frameworks for climate policy under uncertainty, CICERO Working Paper 2001:2

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impacts Assessment. New York: Cambridge University Press.

ACIA, 2004. *Impacts of a Warming Arctic: Arctic Climate Impacts Assessment*. New York: Cambridge University Press.

Ackerman, Frank and Lisa Heinzerling, 2004. Priceless: On Knowing the Price of Everything and the Value of Nothing. The New Press, New York, NY, 288 pp.

Adger, N., 2003, Governing natural resources: institutional adaptation and resilience, Chapter 4 in F. Berkhout, M. Leach, I. Scones, (Eds) Negotiating Environmental Change, Edward Edgar. 2003.

Adger, W. N. 2001. Scales of Governance and Environmental Justice for Adaptation and Mitigation of Climate Change. *Journal of International Development* 13, 921-931.

Agrawala, S. *et al.* (2005) OECD, in press.

Alcamo, J., M. Flörke and M. Märker, 2005. "Scenarios of global water resources: What are the effects of socio-economic drivers as compared to climate change?" *Climatic Change*, submitted.

Alhakami, A. S., & Slovic, P. (1994). A psychological study of the inverse relationship between perceived risk and perceived benefit. Risk Analysis, 14 (6), 1085-1096.

Allen & Ingram, Constraints on future changes in climate and the hydrologic cycle, Nature 419:224, 2002

Allen, M., S. Raper and J. Mitchell (2001) Climate change - Uncertainty in the IPCC's Third Assessment Report. *Science* **293**, 430-433.

Alley *et al.*, Abrupt climate change, Science 299:2005 (2003).

Alley, R. B., J. Marotzke, W. D. Nordhaus, J. T. Overpeck, D. M. Peteet, R. A. Pielke, R. T. Pierrehumbert, P. B. Rhines, T. F. Stocker, L. D. Talley, and J. M. Wallace. 2003. Abrupt climate change. Science 299 (5615):2005-2010.

Amthor, J.S., 2001: Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration, Field Crops Res. 73, 1-14.

Anderson, D. M., J. T. Overpeck, A. K. Gupta 2002, Increase in the Asian southwest monsoon during the past four centuries. Science 297, 596-599.

Andronova, N. G., M.E. Schlesinger: Objective Estimation of the Probability Density Function for Climate Sensitivity, Journal of Geophysical Research, 106:22605–22612, 2001

Apuuli, Bwango. J. Wright, C. Elias, and I. Burton. 2000. "Reconciling National and Global Priorities in Adaptation to Climate Change: An Illustration from Uganda" Environmental Monitoring and Assessment. 61 (1) 145-159

Archer, D. and B. Buffett, 2005., Time-dependent response of the global ocean clathrate reservoir to climatic and anthropogenic forcing, Geochem., Geophys, and Geosys., 6, Q03002, doi:10.1029/2004GC000854 ISSN: 1525-2027.

Arnell, N. W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmetnal Change* 14, 31-52.

Arnell, N. W. Climate change and global water resources: SRES emissions and socioeconomic scenarios. Global Environmental Change. 14: 31-52.

Arnell, N. 2004: Climate change and global water resources: SRES scenarios and socio-economic scenarios. Global Environmental Change, 14, 31-52.

Arnell, N.W., M. G. R. Cannell, M. Hulme, R. S. Kovats, J. F. B. Mitchell, R. J. Nicholls, M. L. Parry, M. T. J. Livermore, and A. White. 2002. "The Consequences of CO2 Stabilisation for the Impacts of Climate Change." Climatic Change 53: 413-446.

Arnell, N.W., E. L. Tompkins, W. N. Adger 2005: Eliciting Information from Experts on the Likelihood of Rapid Climate Change. Risk Analyis 25:1419-1431

Arneson, Richard. 1989. Equality and Equal Opportunity for Welfare. Philosophical Studies 56, 77-93.

Arneson, Richard. 1999. Equal Opportunity for Welfare Defended and Recanted. Journal of Political Philosophy 7.4.

Arneson, Richard. 2000. Welfare Should be the Currency of Justice. Canadian Journal of Philosophy 30. 4, 497-524.

Arvidsson, R., 1996: Fennoscandian earthquakes: whole crustal rupturing related to postglacial rebound. Science, 274, 744-746.

Ausubel, J.H. (no date) A second look at the impacts of climate change. American Scientist 79, 210-221.

Azar, C. & K. Lindgren, Catastrophic events and stochastic cost-benefit analysis of climate change, Climatic Change 56:245, 2003

Azar, C. and T. Sterner, 1996: “Discounting and Distributional Considerations in the Context of climate Change", Ecological Economics, 19: 169-185.

Azar, C. The timing of CO2 emissions reductions: the debate revisited, Int. J. Environ. Pollut.10, 508 (1998b).

Azar, C., 1998a: “Are Optimal Emissions Really Optimal—Four Critical Issues for Economists in the Greenhouse", Environmental and Resource Economics, 11: 301-315.

Azar, C.: 1998, 'The timing of CO2 emissions reductions: the debate revisited', International Journal of Environment and Pollution 10, 508-521.

B. Müller (2002): “Equity in Climate Change: The Great Divide”. Oxford Institute for Energy Studies, Oxford, UK

Bacastow, R. B., J. A. Adams, C. D. Keeling, D. J. Moss, T. P. Whorf, and C. S. Wong. 1980. Atmospheric carbon dioxide, the Southern Oscillation and the weak 1975 El Nino. Science 210:66-68.

Baird, Sandra J.S., J.T. Cohen, J.D. Graham, A.I. Shlyakhter, and J.S. Evans, 1996. “Noncancer Risk Assessment: A Probabilistic Alternative to Current Practice,” Human and Ecological Risk Assessment 2(1), pp. 78-99.

Baker, A. C., Reef corals bleach to survive change, Nature 411, 765 (2001).

Baranzini, A., M. Chesney, and J. Morisset, 2003: “The impact of possible climate catastrophes on global warming policies,” Energy Policy 31(8): 691-701.

Barnard, R.and P. W. Leadley, 2005, Global change, nitrification, and denitrification: A review, GLOBAL BIOGEOCHEMICAL CYCLES, 19, GB1007, doi:10.1029/2004GB002282.

Barnett, J. (2003). The relation between environmental security and climate change is discussed, Global Environmental Change, 13, 7-17.

Barnett, J., W. M. Adger, Climate Dangers and Atoll Countries, Climatic Change 61, 321 (2003).

Barry, Brian. 1998. Sustainability and Intergenerational Justice. In Andrew Dobson ed., Fairness and Futurity. Oxford, 93-117.

Bazermann, M. (2005). Climate change as a predictable surprise, Climatic Change, submitted.

Beckerman, Wilfred and Pasek, Joanna. 2001. Justice, Posterity and the Environment. Oxford.

Bindschadler, R., West Antarctic ice sheet collapse? Science 276, 662-663 (1997).

Bohle, H. G., Downing, T. E. and Watts, M. J. (1994) Climate change and social vulnerability: toward a sociology and geography of food insecurity. Global Environmental Change 4(1), 37-48.

Bosello, F., R. Roson and R. S.J. Tol, Economy-Wide Estimates of the Implications of Climate Change: Human Health**,** July 2005, NOTA DI LAVORO 97.2005

Bray, D., and H. von Storch. 1999. Climate science: an empirical example of postnormal science. Bulletin of the American Meteorological Association 80: 439-455.

Broecker, W. S., Thermohaline circulation, the Achilles heel of our climate system: will man-made

CO2 upset the current balance?, Science 278, 1582 (1997).

Broome, John. 1992. Counting the Cost of Global Warming. Isle of Harris, UK: White Horse Press.

Brovkin V., Bendtsen J., Claussen M., Ganopolski A., Kubatzki C., Petoukhov V. and A. Andreev, 2002: Carbon cycle, vegetation, and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. Global Biogeochemical Cycles, Vol. 16, No. 4, 1139, doi: 10.1029/2001GB001662, 86-1 - 86-20.

Brovkin V., Bendtsen J., Claussen M., Ganopolski A., Kubatzki C., Petoukhov V. and A. Andreev, 2002: Carbon cycle, vegetation, and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. Global Biogeochemical Cycles, Vol. 16, No. 4, 1139, doi: 10.1029/2001GB001662, 86-1 - 86-20.

Bruckner, T., K. Zickfeld, 2005: Low Risk Emissions Corridors for Safeguarding the Atlantic Thermohaline Circulation, Mitigation and Adaptation Strategies for Global Change (accepted).

Bunyavanich S, Landrigan CP, McMichael AJ, Epstein PR. The impact of climate change on child health (review). *Ambul Pediatr*. 2003;3:44–52.

Burton, I. 2004. “Climate Change and the Adaptation Deficit.” Occasional Paper No. 1. Adaptation and Impacts Research Group, Meteorological Service of Canada. Downsview, Canada.

Burton, I. and B, Lim, 2005 “Achieving Adequate Adaptation in Agriculture” Climate Change, 70. 191-200.

Burton, I. and E.May. 2004. “The Adaptation Deficit in Water Resource Management” Climate Change and Development. IDS Bulletin Vol. 35 No. 3 2004.

Burton, I., Huq, S., Lim, B., Pilifosova, O. and Schipper, E.L. (2002) From impact assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy* 2, 145-159.

Cai, W., Shi, G. and Li, Y., in press: Multidecadal fluctuations of winter rainfall over southwest Western Australia simulated in the CSIRO Mark 3 coupled model.

Cai, W., Whetton, P.H. and Karoly, D.J., 2003: The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO2. Journal of Climate, 16, 1525-1538.

Caldeira *et al.*, Climate sensitivity uncertainty and the need for energy without CO2 emission, Science 299:2052, 2003

Callaway, J. M. 2004. “The Benefits and Costs of Adapting to Climate Variability and Change.” In: Organisation for Economic Cooperation and Development. *The Benefits of Climte Change Policies:*

Campbell, I.D. and Campbell, C., 2000: Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**, 263-280.

Campbell-Lendrum, D., A. Pruss-Ustun, *et al.* (2003). How much disease could climate change cause? Climate Change and Health: Risks and Responses. A. McMichael, D. Campbell-Lendrum, C. Corvalan *et al.* Geneva, WHO/WMO/UNEP.

Canals, A.C., A. Calafat, *et al.*, Uncovering the footprint of former ice streams in Antarctica. EOS 84, 97-108 (2003).

Cane, M. A. (2005). "The evolution of El Nino, past and future." Earth and Planetary Science Letters 230(3-4): 227-240.

Cane, M.A., G. Eshel, and R.W. Buckland, Forecasting Zimbabwean maize yield using eastern equatorial pacific sea-surface temperature, *Nature*, *370* (6486), 204-205, 1994.

Cary, G.J., 2002: Importance of climate change for fire regimes in Australia. In: Bradstock R.A., Williams, J.E. and M.A. Gill (eds.), *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, Cambridge (UK), pp.26-44.

Chagnon, S.A. (1999), Impacts of 1997–98 El Niño–

Chambers, R. (1989) Vulnerability, coping and policy. IDS Bulletin 20(2), 1±7.

Chen, C. C., B. A. McCarl, and R. M. Adams. 2001. Economic implications of potential ENSO frequency and strength shifts. Climatic Change 49 (1-2):147-159.

Chipanshi, A.C., R. Chanda and O. Totolo, 2003: Vulnerability Assessment of the Maize Production and Sorghum Crops to Climate Change in Botswana. Climate Change 61: 339-360.

Chua, K. B., W. J. Bellini, *et al.* (2000). "Nipah virus: a recently emergent deadly paramyxovirus." Science 288(5470): 1432-5.

Church, J. A. and J. M. Gregory, 2001. "Changes in Sea Level". In J. T. Houghton, L. G. M. Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (Eds.), *Climate Change 2001: The Scientific Basis*. Cambridge, UK: Cambridge University Press.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., Pachur, H.J., 1999: Simulation of an abrupt change in Saharan vegetation at the end of the mid-Holocene. Geophys. Res. Letters, 24 (No. 14), 2037-2040.

Climate Change 1994: 1995. Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. Intergovernmental Panel of Climate Change. Cambridge University Press, 339 pp.

Climate Change 1995: 1996a. The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel of Climate Change. (Houghton J. T., Meira Filho L. G., Callander B. A. *et al.*, editors). Cambridge University Press, 572 pp.

Climate Risk Management Limited. 2005. The Financial Risks of Climate Change. Nottinghamshire, United Kingdom: Climate Risk Management Limited. 125 pp.

Climate Risk Management Limited. 2005. *The Financial Risks of Climate Change*. Nottinghamshire, United Kingdom: Climate Risk Management Limited. 125 pp.

Cline, W.R., 1996. The Impact of Global Warming on Agriculture: Comment. American Economic Review, 86(5): 1309-1311.

Cohen, G.A. 1989. On the Currency of Egalitarian Justice. Ethics 99, 906-44.

Cole, J. E., J. T. Overpeck, and E. R. Cook. 2002. Multiyear La Nina events and persistent drought in the contiguous United States. Geophysical Research Letters 29 (13).

Cole, J.E., J.T. Overpeck, and E.R. Cook, Multiyear La Nina events and persistent drought in the contiguous United States, *Geophysical Research Letters*, *29* (13), 2002.

Confalonieri, U. (2003). "Climate variability, vulnerability and health in Brazil." Terra Livre 19-1(20): 193-204.

Corfee-Morlot, J. and S. Agrawala, 2004: Overview. Chapter 1 in The Benefits of Climate Change Policies – Analytical and Framework Issues. OECD, Paris.

Corfee-Morlot, J. *et al.* 2005 (GEC article)

Corfee-Morlot, J., N. Höhne: Climate change: long-term targets and short-term commitments. Global Environmental Change 13:277-293, 2003

Costello, C. J., R. M. Adams, and S. Polasky. 1998. The value of El Niño forecasts in the management of salmon: a stochastic dynamic assessment. American Journal of Agricultural Economics 80 (4):765-777.

Cowling, S.A., R. A. Betts, P.M. Cox, V.J. Ettwein, C.D. Jones, M.A. Maslin, S. A. Spall (2004). Contrasting simulated past and future responses of the Amazonian forest to atmospheric change, Philosophical Transactions: Biological Sciences 359, 539 – 547.

Cox P.M., Betts R.A., Collins M., Harris C., Huntingford C., Jones C.D., 2004: Amazon dieback under 27 climate-carbon cycle projections for the 21st century. Theoretical and Applied Climatology, 78, 137- 28 156. 29

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000: Acceleration of global warming due 25 to carbon-cycle feedbacks in a coupled climate model. Nature, 408(6809), 184-187. 26

Cramer W., Bondeau A, Woodward FI, Prentice IC, Betts RA, Brovkin V, Cox PM, Fisher V, Foley JA, 2001.

Cramer, W. and 16 co-authors. 2001. “Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models.” *Global Change Biology*. 7:357-373.

Crisp, Roger. 2003. Equality, Priority and Compassion. Ethics 113, 745-763.

Cubasch, U. *et al.*, in Climate Change 2001: The Scientific Basis, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 525–582.

Cuffet, K.M. and Marshall, S.J. 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature* **404**: 591-594.

D.C. Hall , R.J. Behl (in press): Integrating economic analysis and the science of climate instability. Ecological Economics (in press)

Daniels, Norman. 1985. Just Health Care. Cambridge.

Darwin, Roy, Marinos Tsigas, Jan Lewandrowski, and Anton Raneses [1995]. *World Agriculture and Climate Change*, U. S. Department of Agriculture, Agricultural Economic Report No. 703, June.

Dasgupta, P.: Human Well-Being and the Natural Environment. Oxford University Press, Oxford, 2001

de Siqueira Otávio João Wachholz, Sílvio Steinmetz, Mauro Fernando Ferreira, Andréia Castro Costa e Marcos Antônio Wozniak (2000). Mudanças climáticas projetadas através dos modelos giss e reflexos na produção agrícola brasileira. Revista Brasileira de Agrometeorologia, Santa Maria, v. 8, n. 2, p. 311-320, 2000.

DEFRA (2005). Avoiding Dangerous Climate Change, UK Department of Environment, Food, and Rural Affairs, Feb 1-3, Exeter, UK. Available at http://www.stabilisation2005.com

Dennis, C., 2002: Nature, 415, 947, Reef under threat from 'bleaching' outbreak.

Dessai, S. & M. Hulme: Does climate policy need probabilities? Working Paper No. 34, Tyndall Centre for Climate Change Research, Norwich, UK, 2003

Dessai, S. *et al.* Defining and experiencing dangerous climate change, Climatic Change 64, 11 (2004).

Devereaux, S., and Edwards, J., Climate Change and Food Security, IDS Bulletin, Volume 35, number 3. July 2004.

DFID, 2004, Climate Change and Poverty, Making Development Resilient to Climate Change.

Dickens, G.R., 2001: Modeling the global carbon cycle with gas hydrate capacitor: Significance for the latest Paleocene thermal maximum. In: Natural Gas Hydrates: Occurrence, Distribution, and Detection [C.K. Paull, and W.P. Dillon (eds.)]. Geophysical Monograph 124, American Geophysical Union, Washington, DC, 19-38.

DIW Berlin: Politikberatung kompakt 13

Dobson, Andrew. 1998. Justice and the Environment. Oxford.

Doll, P. and S. Siebert. 2002. Global modeling of irrigation water requirements. Water Resources Research. 38 (4): Art. No. 1037.

Done, T.J., Whetton, P., Jones, R., *et al.*, 2003: Global Climate Change and Coral Bleaching on the Great Barrier Reef. Australian Institute of Marine Science, Final Report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mines.

Donner, S.D., C. J. Kucharik, and M. Oppenheimer, 2004,The influence of climate on in-stream removal of nitrogen, Geophys. Res. Letters, 31, L20509, oi:10.1029/2004GL020477.

Dourson, Michael L. and J.F. Stara, 1983. “Regulatory History and Experimental Support of Uncertainty (Safety) Factors,” Regulatory Toxicology and Pharmacology, 3(3), pp. 224-38.

Driver, Julia. 2005. Ideal Decision-Making and the Green Virtues. In Walter Sinnott-Armstrong and R.B. Howarth (eds.). Global Warming: Interdisciplinary Perspectives. Cambridge.

Dworkin, Ronald. 2000. Sovereign Virtue. Harvard.

E. Kriegler, T. Bruckner, 2004: Sensitivity Analysis of Emissions Corridors for the 21st Century, Climatic Change 66, 345-387

Easterling *et al.*, Climate extremes: observations, modelling, and impacts, Science 289:2068, 2000

Easterling *et al*, Coping with Global Climate change: The Role of Adaptation in the United States, Pew Centre, June 2004, available www.pewclimate.org. [also has good reference in bibliography

Eastman, J.L., Coughenour, M.B., Pielke, R.A., (2001) The regional effects of CO_2 and landscape change using a coupled plant and meteorological model. Global Change Biology 7, 797.

ECF (2004), ECF Symposium, Key vulnerable regions and climate change, 27-30 October 2004, Beijing

Emanuel, K. 2005. “Increasing destructiveness of tropical cyclones over the past 30 years.” *Nature*. 436: 686-688.

Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436, 686-688 (2005).

Enting I.G., Wigley T.M.L., Heimann M., Future Emissons and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses. CSIRO Tech Pap. No 31, 1994.

Evans, John S., G.M. Gray, R.L. Sielken Jr., A.E. Smith, C. Valdez-Flores, and J.D. Graham, 1996. “Use of Probabilistic Expert Judgment in Uncertainty Analysis of Carcinogenic Potency,” Regulatory Toxicology and Pharmacology, 20(1 part 1), pp. 15-36.

Fankhauser, S., Tol, R.S.J., Pearce, D.W., 1997. The aggregation of climate change damages: a welfare theoretic approach. Environ. Resource Econ. 10, 249–266.

Fedorov, A. V., and S. G. Philander. 2000. Is El Niño Changing? Science 288 (5473):1997-2002.

Final Report Project FKZ 904 41 362 for the Federal Ministry for the Environment

Finkel, Adam M., 1990. Confronting Uncertainty in Risk Management: A Guide for Decision-Makers. Center for Risk Management, Resources for the Future, Washington, DC: monograph, 87 pp.

Finkel, Adam M., 1994. “Stepping Out of Your Own Shadow: A Didactic Example of How Uncertainty Can Inform and Improve Decision-Making,” Risk Analysis, 14(5), pp. 751-761.

Finkel, Adam M., 2003. “Too Much of the [National Research Council’s] ‘Red Book’ is Still Ahead of its Time.” Human and Ecological Risk Assessment, 9(5), pp. 1253-1271.

Finucane, M. L., Alhakami, A. S., Slovic, P., & Johnson, S. M. (2000). The affect heuristic in judgments of risks and benefits. Journal of Behavioral Decision Making, 13, 1-17.

Fischhoff, B., Slovic, P., Lichtenstein, S., Read, S., & Combs, B. (1978). How safe is safe enough? A psychometric study of attitudes toward technological risks and benefits. Policy Sciences, 9, 127-152.

Folland, C.K. *et al.*, 2001: Global temperature change and its uncertainties since 1861. Geophysical Research Letters 28:2621-2624

Forest, C. E., P. H. Stone, A. P. Sokolov, M. R. Allen, M. D. Webster: Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations. Science 295:113-117 (2001)

Frankfurt, Harry. 1987. Equality as a Moral Ideal. Ethics 98, 21-43.

Fried, J.S., Tor, M.S. and E. Mills, 2004: The impacts of climate change on wildfire severity: A regional forecast for northern California. *Climatic Change*, **64**, 169-191.

Friedlingstein, P., J.-L. Dufresne, P.M. Cox, and P. Rayner, 2003: How positive is the feedback between climate change and the carbon cycle? Tellus Series B, 55(2), 692-700.

Friend AD, Kucharik C, Lomas MR, Ramankutty N, Sitch S,

Fuessel, H.-M., R. J. T. Klein (2004): Conceptual frameworks of adaptation to climate change and their applicability to human health. PIK Report No. 91, Potsdam, Germany

Füssel, H.-M., F.L. Toth, J.G. van Minnen, F. Kaspar (2003): Climate impact response functions as impact tools in the tolerable windows approach. Climatic Change 56(1):91-117, 2003

Füssel, H.-M., J. G. van Minnen (2001): Climate impact response functions for terrestrial ecosystems. Integrated Assessment 2(4):183-197

Füssel, H.-M., R.J.T. Klein (2005): `Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking’. Climatic Change (in press).

Füssel, H.-M.: The ICLIPS Impacts Tool: A Graphical User Interface to Climate Impact Response Functions for Integrated Assessments of Climate Change. Integrated Assessment 2(4):116-125, 2003

Fyfe, J.C., 2003: Extratropical southern hemisphere cyclones: harbingers of climate change? Journal of Climate, 16, 2802-2805.

Fyfe, J.C., Boer, G.J. and Flato, G.M., 1999: The arctic and Antarctic Oscillations and their projected changes under global warming. Geophysical Research Letters, 26, 1601-1604.

Gardiner, Stephen M. 2004a. Ethics and Global Climate Change. Ethics 114: 555-600.

Gardiner, Stephen M. 2004b. A Core Precautionary Principle. International Journal of Global Environmental Issues, Vol. 5, No. 2. (??

Gelver E.S. and S.M. Semenov, 2005: The influence of climate change over Russia's territory at the end of 20th century on the availability of heat for the agricultural plants. In: Problems of Ecological Monitoring and Ecosystem Modelling, vol. XX, p. 303 - 310. (in Russian).

Generated Weather in the United States, Bull. Am. Meteor. Soc., 80, 1819-1827.

Geng, Q. and Sugi, M., 2003: Possible changes in extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols – study with high-resolution AGCM. Journal of Climate, 16, 2262-2274.

Gillett, N.P., F.W. Zwiers, A.J. Weaver and P.A. Stott, 2003: Detection of human influence on sea-level pressure. Nature, 422, 292-294.

Gilovich, T., Griffin, D., & Kahneman, D. (Eds) (2002). Heuristics and biases: The psychology of intuitive judgment. New York, Cambridge University Press.

Githeko, A. K., S. W. Lindsay, *et al.* (2000). "Climate change and vector borne diseases: a regional analysis." Bulletin of the World Health Organization 78(9): 1136-1147.

Gjerde, J., S. Grepperud, S. Kverndokk, Optimal climate policy under the possibility of a catastrophe, Resource and Energy Economics 21:289, 1999

Goklany, I. M. (2002): From precautionary principle to risk-risk analysis. Nature Biotechnology 20:1075

Goklany, I. M., “Relative Contributions of Global Warming to Various Climate Sensitive Risks, and Their Implications for Adaptation and Mitigation,” Energy & Environment 14: 797-822, 2003.

Goldberg, D., and Wagner, M., 2004, Petitioning for Adverse Impacts of Global Warming in the Inter-American Human Rights, System, Oxford University Press (forthcoming).

Gray, W. M., 2003. “Twentieth Century Challenges and Milestones” in: Hurricane: Coping with Disaster, R. Simpson, ed., AGU, Washington, DC

Gregory, J.M., P. Huybrechts, S.C. Raper, Threatened loss of the Greenland ice-sheet, Nature 428:616 (2004).

Grubler, A. and N. Nakicenovic, 2001: “Identifying Dangers in an Uncertain Climate," Nature 412:15.

Gupta, J., O. Xander and E. Rotenberg (2003), The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention, Environmental Science and Policy 6, 475-486.

H.-M. Füssel: Vulnerability to Climate Change: A Comprehensive Conceptual Framework. University of California International and Area Studies Breslauer Symposium Paper 6, Berkeley, CA, USA, 2005. Available at http://repositories.cdlib.org/ucias/breslauer/6/.

Ha-Duong, M. *et al.*, Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement, Nature 390, 270 (1997).

Hall, J.W., Fu, G. and Lawry, J. Imprecise probabilities of climate change: aggregation of fuzzy scenarios and model uncertainties, Climatic Change, in review

Hallegatte S., J.-C. Hourcade and P. Dumas, Why economic dynamics matter in the assessment of climate change damages: illustration on extreme events, accepted by Ecological Economics, preprint available on http://www.centre-cired.fr/forum/article77.html?lang=en

Halpin, P.N. (1997) Global climate change and natural-area protection: Management responses and research directions Ecological Applications 7, 828-843.

Hamilton, C., Turton, H., Pollarde, P., (2001), “Climate Change and Commonwealth Nations”, Discussion Paper 40, The Australia Institute, 2001 (available at www.tai.org.au).

Hammitt, James K. and A.I. Shlyakhter, 1999. "The Expected Value of Information and the Probability of Surprise," Risk Analysis, 19(1), pp. 135-52.

Hammitt, James K., Robert J. Lempert, and Michael E. Schlesinger, "A Sequential-Decision Strategy for Abating Climate Change," Nature, May 28, 1992, 357, 315—318.

Hanemann, W.M., 2000. Adaptation and its Measurement: An Editorial Comment. Climatic Change, 45: 571-581.; Kaufmann, R., 1998. Commentary: The Impact of Climate Change on US Agriculture: A Response to Mendelsohn *et al.* (1994). Ecological Economics, 26: 113-119

Hanna, E., P. Huybrechts, and T.L. Mote, 2002: Surface mass balance of the Greenland ice sheet from climate-1 analysis data and accumulation/runoff models. Annals of Glaciology, 35, 67-72.

Hansen, J. (and 14 co-authors). 2005. "Earth's Energy Imbalance: Confirmation and Implications." *Science* 308: 1431-1435.

Hansen, J., 2005: A slippery slope: How much global warming constitutes "dangerous anthropogenic interference?". Climatic Change 68:269-279

Hansen, J.: 2004, Defusing the Global Warming Time Bomb, *Sci. Amer.*, **290**, 68-77

Hare, B. and Meinshausen, M., 2005: How much warming are we committed to and how much can be avoided? Accepted by Climatic Change

Hare, W. 2003. "Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC." Berlin: Wissen

Hartmann D.L., J.M. Wallace, V. Limpasuvan, D.W.J. Thompson and J.R. Holton, 2000: Can ozone depletion and global warming interact to produce rapid climate change? Proceedings of the National Academy of Sciences of the United States, 97, 1412-1417.

Hausman, Daniel M. and McPherson, Michael S. 1996. Economic Analysis and Moral Philosophy. Cambridge University Press.

Hay, S. I., C. A. Guerra, *et al.* (2005). "Urbanization, malaria transmission and disease burden in Africa." Nature Reviews Microbiology 3(1): 81-90.

Hay, S. I., G. D. Shanks, *et al.* (2005). "Climate variability and malaria epidemics in the highlands of East Africa." Trends in Parasitology 21(2): 52-53.

Helton, J. C., D. E. Burmaster: Guest editorial: Treatment of aleatory and epistemic uncertainty in performance assessments for complex systems. Reliability Engineering & System Safety 54:91-94, 1996

Higgins, P. A. T., and M. Vellinga. 2004. Ecosystem responses to abrupt climate change: Teleconnections, scale and the hydrological cycle. Climatic Change 64 (1-2):127-142.

Higgins, P. A. T., M. D. Mastrandrea, and S. H. Schneider. 2002: "Dynamics of Climate and Ecosystem Coupling: Abrupt Changes and Multiple Equilibria," Philosophical Transactions of the Royal Society of London (Series B-Biological Sciences) 357: 647-655.

Higgins, P.A.T., Schneider, S.H. 2005. Long-term potential ecosystem responses to greenhouse gas-induced thermohaline circulation collapse. Global Change Biology 11, 699.

Hijioka, Y., Takahashi, K., Matsuoka, Y., and Harasawa, H., 2002. Impact of global warming on waterborne diseases. Journal of Japan Society on Water Environment 25,647-652.

Hitz, S. and J. B. Smith. 2004. "Estimating Global Impacts from Climate Change" *Global Environmental Change* 14(3):201-218.

Hitz, S. and Smith J., 2004: Estimating Global Impacts from Climate Change. Chapter 2 in The Benefits of Climate Change Policies – Analytical and Framework Issues. OECD, Paris

Hoegh-Guldberg, O., Climate change, coral bleaching and the future of the world's coral reefs, Marine and Freshwater Research 50, 839-866 (1999).

Hoegh-Guldberg, O., Jones, R.J, *et al.*, 2002: Is coral bleaching really adaptive? Nature, 415, 601-602.

Houghton, J.T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. and Johnson, C. A., 2001: Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, Geneva. Cambridge University Press, Cambridge, UK, and New York, USA, 881 pp.

Howarth, Richard. 1997. Sustainability as Opportunity. Land Economics 73.4, 569-579.

Hsee, C. K., & Rottenstreich, Y. (2004). Music, pandas, and muggers: On the affective psychology of value. Journal of Experimental Psychology: General, 133 (1), 23-30.

Hughes, T. P., *et al.*, Climate change, human impacts, and the resilience of coral reefs, *Science* **301**, 929-933, 2003.

Huq, S., A.Rahman, M.Konate, Y.Sokona and H.Reid, Mainstreaming Adaptation to Climate Change in Least Developed Countries, IIED, April 2003. From IIED.

Huybrechts, P., de Wolde, J., 1999. The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming. Journal of Climate 12, 2169–2188.

Huybrects, P., 2004: Antarctica: modelling, in: Bamber. J.L. and A.J. Payne (eds.): Mass balance of the cryosphere: observations and modelling of contemporary and future changes, *Cambridge University Press* (Cambridge), 491-523.

IISD, 2003, Livelihoods and Climate Change: combining disaster risk reduction, natural resource management and climate change adaptation in a new approach to the reduction of vulnerability and poverty, A conceptual framework paper prepared by the task Force on Climate Change, Vulnerable Communities and Adaptation. www.iisd.org

Ingham & Ulph, Uncertainty, Irreversibility, Precaution, and the Social Cost of Carbon, Tyndall Centre Working Paper 37, Oct 2003

Institut de Veille Sanitaire (2003): Impact sanitaire de la vague chalaire d'aout 2003 en France. Bilans et perspectives. Available at http://www.invs.sante.fr/publications/2003/bilan-chaleur-1103

International Federation of Red Cross and Red Crescent (2004): World Disasters Report. Available at http://www.ifrc.org/publicat/wdr2004/chapter2.asp

Introduction in Mehta. L., Leach, M., Scoones, I., (eds) 2001, 'Environmental governance in an uncertain world', IDS Bulletin Vol 32 No 4. Brighton: IDS

Introduction, in Newell, P., 1999, 'Globalisation and the governance of the environment', IDS Bulletin Vol 30 No 3. Brighton: IDS

IPCC 1996. Climate Change 1995. Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analyses. Report of Working Group II. Cambridge University Press, Cambridge, UK. See especially Reilly J. et. al. "Agriculture in a Changing Climate: Impacts and Adaptations. Pp.427-467

IPCC 2001. Climate Change 2001. Impacts, Adaptation and Vulnerability. Report of Working Group II. Cambridge university press, Cambridge, UK.

Izrael Yu. A. 2005. Efficient ways for keeping climate at the present level - the main aim of the climate problem solution. Meteorology and Hydrology. N10, p. 5 -9 (in Russian)

Izrael Yu. A. and S.M. Semenov, 2005: Calculations of a change in CO2 concentration in the atmosphere for some stabilization scenarios of global emissions using a model of minimal complexity. Russian Meteorology and Hydrology, N 1, pp. 1-8.

Izrael Yu. A., Semenov S. M.: 2003. Example calculation of critical limits for greenhouse gas content in the atmosphere using a minimal simulation model of the greenhouse effect. Doklady Earth Sciences (English Translation of Doklady Akademii nauk, vol. 390, Nos 1-4, May-June 2003), Volume 390, Number 4, p. 611-614.

Izrael, Yu.A., 2004: On the concept of dangerous anthropogenic interference with the climate system and capacities of the biosphere. Meteorology and Hydrology, N 4, pp. 30-37. (in Russian).

J.C. Helton and W.L. Overkamp, 2004: Special issue on "Alternative Representations of Epistemic Uncertainty". Reliability Engineering & System Safety 85 (1-3)

Jacoby, H. D.: Informing climate policy given incommensurable benefits estimates. Global Environmental Change 14:287-297, 2004

Jamieson, D. 1996. Ethics and intentional climate change. *Climatic Change* 33:323-336.

Jamieson, Dale. 1992. Ethics, Public Policy and Global Warming. Science, Technology and Human Values 17:139-153. Reprinted in Jamieson 2002.

Jamieson, Dale. 2002. Morality's Progress. Oxford: Oxford University Press.

Jamieson, Dale. 2005. Adaptation, Mitigation and Justice. In Walter Sinnott-Armstrong and R.B. Howarth (eds.). Global Warming: Interdisciplinary Perspectives. Cambridge.

Johnston, 1987: Suppression of earthquakes by large continental glaciers. Nature, 330, 467-469.

Jones, C.D., McConnell C.L., Coleman K., Cox P.M. , Falloon P., Jenkinson D.S., Powlson D.S., 2005: The sensitivity of projected soil carbon storage under climate change to the representation of soil carbon dynamics. Global Change Biology, in press.

Jones, Peter G., Philip K. Thornton., 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environmental Change 13 (2003) 51-59.

Jones, R. (2004) Managing climate change risks OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers

Jones, R.N. 2001. "An environmental risk assessment/management framework for climate change impact assessments" Natural Hazards, 23. 197-230

Jones, P.G., and P. K. Thornton. 2003. "The potential impacts of climate change on maize production in Africa and Latin America in 2055." Global Environmental Change. 13:51-59.

Kahneman, D., & Tversky, A., (1979). Prospect theory: An analysis of decision under risk. Econometrica, 47, 263-291.

Kahneman, D., Slovic, P., & Tversky, A. (Eds) (1982). Judgment under uncertainty: Heuristics and biases. New York: Cambridge University Press.

Katz, R. W.: Techniques for estimating uncertainty in climate change scenarios and impact studies. Climate Research 20:167-185, 2002

Keating, B. and McGuire, W., 2004; Instability and structural failure at volcanic ocean islands and the climate change dimension. Advances in Geophysics, 47, 175-270.

Keller, K., BM Bolker, DF Bradford: Uncertain climate thresholds and optimal economic growth. Journal of Environmental Economics and Management 48:723-741, 2004

Keller, K., K. Tan, F. M. M. Morel, and D. F. Bradford. 2000. Preserving the ocean circulation: Implications for climate policy. Climatic Change 47 (1-2):17-43.

Keller, K., Yohe, G., and Schlesinger, Managing the Risks of Climate Thresholds: Uncertainties and Information Needs, submitted to Climatic Change.

Keller, Tan, Morel, Bradford, Preserving the Ocean Circulation: Implications for Climate Policy, Climatic Change 47, 17-43 (2000).

Kelly, D.L. and Kolstad, C.D. (1999). Bayesian learning, growth, and pollution, Journal of Economic Dynamics and Control, 23, 491-518.

Kemfert, C. and K, Schumacher *Costs of Inaction and Costs of Action in Climate Protection: Assessment of Costs of Inaction or Delayed Action of Climate Protection and Climate Change*

Kennedy, D., D. Holloway, E. Weinthal, W. Falcon, P. Ehrlich, R. Naylor, M. May, S.H. Schneider, S. Fetter, and J.-S. Choi, 1998: "Environmental Quality and Regional Conflict," A report to the Carnegie Commission on Preventing Deadly Conflict. Carnegie Corporation, New York, 72 pp.

Kenny GJ, Warrick RA, Campbell BD, Sims GC, Camilleri M, Jamieson PD, Mitchell ND, 2000. Investigating climate change impacts and thresholds: an application of the CLIMPACTS integrated assessment model for New Zealand agriculture. Climate Change 46:91–113 8

Kheshgi H.S. Evasion of CO2 injected into the ocean in the context of CO2 stabilization. Energy 29 (2004) 1479–1486.

Kheshgi H.S., Jain A.K. Projecting future climate change: Implications of carbon cycle model intercomparisons. Global Biogeochemical Cycles, vol. 17, No. 2, 1047, doi:10.1029/2001GB001842, 2003. p. 16-1 - 16-17.

Kheshgi H.S., Smith S.J., Edmonds J. A. Emissions and atmospheric CO2 stabilization: long-term limits and paths. 5263783.tex; 10/12/2003; 12:34; p.4 (in press)

Kiilsholm, S., J.H. Christensen, K. Dethloff, and A. Rinke, 2003: Net accumulation of the Greenland ice sheet: High resolution modeling of climate changes. Geophysical Research Letters, 30(9).

Klein, R.T.J. 2001. *Adaptation to Climate Change in German Development Assistance – An Inventory of Activities and Opportunities, with a Special Focus on Africa.* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn.

Kleypas, J.A., R.W. Buddemeier, D. Archer, J.P. Gattuso, C. Langdon, B.N. Opdyke, Geochemical consequences of increased atmospheric carbon dioxide on coral reefs, Science 284, 118-120 (1999).

Knutson, T. R. and R. E. Tuleya. 2004. " Impact of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization." Journal of Climate. 17(18): 3477-3495.

Knutti, R., and T. F. Stocker. 2002. Limited predictability of the future thermohaline circulation close to an instability threshold. Journal of Climate 15 (2):179-186.

Knutti, R., Joos, F., Müller, S.A., Plattner, G.-K., Stocker, T.F. (2005) Probabilistic climate change projections for stabilization profiles. Geophys. Res. Let. (in press).

Kopp, Raymond J., and M. Hazilla, 1990. "The Social Cost of Environmental Quality Regulations: A General Equilibrium Analysis," Journal of Political Economy, 98, pp. 853-873.

Kovats, R. S., S. J. Edwards, S. Hajat, B. G. Armstrong, K. L. Ebi, B. Menne, and The Collaborating Group. 2004. "The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries." Epdiemeological Infections. 132: 443-453.

Kovats, R. S., T. Wolf, *et al.* (2004). "Heatwave of August 2003 in Europe: provisional estimates of the impact on mortality." Eurosurveillance Weekly 8(11).

Krabill, W., *et al.* (2004), Greenland Ice Sheet: Increased coastal thinning, Geophys. Res. Lett., 31, L24402, doi:10.1029/2004GL021533.

Kuhnel, I., and L. Coates. 2000. El Niño-Southern Oscillation: Related probabilities of fatalities from natural perils in Australia. Natural Hazards 22 (2):117-138.

Kuntz-Duriseti, K., Evaluating the economic value of the precautionary principle: using cost benefit analysis to place a value on precaution, Environmental Science & Policy 7:291 (2004).

Kushner, Paul J., Isaac M. Held, Thomas L. Delworth, 2001: Southern Hemisphere Atmospheric Circulation Response to Global Warming. Journal of Climate: 14, 2238-2249.

Kuzmina, S. I., L. Bengtsson, O. M. Johannessen, H. Drange,L.P. Bobylev, and M.W. Miles,The North Atlantic Oscillation and greenhouse-gas forcing, GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L04703, doi:10.1029/2004GL021064, 2005

Kyoto and Beyond, Swedish Environmental Protection Agency 2002

Lambeck, K. and Purcell, A., 2003: Glacial rebound and crustal stress in Finland. POSIVA 2003-10. See www.Posiva.fi/englanti/.

Lamont, Julian. Distributive Justice. Stanford Encyclopedia of Philosophy. Available at < http://plato.stanford.edu/entries/justice-distributive/>

Latif, M., E. Roeckner, U. Mikolajewski, and R. Voss. 2000. Tropical stabilization of the thermohaline circulation in a greenhouse warming simulation. Journal of Climate 13:1809-1813.

Lavorel, S., 2003: Global change, fire, society and the planet. *Global Change Newsletter*, **48**, 9-12.

Leemans, R. and B. Eickhout, 2004: "Another reason for concern: regional and global impacts on ecosystems for different levels of climate change," Global Environmental Change (Part A) 14: 219-228.

Leemans, R. and B. Eikhout. 2003. "Analysing changes in ecosystems for different levels of climate change." Paris: Organisation for Economic Cooperation and Development.

Legler, D. M., K. J. Bryant, and J. J. O'Brien. 1999. Impact of ENSO-related climate anomalies on crop yields in the US. Climatic Change 42 (2):351-375.

Lehodey, P., M. Bertignac, J. Hampton, A. Lewis, and J. Picaut. 1997. El Niño Southern Oscillation and tuna in the western Pacific. Nature 389 (6652):715-718.

Leiwserowitz, A. (2005) Climate Change Risk Perception and Policy Preferences: The role of affect, imagery, and values, Climatic Change (in press).

Lempert, R. and M. E. Schlesinger (2001) Climate-change strategy needs to be robust. *Nature* **412**, 375-375.

Lempert, R. J. 2002. A new decision science for complex systems. Proceedings of the National Academy of Sciences of the United States of America 99:7309-7313.

Lempert, Sanstad, Schlesinger, Robust responses to the threat of abrupt climate change, paper presented at IEA Meeting Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy.

Lenihan, J. M., R. Drapek, D. Bachelet, and R. P. Neilson. 2003. “Climate Change Effects on Vegetation Distribution, Carbon, and Fire in California.” Ecological Applications, 13(6), 2003, pp. 1667–1681.

Lichtenstein, S., Slovic, P., Fischhoff, B., Layman, M., & Combs, B. (1978). Judged frequency of lethal events. Journal of Experimental Psychology: Human Learning and Memory, 4, 551-578.

Lieshout van, M., R.S. Kovats, M.T.J. Livermore and P. Martens, 2004: Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. Global Environmental Change, volume 14, number 1, pp. 87-99.

Link, P. M., and R. S. J. Tol. 2004a. Economic impacts in population dynamics of fish on the fisheries in the Barents Sea: Working paper, Hamburg University, Department of Economics, Research Unit Sustainability and Global Change, Center for Marine and Atmospheric Sciences (ZMAW).

Link, P. M., and R. S. J. Tol. 2004b. Possible Economic Impacts of a Slowdown of the Thermohaline Circulation: An Application of FUND: Working paper, Hamburg University, Department of Economics, Research Unit Sustainability and Global Change, Center for Marine and Atmospheric Sciences (ZMAW).

Link, P.M., and R.S.J. Tol, Economic impacts in population dynamics of fish on the fisheries in the Barents Sea, pp. 32, Working paper, Hamburg University, Department of Economics, Research Unit Sustainability and Global Change, Center for Marine and Atmospheric Sciences (ZMAW), 2003.

Liu, X.W. and Millero, F.J., 2002. The solubility of iron in seawater. Mar. Chem., 77(1): 43-54.

Loewenstein, G. F., Weber, E. U., Hsee, C. K., & Welch, N. (2001). Risk as feelings. Psychological Bulletin, 127 (2), 267-286.

Lovejoy and Hannah, Yale Univ Press, 2005

Lund, J. *et al.* 2003. “Water Resources” in: Wilson, T., L. Williams, J. Smith, and R. Mendelsohn (eds.). 2003. Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy. Report to the California Energy Commission. Palo Alto, California: Electric Power Research Institute.

Lutz, W., W. Sanderson, *et al.* (2001). "The end of world population growth." Nature 412(6846): 543-5.

M. G. Morgan, P. J. Adams, D. W. Keith (2006): Elicitation of Expert Judgments of Aerosol Forcing. Climatic Change (in press; available online)

MA. 2003. *Ecosystems and Human Well-being: A Framework for Assessment*. Washington, DC: Island Press.

MacAyeal, D.R. 1992. The basal stress distribution of ice stream E, Antarctica, inferred by control methods, Journal of Geophysical Research, vol. 97, series B1, p. 595-603.

MacAyeal, D.R., T.A. Scambos, C.L. Hulbe, and M.A. Fahnestock, 2003: Catastrophic ice-shelf break-up by an ice-shelf fragmentation-capsize mechanism. Journal of Glaciology, 49, 22-36.

Machina, Mark J., 1987. “Decision Making in the Presence of Risk,” Science 236 (May 1, 1987), pp.

537-543.

Magrin, G.O., M. I. Travasso. 2002. An Integrated Climate Change Assessment from Argentina (Chapter 10) In: Effects of Climate Change and Variability on Agricultural Production Systems. Otto Doering III; J.C.Randolph; J.Southworth and R.A.Pfeifer (Eds). Kluwer Academic Publishers, Boston. pp193-219.

Manning, M., M. Petit: A Concept Paper for the AR4 Cross Cutting Theme: Uncertainties and Risk. IPCC, 2004

Marshall, G.J., 2003: Trends in the Southern Annular Mode from observations and reanalyses. Journal of Climate, 16, 4134-4143.

Martens, P., Kovats, R.S., Nijhof, S., de Vries, P., Livermore, M.T.J., Bradley, D.J., Cox, J., and McMichael, A.J., 1999. Climate change and future populations at risk of malaria. Global Environmental Change 9,S89-S107.

Martin, D., D. Belanger, P. Gosselin, J. Brazeau, C. Furgal., and S. Dery, 2005: *Climate change, drinking water, and human health in Nunavik: Adaptation Strategies. Final report submitted to the Canadian Climate Change Action Fund, Natural Resources Canada.* CHUL Research Institute, Ste-Foy, Quebec.

Martin, P.H. and Lefebvre, M.G., 1995. Malaria and climate: Sensitivity of malaria potential transmission to climate. Ambio 24,200-207.

Maslin, Mark. 2004. "Ecological versus climatic thresholds." *Science* 306:2197-8.

Mastrandrea, M. D., and S. H. Schneider. 2004. Probabilistic integrated assessment of "dangerous" climate change. Science 304 (5670):571-575.

Mastrandrea, M.D. and Schneider, S.H. Climate Policy 1, 2001. Integrated Assessment of Abrupt Climatic Changes.

Matear, R. J., and A. C. Hirst. 2003. Long-term changes in dissolved oxygen concentrations in the oceans caused by protracted global warming. Global Biogeochemical Cycles 17 (4):doi: 10.1029/2002GB001997.

Matsui, Y. (2002) “Some Aspects of the Principle of ‘Common but Differentiated Responsibilities’”, in International Environmental Agreements: Politics, Law and Economics, 2, 151-171.

Matthews, H. D., A. J. Weaver, K. J. Meissner 2005, Terrestrial Carbon Cycle Dynamics under Recent and Future Climate Change, J. Clim 18, 1609-1627.

McInnes, K.L., R. Suppiah, P.H. Whetton, K.J. Hennessy and R.N. Jones, 2002: Climate change in South Australia. Report on assessment of climate change, impacts and possible adaptation strategies relevant to South Australia. CSIRO Atmospheric Research, Aspendale, Victoria.

McMichael, A., D. Campbell-Lendrum, S. Kovats, S. Edwards, P. Wilkinson, T. Wilson, R. Nicholls, S. Hales, F. Tanser, D. LeSueur, M. Schlesinger, and N. Andronova. 2004. Climate Change. In: M. Ezzati, A. Lopez, A. Rodgers and C. Murray (Editors), Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors. World Health Organization, Geneva.

McMichael, A.J., Campbell-Lendrum, D, Kovats, R.S., Edwards, S., Wilkinson, P, Edmonds, N, Nicholls, N., Hales, S., Tanser, F.C., Le Sueur, D., Schlesinger, M, Andronova, N., 2004: Climate Change. In Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors. Vol 2; Ezzati, M., Lopez, A.D., Rogers, A., Murray, C.J. (eds) WHO, Geneva; Ch 20.

McPherson HG, Salinger MJ (2000) Investigating climate change impacts and thresholds:

Meehl, G.A., and J.M. Arblaster, 2003: Mechanisms for projected future changes in south Asian monsoon precipitation. Climate Dynamics, 21, 659-675.

Meinshausen, M., B. Hare, T. M. L. Wigley, D. van Vuuren, M. G. J. den Elzen, R. Swart, 2005: Multi-gas emission pathways to meet climate targets. Accepted by Climatic Change.

Meinshausen, M.: 2005 (forthcoming), 'What does a 2°C target mean for greenhouse gas concentrations? - A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates. ' in Schellnhuber, J.S., Cramer, W., Nakicenovic,N., Wigley, T.M.L. and Yohe, G. (eds.), Avoiding Dangerous Climate Change, Cambridge University Press, Cambridge.

Mendelsohn, R. and Nordhaus, W., 1996. The Impact of Global Warming on Agriculture: Reply. American Economic Review, 86(5): 1312-1315

Mendelsohn, R., Dinar, A., Dalfelt, A., 2000: Climate Change Impacts on African Agriculture, World Bank Report. The World Bank.

Mendelsohn, R., Nordhaus, W. and Shaw, D., 1994. The Impact of Global Warming on Agriculture: A Ricardian Analysis. American Economic Review, 84(4): 753-771

Mercer, J.H., West Antarctic ice sheet and CO2 greenhouse effect, Nature 271, 321-325 (1978).

Metz, B., M. Berk, M. den Elzen, B. de Vries, D. van Vuuren, Towards an equitable global climate change regime: compatibility with Article 2 of the Climate Change Convention and the link with sustainable development, Climate Policy 84:1 (2002).

Millennium Ecosystem Assessment, 2005a. Living Beyond Our Means: Natural Assets and Human Well-Being (Statement of the MA Board) 2005 www.MAweb.org.

Millennium Ecosystem Assessment, 2005b. Millennium Ecosystem Assessment (MA) Synthesis Report. www.MAweb.org

Mills. E/ (2005): “Insurance in a Climate of Change.” *Science*, : 1040-1044

Morgan, M. G., D. W. Keith: Subjective Judgements by Climate Experts. Environmental Science & Technology 29:468A-476A, 1995

Morgan, M. Granger and Max Henrion, 1990. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press.

Morgenstern, Richard D., W. Harrington, and P. Nelson, 2000. “On the Accuracy of Regulatory Cost Estimates,” Journal of Policy Analysis and Management, 19(2), pp. 297-322.

Morita, T., Nakicenovic, N. and Robinson, J.: 2000, 'Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES)', Environmental Economics and Policy Studies 3, 65-88.

Moss, R. H.: Avoiding ‘dangerous’ interference in the climate system. The roles of values, science and policy. Global Environmental Change 5:3-6, 1995

Moss, R.H. and S.H. Schneider, 2000: ““Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting", Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC, ed. R. Pachauri, T. Taniguchi, and K. Tanaka. Geneva, Switzerland: World Meteorological Organization, 33-51.

Muir-Wood, 2000: Deglaciation seismotectonics: a principal influence on intraplate seismogenesis at high latitudes. Quaternary Science Reviews, 19, 1399-1411.

Munich Re. 2006. Topics-Geo – Annual Review: Natural Catastrophes 2005. 56 pp. [available from Munchener Ruckversicherungs Gesellschaft, Konigstrasse 107, 80802 Munchen, Germany. www.munichre.com/publications/302-04772_en.pdf.]

Murphy *et al.*, Quantification of modelling uncertainties in a large ensemble of climate change simulations, Nature 430:768, 2004

Myer, G.A. and J.L. Pierce, 2003: Climatic controls on fire-induced sediment pulses in Yellowstone National Park and central Idaho. *Forest Ecology and Management*, **178**, 89-104.

Myers, N. and Kent, J, Environmental Exodus. An Emergent Crisis in the Global Arena, Washington, DC. Climate Institute.

Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B. da Fonseca, and J. Kent. 2000. “Boidiversity hotspots for conservation priorities.” Nature 403: 853-858.

Narain, Optimal response under endogenous abrupt climate change risk: experiments with the DICE model, paper presented at IEA Meeting Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy.

Narayan, D., R. Chambers, M. K. Shah and P. Petesch [eds.]: Voices of the Poor: Crying Out for Change. Oxford University Press, New York, 2000

National Academy of Sciences, 1991; The Policy Implications of the Greenhouse Effect; National

Academies Press, Washington DC

National Research Council, 1994. Science and Judgment in Risk Assessment. Washington, DC: National Academy Press (see esp. Chapter 9—"Variability")

National Research Council, 1995. Technical Bases for Yucca Mountain Standards. Washington, DC: National Academy Press.

New, M., M. Hulme: Representing uncertainty in climate change scenarios: a Monte-Carlo approach. Integrated Assessment 1:203-213, 2000

Nicholls *et al.* forthcoming

Nicholls, R. J. 2004. "Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios." *Global Environmental Change.* 14: 69-86.

Nicholls, R. J. and R. S. J. Tol. (In Press). "Impacts and Response to Sea Level Rise: A Global Analysis of the SRES Scenarios Over the 21st Century." *Philosophical Transactions of the Royal Society A.* Sea-Level Rise volume

Niemeyer, S., J. Petts, and K. Hobson, *Rapid Climate Change and Society: Assessing Responses and Thresholds, Risk Analysis, Vol. 25, No. 6, 2005* DOI: 10.1111/j.1539-6924.2005.00691.x

Nisbet, The potential for geological surprise in the coupled atmosphere-ocean-cryosphere-biosphere system, paper presented at IEA Meeting Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy.

Nordhaus, W. 2006. "Geography and Macroeconomics: New Data and New Findings." New Haven, Connecticut: Yale University.

Nordhaus, W. D. 1994. Managing the global commons: The economics of climate change: The MIT press, Cambridge, Massachusetts.

Nordhaus, W.D.: Expert opinion on climatic change, American Scientist 82 (1994) 45–52.

Nordhaus, William D., and J. Boyer. 2000. Warming the world: Economic models of global warming: MIT Press.

Norton, Bryan. 1998. Ecology and Opportunity: Intergenerational Equity and Sustainable Options. In Andrew Dobson ed., Fairness and Futurity. Oxford University Press, 118-150.

Nozick, Robert. 1974. Anarchy, State and Utopia. Basic Books.

Nussbaum, Martha. 2000. Women and Human Development. Cambridge University Press.

Nyong, A., Impacts of Climate change in the Tropics: The African Experience, Keynote Presentation at Exeter Avoiding Dangerous Climate Change Symposium, 1-3 February, 2005, p.9.

O'Brien, Karen et.al. Whats in a word? Conflicting Interpretations of vulnerability in climate change research, CICERO working paper 04, www.cicero.org – has very good recent literature section

O'Brien, K.L., Sygna, L. and J.E. Haugen. 2004. Resilient of Vulnerable? A Multi-Scale Assessment of Climate Impacts and Vulnerability in Norway. *Climatic Change* 64: 193-225.

O'Neill, B. C., and M. Oppenheimer. 2002. Climate change - dangerous climate impacts and the Kyoto protocol. Science 296 (5575):1971-1972.

O'Neill, B.C. and M. Oppenheimer, 2004. Climate Change Impacts Sensitive to Path to Stabilization. Proc. Nat. Acad. Sci., 101, 16,411-16,416.

OECD (2003). Development and Climate Change in Nepal: Focus on Water Resources and Hydropower. Document COM/ENV/EPOC/DCD/DAC(2003)1/FINAL. OECD Environment Directorate. Paris, France, 2003

OECD 2005, *Bridge Over Troubled Waters: Linking Climate Change and Development*, Paris.

Office of Management and Budget, U.S., 2003. Circular A-4: Regulatory Analysis. Executive Office of the President, September 17, 2003, 48 pp.

Okrent, David, 1998. "Comment: Pigford, Shrader-Frechette & the NRC Report on Yucca Mountain," RISK: Health, Safety & Environment, 9, pp. 1-6.

Oppenheimer and Alley citations.

Oppenheimer, M. (2005). Defining Dangerous Anthropogenic Interference: The Role of Science, the Limits of Science, Risk Analysis, in press.

Oppenheimer, M. and A. Petsonk, 2003, Global Warming: The Intersection of Long-Term Goals and Near-Term Policy in Michel, D. (ed.), Climate Policy for the 21st Century: Meeting the Long-Term Challenge of Global Warming, Center for Transatlantic Relations, Johns Hopkins University, Washington, pp.79-112.

Oppenheimer, M. and A. Petsonk, 2005, Article 2 of the UNFCCC: Historical Origins, Recent Interpretations, Climatic Change 73:195-226

Oppenheimer, M. and R.B. Alley, 2005, Ice Sheets, Global Warming, and Article 2 of the UNFCCC (with R.B. Alley), Climatic Change, in press.

Oppenheimer, M., Global warming and the stability of the Western Antarctic Ice Sheet, Nature 393, 325 (1998). 2-3C threshold for disintegration.

Oppenheimer, M.and R.B. Alley, The West Antarctic Ice Sheet and Long Term Climate Policy, Climatic Change 64, 1-10 (2004).

Ostermeier, G.M. and Wallace, J.M., 2003: Trends in the North Atlantic Oscillation – Northern Hemisphere Annular Mode during the twentieth century. Journal of Climate, 16, 336-341.

Otto-Bliesner, B.L., S.J. Marshall, J.T. Overpeck, G.H. Miller and A. Hu. 2006. “Simulating Arctic Climate Warmth and Icefield Retreat in the last Interglaciation.” *Science* 311.

Overpeck, J.T., B.L. Otto-Bliesner, G.H. Miller, D.R. Muhs, R.B. Alley, and J.T. Kiehl. 2006. “Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise.” *Science* 311: 1747-1750.

Palmer, T. N., and J. Räisänen, 2002. Quantifying the risk of extreme seasonal precipitation events in a changing climate, Nature 415, 512 - 514

Parfit, Derek. 1997. Equality and Priority. Ratio 10: 202-221.

Parmesan, C. and G. Yohe, 2003: “A Globally Coherent Fingerprint of Climate Change Impacts Across Natural Systems," Nature 421: 37-42.

Parmesan, C. and G. Yohe. 2003. “A globally coherent fingerprint of climate change impacts across natural systems.” *Nature* 421: 37-42.

Parry M., N. Arnell; T. McMichael, R. Nicholls, P. Martens, S. Kovats, M. Livermore, C. Rosenzweig, A. Iglesias, and G. Fischer. 1999. “Millions at Risk: Defining Critical Climate Change Threats and Targets,” *Global Environmental Change,* 11: 181-183.

Parry M.L., Rosenzweig C., Iglesias A., Livermore M and G. Fishere, 2004: Effects of climate change on global food production under SRES climate and socio-economic scenarios. Global Environmental Change, volume 14, number 1, pp. 53-67.

Parry ML, Carter TR, Hulme M (1996) What is dangerous climate change? Global Environmental, Change 6, 1-6

Parry, M., Carson, I., Rehman, T., Tranter, R., Jones, P., Mortimer, D., Livermore, M. and Little, J. (1999) *Economic Implications of Climate Change on Agriculture in England and Wales*, Jackson Environmental Institute, University of East Anglia, Norwich.

Patwardhan, A., S.H. Schneider, and S.M. Semenov, 2003: “Assessing the Science to Address UNFCCC Article 2: A concept paper relating to cross cutting theme number four.” IPCC.

Paustenbach, Dennis J., 2002. “Primer on Human and Environmental Risk Asessment,” pp. 3-83 in Human and Ecological Risk Assessment: Theory and Practice, D.J. Paustenbach, ed., Wiley-Interscience, New York, NY.

Pearce, D.W., 2003. The social cost of carbon and its policy implications. Oxford Review of Economic Policy 19(3), August.

Peterson B.J., Holmes R.M., McClelland J.W., Vörösmarty C.J., Lammers R.B.,

Pielke, R. A. and Downton, M.W. Precipitation and Damaging Floods: Trends in the United States, 1932–97, J. Clim 13, 3625-3637.

Pielke, R. A., and C. N. Landsea. 1999. La Nina, El Niño, and Atlantic hurricane damages in the United States. Bulletin of the American Meteorological Society 80 (10):2027-2033.

Pitinni, M. and M.Rahman (2004) “The Social Cost of Carbon Review” in *Benefits of Climate Policies:Improving Information for Policymakers,* OECD, Paris

Pittock, A. Barrie, 2005. Climate change: turning up the heat. CSIRO Publishing, 328pp.

Pittock, B.A. (ed.), 2003: Climate Change: An Australian Guide to the Science and Potential Impacts. Australian Greenhouse Office, Canberra. Available at www.greenhouse.gov.au.

Pittock, B.A. Coral reefs and environmental change: adaptation to what?, Amer. Zool. 39:10, 1999

Polsky, C. and Easterling, W.E., 2001. Adaptation To Climate Variability and Change in the US Great Plains: A Multi-Scale Analysis of Ricardian Climate Sensitivities. Agriculture, Ecosystems, and Environment, 85(1-3): 133-144

Polsky, C., 2004. Putting Space and Time in Ricardian Climate Change Impact Studies: The Case of Agriculture in the U.S. Great Plains. Annals of the Association of American Geographers, 94(3): 549-564

Porter, Michael E., and C. van der Linde, 1995. “Toward a New Conception of the Environment-Competitiveness Relationship,” Journal of Economic Perspectives, 9(4), pp. 97-118.

Pratt, John W., and R.J. Zeckhauser, 1982. “Inferences from Alarming Events,” Journal of Policy Analysis and Management, 1(3), pp. 371-85.

Presidential/Congressional Commission on Risk Assessment and Management, 1997. Final Report, 2 vols., Washington, DC (see http://www.riskworld.com/Nreports/1996/risk_rpt/Rr6me001.htm for full text)

Price, J. T. and T. L. Root, Ecosystem functioning under abrupt climate change, potential surprises and adaptations, paper presented at Abrupt Climate Change Strategy Workshop

Price, J. T., The likelihood of surprises in ecosystem functioning under abrupt climate change, paper presented at IEA Meeting Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy.

PRUDENCE,

Putilov V. Ya. (ed.): 2003. Ecology of Power Engineering. Published by Moscow Energy Engineering Institute, Moscow. (in Russian)

R. N. Jones (2001): An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments. Natural Hazards 23:197-230

Rahmstorf, S. and K. Zickfeld (2005) Thermohaline circulation changes: a question of risk assessment, Climatic Change 68, 241-247.

Rahmstorf, S., T. Kuhlbrodt, K. Zickfeld, G. Buerger, F. Badeck, S. Pohl, S. Sitch, H. Held, T. Schneider von Deimling, D. Wolf-Gladrow, M. Schartau, C. Sprengel, S. Sundby, B. Adlandsvik, F. Vikebo, R. Tol, M. Link (2003): Integrated Assessment of Changes in the Thermohaline Circulation - INTEGRATION Status Report. Potsdam Institute for Climate Impact Research, Potsdam, Germany. Available at http://www.pik-potsdam.de/~stefan/projects/integration/publications.html

Rahmstorf, S., The Thermohaline Circulation: A System with Dangerous Thresholds?, Climatic Change 46, 247-256 (2000). To prevent collapse, less than 4-5C warming over 100 years.

Rayner S and E Malone (eds) 1998. *Human Choice and Climate Change*, Volume 1, Battelle Press, Washington DC.

Reilly, J. and Schimmelpfennig, D. (2000). Irreversibility, uncertainty, and learning: Portraits of adaptation to long-term climate change. Climatic Change, 45:253–278.

Reilly, J., P. H. Stone, C. E. Forest, M. D. Webster, H. D. Jacoby and R. G. Prinn (2001) Climate change - Uncertainty and climate change assessments. *Science* **293**, 430-433.

Revelle, R. 1983. ‘Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide’, in *Changing Climate*, National Academy Press, Washington, D.C.

Rial, J. A. *et al.*, Nonlinearities, feedbacks and critical thresholds within the Earth’s climate system, Climatic Change 65:11 (2004).

Rignot, E., D. Braaten, P. Gogineni, W. Krabill, and J. McConnell (2004), Rapid ice discharge from southeast Greenland glaciers, Geophys. Res. Lett., 31, L10401, doi:10.1029/2004GL019474.

Rodo, X., M. Pascual, G. Fuchs, and A. S. G. Faruque. 2002. ENSO and cholera: A nonstationary link related to climate change? Proceedings of the National Academy of Sciences of the

United States of America 99 (20):12901-12906.

Rogers, P, 2004, Climate Change and Security, IDS Bulletin, Volume 35, number 3, July 2004.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds. 2003. “Fingerprints of global warming on wild animals and plants.” *Nature* 421: 57-60.

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, and J. A. Pounds, 2003: “'Fingerprints' of Global Warming on Animals and Plants," Nature 421: 57-60.

Rosenzweig, C. and Iglesias, A. (eds.), 1994. Implications of Climate Change for International Agriculture: Crop Modeling Study. Washington, DC: U.S. Environmental Protection Agency, EPA 230-B-94-003.

Rosenzweig, C., F. N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield. 2002. “Increased crop damage in the US from excess precipitation under climate change.” Global Environmental Change 12:197-202.

Rosenzweig, C., F. N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield. 2002. “Increased crop damage in the US from excess precipitation under climate change.” *Global Environmental Change* 12:197-202.

Rothman, D.: Measuring Environmental Values and Environmental Impacts: Going from the Local to the Global. Climatic Change 44:351-376, 2000

Rotmans, J., M. B. A. van Asselt: Uncertainty in integrated assessmemt modelling: A labyrinthic path. Integrated Assessment 2:43-55, 2001

Rottenstreich, Y., & Hsee, C. K. (2001). Money, kisses, and electric shocks: On the affective psychology of risk. Psychological Science, 12 (3), 185-190.

Royal Society, Ocean Acidification due to increasing Atmospheric Carbon Dioxide, London, 2005 (http://www.royalsoc.ac.uk/document.asp?tip=0&id=3249)

Ruosteenoja, K., T.R. Carter, K. Jylhä and H. Tuomenvirta, 2003: Future climate in world regions: an intercomparison of model-based projections for the new IPCC emissions scenarios. *The Finnish Environment* 644, Finnish Environment Institute, 83 pp.

Sadler B.S., Mauger G.W. and Stokes R.A., 1988: The water resource implications of a drying climate in south-west Western Australia. In: Pearman (ed.) Greenhouse: Planning for Climate Change, pp 296-301. CSIRO 1988. ISBN 0 643 04863 4.

Sadler, B., 2003: Informed adaptation to a changed climate state: is south-western Australia a national canary? Proceedings, Living With Climate Change Conference, Canberra, 19 December 2002. National Academies Forum, Canberra.

Sadler, B.S. (ed.), 2002: Climate variability and change in south west Western Australia. Indian Ocean Climate Initiative, 43 pp. available at www.ioci.org.au

Sagoff, Mark. 1988. The Economy of the Earth. Cambridge, UK: Cambridge University Press.

Sarmiento, J. L., and C. Le Quéré. 1996. Oceanic carbon dioxide uptake in a model of century-scale global warming. Science 274:1346-1350.

Sauber, J.M. and Molnia, B.F., 2004: Glacier ice mass fluctuations and fault instability in tectonically active Southern Alaska. Global and Planetary Change, 42, 279-293.

Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, Geophys. Res. Lett., 31, L18402, doi:10.1029/2004GL020670.

Scambos, T., C. Hulbe, and M. Fahnestock (2003), Climate-induced ice shelf disintegration in the Antarctic Peninsula, in Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives, Antarct. Res. Ser., vol. 79, edited by E. Domack *et al.*, pp. 79 – 92, AGU, Washington, D. C.

Schaeffer, M., F. M. Selten, J. D. Opsteegh, and H. Goosse. 2002. Intrinsic limits to predictability of abrupt regional climate change in IPCC SRES scenarios. Geophysical Research Letters 29 (16).

Schär, C., and Jendritzky, G. 2004. Climate change: hot news from summer 2003. Nature 432(7017):559-60.

Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller. 2004. “The role of increasing temperature variability in European summer heatwaves.” Nature. 427: 332-336.

Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller. 2004. “The role of increasing temperature variability in European summer heatwaves.” *Nature*. 427: 332-336.

Scherer, R.P., A. Aldahan, S. Tulaczyk, G. Possnert, H. Engelhardt, B. Kamb, Pleistocene collapse of the West Antarctic ice sheet, Science 281, 82-85 (1998).

Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, F., Raynaud, M., Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X., Jonas, P., Charlson, R., Rodhe, H., Sadasivan, S., Shine, K.P., Fouquart, Y., Ramaswamy, V., Solomon, S., Srinivasan, J., Albritton, D.L., Isaksen, I., Lal, M., Wuebbles, D.J., 1996. Radiative forcing of climate change. In: Houghton, J.T., Meiro Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995: The Science of Climate Change — Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 65– 131.

Schlenker, W., Hanemann, W. M., Fisher, A. C. (2005): "Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach," *American Economic Review*, 95(1):395-406

Schlesinger, W. H. and J. Lichter. 2001. “ Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO2.” Nature 411: 466-469.

Schmidtz, David. 2001. A Place for Cost-Benefit Analysis. Nous-Supplement 11: 148-171.

Schmittner, A. M., “Decline of the marine ecosystems caused by a reduction in the Atlantic overturning circulation.”, Nature 434: 628-633, 2005.

Schneider, S. H. (2001): “What is 'Dangerous' Climate Change?” Nature, 411: 17-19.

Schneider, S. H. (2002) Can we estimate the likelihood of climatic changes at 2100? *Climatic Change* **52**, 441- 451.

Schneider, S. H. (2003): “Abrupt Non-Linear Climate Change, Irreversibility and Surprise", OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers, Working Party on Global and Structural Policies, 32 pp. Available online at: http://www.oecd.org/dataoecd/9/59/2482280.pdf

Schneider, S. H., B. L. Turner II, H. Morehouse Garriga: Imaginable surprise in global change science. Journal of Risk Research 1:165-185, 1998

Schneider, S. H., Kuntz-Duriseti, K. and Azar, C. (2000):Costing non--linearities, surprises,and irreversible events. Pacific-Asian Journal of Energy 10, 81-106.

Schneider, S. H.: Abrupt non-linear climate change, irreversibility and surprise. Global Environmental Change 14:245-258, 2004.

Schneider, S.H. and C. Azar, 2001: ““Are Uncertainties in Climate and Energy Systems a Justification for Stronger Near-term Mitigation Policies?” Proceedings of the Pew Center Workshop on The Timing of Climate Change Policies, ed. E. Erlich, 85-136. Washington D.C., 11-12 October 2001.

Schneider, S.H. and R. S. Chen (1980). Carbon-Dioxide warming and coastline flooding – physical factors and climatic impact, Annual Reviews of Energy 5, 107-140.

Schneider, S.H., and Mastrandrea, M.D. (2005) Probabilistic Assessment of “Dangerous” Climate Change and Emissions Scenarios. Proceedings of the National Academy of Sciences, in press.

Schroter et.al. Modeling the vulnerability of eco-social systems to global change: Human Adaptive capacity to changes in ecosystems service provisions, October 2003, ATEAM EU-funded project results

Scott, D., G. McBoyle, and B. Mills. 2003. Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. Climate Research 23: 171-181.

Semenov S. M., Gelver E. S., Yasyukevich V. V. 2002: Temperature conditions for Development of two species of malaria pathogens in the vector organism in Russia in the 20th century. Doklady Biological Sciences. Volume 387, November-December 2002, p. 523-528 Translated from Doklady Akademii Nauk, Vol. 387, No. 1, 2002, 131–136.

Semenov S. M.: 2004. Modeling of anthropogenic perturbation of the global CO2 cycle. Doklady Earth Sciences (English Translation of Doklady Akademii nauk, vol. 398, No 6,), Volume XXX, Number 8, p. XXX-XXX.

Semenov S.M and Gel'ver E.S., 2003: Climatic changes in the total annual precipitation and frequency of measured precipitation over the territory of Russia and adjacent countries in the 20th century. Doklady Earth Sciences. Geophysics. Vol. 393a, No 9, pp. 1338-1341. Translated from Doklady Akademii Nauk, Vol. 393, No. 6, 2003, pp. 818-821.

Semenov S.M., 2004: Greenhouse gases and present climate of the Earth. Moscow, Publishing center "Meteorology and Hydrology", 175 pp. (in Russian)

Semenov S.M., Koukhta B.A., Gel'ver E.S. Nonlinearity of climate-driven changes in phenological dates in woody plants. Doklady Biological Sciences, Vol. 396, 2004, pp. 221–223. Translated from Doklady Akademii Nauk, Vol. 396, No. 3, 2004, pp. 427–429.

Sen, Amartya. 1999. Development as Freedom. Oxford University Press.

Sen, A. K. 1981 Poverty and Famines. Clarendon Press, Oxford, UK.

Shepherd, A., D. Wingham, A. Payne, and P. Skvarca, 2003: Larsen ice shelf has progressively thinned. Science, 302, 856-859.

Shiklomanov A.I., Shiklomanov I.A., Rahmstorf S., 2002: Increasing River Discharge to the Arctic Ocean. Science, vol. 298, 13 DECEMBER 2002, www.sciencemag.org

Shrader-Frechette, Kristin, 1992. "Risk Estimation and Expert Judgment: The Case of Yucca Mountain," RISK: Health, Safety & Environment, 3, pp. 283-302.

Shrader-Frechette, Kristin, 1996. "Nuclear Waste: The Academy and Million-Year Estimates." Quarterly Review of Biology, 71(3), pp. 381-385.

Shue, Henry. 1999a. Bequeathing Hazards: Security Rights and Property Rights of Future Humans. In Global Environmental Economics: Equity and the Limits to Markets, eds. M. Dore and T. Mount, pp. 38-53. Oxford: Blackwell.

Shue, Henry. 1999b. Global Environment and International Inequality. International Affairs 75: 531-545

Shue, Henry. 2001. Climate. In A Companion to Environmental Philosophy, ed. Dale Jamieson, pp. 449-459. Oxford: Blackwell.

Shue, Henry. 2004. A Legacy of Danger: The Kyoto Protocol and Future Generations'. In Globalisation and Equality, eds. Keith Horton and Haig Patapan. Routledge.

Shukla *et al.*, Climate Change and India, vulnerability assessment and adaptation, 2003

Siegenthaler U., Joos F. Use of a simple model for studying oceanic tracer distributions and the global carbon cycle, Tellus, Ser. B, 44, 186–207, 1992.

Silverman, D. 1997. Introducing Qualitative Research. Pgs 1-7 in Qualitative Research: Theory, Method, and Practice (D. Silverman, Ed.). Sage Publications, London.

Silverman, D. 2001. Interpreting Qualitative Data: Methods for Analysing Talk, Text, and Interaction. Sage Publications, London.

Simon, Herbert. 1955. A Behavioral Model of Rational Choice. Quarterly Journal of Economics 69: 99-118.

Sinnott-Armstrong, Walter. 2005. Individual Responsibility for Global Warming. In Walter Sinnott-Armstrong and R.B. Howarth (eds.). Global Warming: Interdisciplinary Perspectives (forthcoming).

Slovic, P. (1987). Perception of risk. Science, 236, 280-285.

Slovic, P. (2000): The perception of risk. London, Sterling, VA : Earthscan Publications.

Slovic, P. Flynn, J., & Layman, M. (1991). Perceived risk, trust, and politics of nuclear waste.

Science, 254, 1603-1607.

Slovic, P., 2000: The perception of risk. Earthscan Publications, London

Slovic, P., Fischhoff, B., & Lichtenstein, S. (1978). Accident probabilities and seat belt usage: A psychological perspective. Accident Analysis and Prevention, 10, 281-285.

Slovic, P., Fischhoff, B., & Lichtenstein, S. (1979). Rating the risks. Environment, 2 (3), 14-20.

Slovic, P., Fischhoff, B., & Lichtenstein, S. (1980). Facts and fears: Understanding perceived risks. In R. C. Schwing & W. A. Albers, Jr (Eds.), Societal Risk Assessment: How Safe is Safe Enough? New York: Plenum.

Smith B, White A, Young-Molling C., 31 2001: Global response of terrestrial ecosystem structure and function to CO2 and climate change: 32 results from six dynamic global vegetation models. Global Change Biology, 7 (4) , 357-374. 33

Smith, Andrew E., P.B. Ryan, and J.S. Evans, 1992. "The Effect of Neglecting Correlations when Propagating Uncertainty and Estimating the Population Distribution of Risk," Risk Analysis, 12(4), pp. 467-74.

Smith, J. B. *et al.*, in Climate Change 2001: Impacts, Adaptation, and Vulnerability, J. J. McCarthy *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 913–967.

Smith, J. B., H. J. Schellnhuber, M. Q. Mirza, S. Fankhauser, R. Leemans, E. Lin, L. Ogallo, B. Pittock, R. Richels, C. Rosenzweig, U. Safriel, R.S.J. Tol, J. Weyant, and G. Yohe. 2001. "Vulnerability to Climate Change and Reasons for Concern: A Synthesis." in: J. McCarthy, O. Canziana, N. Leary, D. Dokken, and K. White (eds.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* New York, Cambridge University Press. pp 913-967.

Sperling, F. et.al.: *Poverty and Climate Change - Reducing the Vulnerability of the Poor through Adaptation*; GTZ; 2003.

Stayner, Leslie, Mark Toraason, and Dale Hattis, eds., 2002. Of Mice, Men, and Models: Future Research for Improving Risk Assessment Methods. Special issue of Human and Ecological Risk Assessment, 8(6), October 2002, pp. 1195-1487. CRC Press, Boca Raton, FL

Stewart *et al.*, 2000: Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Quarternary Science Reviews, 19, 1367-1391.

Stewart, I.T., Cayan, D.R., Dettinger, M.D. (2004) Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. Climatic Change 62, 217-232.

Stocker, T. F., and A. Schmittner. 1997. Influence of CO2 emission rates on the stability of the thermohaline circulation. Nature 388:862-865.

Stott, P. A., D. A. Stone, and M. R. Allen. 2004. "Human contribution to the European heatwave of 2003." Nature 432: 610-614.

Stott, P. A., D. A. Stone, and M. R. Allen. 2004. "Human contribution to the European heatwave of 2003." *Nature* 432: 610-614.

Stouffer, R.J., and S. Manabe, 2003: Equilibrium response of thermohaline circulation to large changes in atmospheric CO2 concentration. Climate Dynamics, 20, 759-773.

Strauss, A. L., and J. Corbin. 1998. Basics of qualitative research: techniques and procedures for developing grounded theory. SAGE Publications, London.

Struyf, E., S. Van Damme, and P. Meire (2004). Possible effects of climate change on estuarine nutrient fluxes: a case study in the highly-nutrified Schelde estuary (Belgium, The Netherlands), Estuarine Coastal and Shelf Science, 60, 649-661.

Swart, R., Berk, M., Janssen, M., Kreileman, E., and Leemans, R., 1998: The safe landing approach: risks and trade-offs in climate change. pp. 193-218 in Alcamo, J., Leemans, R., Kreileman, E.: Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model, Pergamon, Oxford

Swart, R., Mitchell, J., Morita, T., and Raper, S. (2002) Stabilisation scenarios for climate impact assessment, *Global Environmental Change*, **12**, 155-166.

Swetnam, T. W., and J. L. Betancourt. 1990. Fire - Southern Oscillation Relations in the

Southwestern United-States. Science 249 (4972):1017-1020.

Tabara, D., D. Sauri, and R. Cerdan. 2003. Forest fire risk management and public participation in changing socioenvironmental conditions: a case study in a Mediterranean region. Risk Analysis 23: 249-260.

Tanzler, D. Carius A., and Oberthur, S., 2002, Climate Change and Conflict Prevention, Can Climate change impacts increase conflict potentials? What is the relevenace of this issue for the international process on climate change? A Report for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Tebaldi, C., L. O. Mearns, D. Nychka, and R. L. Smith (2004), Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations, *Geophys. Res. Lett.*, *31*, L24213, doi:10.1029/2004GL021276

Temkin, Larry, 1993, *Inequality*, Oxford: Oxford University Press.

TERI, Environmental Threats, vulnerability and adaptation, Case Studies from India.

Thomas, C., A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. F. de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips, and S. E. Williams. 2004. “Extinction risk from climate change.” Nature 427: 145-148.

Thomas, C., A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. F. de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips, and S. E. Williams. 2004. “Extinction risk from climate change.” *Nature* 427: 145-148.

Thompson, D.W.J. and J.M. Wallace, 2000: Annular modes in the extratropical circulation. Part II: trends. Journal of Climate, 13, 1018-1036.

Thompson, D.W.J. and Solomon, S., 2002: Interpretation of recent southern hemisphere climate change. Science, 296, 895-899.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. Nature 398 (6729):694-697.

Titus, J.G. and V.K. Narayanan. 1996. The risk of sea-level rise. *Climatic Change* 33:151-212.

Tol, R. S. J. 2002. “Estimates of the Damage Costs of Climate Change. Part 1: Benchmark Estimates .” *Environmental and Resource Economics* 21: 41-73.

Tol, R. S. J., 2002. “Estimates of the Damage Costs of Climate Change. Part II: Dynamic Estimates.” Environmental and Resource Economics 21: 135-160.

Tol, R. S. J., S. Fankhauser, O. J. Kuik, and J. B. Smith. 2003. “Recent economic insights int the impacts of climate change.” In: C. Giupponi and M. Shechter (eds.). Climate Change and the Mediterranean: Socio-economic Perspective so Impacts, Vulnerability, and Adaptation. Northampton, Massachusetts: Edward Elgar. pp. 15-31.

Tol, R.S.J. and Dowlatabadi, H., 2002. Vector-borne diseases, development, and climate change. Integrated Environmental Assessment 2,173-181.

Tol, R.S.J., Potential slowdown of the thermohaline circulation and climate policy, Discussion Paper DS98/06 Institute for Environmental Studies Vrije Universiteit Amsterdam, 1998.

Tol, R.S.J., T.E.Downing, Kuikb, O.J., Smith, J.B. (2004). Distributional aspects of climate change impacts, Global Environmental Change 14, 259–272

Tolhurst, K., 2003: Impact of climate change on forest fire size and severeity. In: *Proc. Climate Impacts on Australia’s Natural Resources: Current and Future Challenges*. 25-27 November, 2003, Surfers Paradise, Queensland. Published by Queensland Department of Natural Resources and Mines, pp.36-38.

Tonn, Bruce. 2003. An Equity First, Risk-based Framework for Managing Global Climate Change. Global Environmental Change 13, 295-306.

Torvanger *et al.*, CICERO Report 2004:02

Toth, F. L., 2004: Top-down approaches to Article 2: Methods and Models. pp. 34-38 in Report of the IPCC Expert Meeting on the Science to Address UNFCCC Article 2 including Key Vulnerabilities. 18-20 May 2004, Buenos Aires, Argentina.

Toth, F.L. (ed.): Special Issue Integrated Assessment of Climate Protection Strategies. Climatic Change 56(1-2), 2003

Toth, F.L., T. Bruckner, H.-M. Füssel, M. Leimbach, G. Petschel-Held, H.-J. Schellnhuber: Exploring Options for Global Climate Policy: A New Analytical Framework. Environment 44(5):22-34, 2002

Toth, F.L., T. Bruckner, H.-M. Füssel, M. Leimbach, G. Petschel-Held: Integrated assessment of long-term climate policies: Part 1 - Model presentation. Climatic Change 56(1):37-56, 2003a

Toth, F.L., T. Bruckner, H.-M. Füssel, M. Leimbach, G. Petschel-Held: Integrated assessment of long-term climate policies: Part 2 - Model results and uncertainty analysis. Climatic Change 56(1):57-72, 2003b

Traxler, Martino. 2002. Fair Chore Division for Climate Change. Social Theory and Practice 28, 101-43.

Turley, C. J. Blackford, S. Widdicombe, D. Lowe, F. Gilbert and P. Nightingale (2005), Reviewing the Impact of Increased Atmospheric CO2 on Oceanic pH and the Marine Ecosystem, presented at Symposium on Avoding Dangeros Climate Change, UK Department of Environment, Food, and Rural Affairs, Feb 1-3, Exeter, UK.

Tversky, A., & Kahneman, D. (1973). Availability: A heuristic for judging frequency and probability. Cognitive Psychology, 5, 207-232.

Tversky, A., & Kahneman, D. (1981). The framing of decisions and the psychology of choice. Science, 211, 453-458.

Tyndall Centre for Climate Change Research, January 2004, Neil Adger.et. al, New Indicators of Vulnerability and adaptive capacity. Tyndall Technical Report 7 and Tyndall Working Paper 38. www.tyndall.ac.uk. Good but very dense to read.

UK Foresight studies

UN Framework Convention on Climate Change.1992.

UNDP Adaptation Framework & all background technical papers. Available from IIED and UNDP website. www.undp.org/gef/

UNFCCC secretariat document on methods/tool appraoches to adaptation/vulnerability, November 2004

van Lieshout, M., Koavates, R.S., Livermore, M.T.J. and Martens, P. 2004. Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. Global Environmental Change 14, 87-99.

van Minnen, J. G., J. Onigkeit, J. Alcamo, Critical climate change as an approach to assess climate change impacts in Europe: development and application, Environmental Science & Policy 5:335, 2002

Vaughan, D.G. (2005) How Does the Antarctic Ice Sheet Affect Sea Level Rise? Science 308, 1877-1878.

Vaughan, D.G., 2006: West Antarctic Ice Sheet collapse - the fall and rise of a paradigm. Clim. Change, in press

Vaughan, D.G., J.R. Spouge, Risk estimation of collapse of the West Antarctic Ice Sheet, Climatic Change 52, 65-91 (2002).

Vellinga, M., and R. A. Wood. 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. Climatic Change 54 (3):251-267.

Visser M.E. & L.J.M. Holleman 2001. Warmer springs disrupt the synchrony of oak and winter moth phenology. Proc. R. Soc. Lond. B 268: 289-294.

Vogel, C. "Seven Fat Years and Seven Lean Years? Climate Change and Agriculture in Africa". DS Bulletin, Volume 36 No. 2 June 2005

Vörösmarty, C.J., Green P., Salisbury J., Lammers R. (2000): Global water resources: Vulnerability from climate change and population growth. Science 289: 284-288.

Wallner, A., M. Hunziker, and F. Kienast. 2003. Do natural science experiments influence public attitudes towards environmental problems? Global Environmental Change - Human and Policy Dimensions 13: 185-194.

Washington, R., et. al. , African Climate Report, Report Commission by the UK Government to Review African Climate science, policy and options for action, DEFRA.

Watson, R. T. and the Core Writing Team (eds.). 2001. *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Cambridge University Press.

Weber, E. (2005). Experience-Based and Description-based Perceptions of Long-Term Risk: Why Global Warming Does Not Scare Us (Yet), Climatic Change, submitted.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R. Sarofim, M. Sokolov,, A. Stone, P. and Wang, C.: Uncertainty analysis of climate change and policy response, Climatic Change 61, 295-320 (2003).

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang. 2005. “Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment.” *Science* 309: 1844-1846.

White, G.F., Kates, R.W., and Burton, I. 2001. “Knowing Better and Losing Even More: the use of knowledge in hazards management”. Environmental Hazards. 3. 81-92

Whitehead, A. 2002. Tracking livelihood change: theoretical, methodological, and empirical perspectives from North-East Ghana. Journal of Southern African Studies 28: 575-598.

Whitlock, C., Shafer, S.L. and J. Marlon, 2003: The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management*, **178**, 5-21.

Wiener, Jonathan B., 1998. “Managing the Iatrogenic Risks of Risk Management,” RISK: Health, Safety & Environment, 9, pp. 39-82.

Wigley, T. M. L, Richels, R. and Edmonds, J., Economic and environmental choices in the stabilization of atmospheric CO2 concentration, Nature 379, 242 (1996).

Wigley, T. M. L. 2004. Choosing a stabilization target for CO2. Climatic Change 67:1-11.

Wigley, T. M. L. and S. C. B. Raper, Interpretation of High Projections for Global-Mean Warming, Science 293, pp. 451-4, (2001).

Wigley, T.M.L, 2005. The Climate Change Commitment, Science 307, pp. 1766-1769.

Wigley, T.M.L., Richels, R. and Edmonds, J.: submitted, 'Overshoot Pathways to CO2 stabilization in a multi-gas context', in Schlesinger, M.E. and Weyant, J.P. (eds.), Human Induced Climate Change: An Interdisciplinary Perspective, Cambridge University Press, Cambridge, UK. Yamin *et al.*, 2005 Exeter volume.

Williams, A.J., D.J. Karoly and N. Tapper, 2001: The sensitivity of Australian fire danger to climate change. *Climatic Change*, **49**, 171-191.

Williams, S. E., Bolitho, E. E., Fox, S. (2003): Climate change in Australian tropical rainforests: an impending environmental catastrophe. Proceedings of the Royal Society of London B 270:1887-1892

Wisner, B., P. Blaikie, T. Cannon, and I. Davis. 2004. At Risk: Natural Hazards, People’s Vulnerability and Disasters, 2nd edition. London: Routledge.

Wood, R.A., M. Vellinga, and R. Thorpe, Global warming and thermohaline circulation stability, Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences, 361 (1810), 1961-1974, 2003.

World Food Programme 200x

Wright, E. L. & J. D. Erickson, Incorporating catastrophes into integrated assessment: science, impacts, and adaptation, Climatic Change 57:265, 2003

Wright, W.J. and Jones, D.A., 2003: Long-term rainfall decline in southern Australia. Proceedings National Drought Forum – Science for Drought, 15-16 April 2003, Brisbane.

Wu, P.; Johnston, P.; Lambeck, K., 1999. Postglacial rebound and fault instability in Fennoscandia. Geophysical Journal International, 139, pp. 657-670

Wynne, B.: Uncertainty and environmental learning: Reconceiving science and policy in the preventive paradigm. Global Environmental Change 2:111-127, 1992

Yohe, G. and R.S.J. Tol, (2002), “Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity”, *Global Environmental Change*, **12**, 25–40.

Yohe, G., Andronova, N., and M. Schlesinger (2004). To Hedge or Not Against an Uncertain Climate Future?, Science 306, 416-417 [DOI: 10.1126/science.1101170].

Zeng, X.-D., S.S.P. Shen, X. Zeng, and R.E. Dickinson, 2004: Multiple equilibrium states and the abrupt transitions in a dynamical system of soil water interacting with vegetation. Geophys. Res. Lett., 31, L05501, doi:10.1029/2003GL018910.

Zickfeld, K, and T. Bruckner. 2003. Reducing the Risk of Abrupt Climate Change: Emissions Corridors Preserving the Atlantic Thermohaline Circulation. Integrated Assessment 4:106-115.

Ziervogel, G., and T. Downing. 2004. Stakeholder networks: improving seasonal climate forecasts. Climatic Change 65: 73-101.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen, Surface melt-induced acceleration of Greenland ice-sheet flow, Science, 297, 218– 222, 2002.