

An Overview of “Dangerous” Climate Change

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Abstract

This paper briefly outlines the basic science on climate change, as well as the IPCC assessments on emissions scenarios and climate impacts, to provide a context for the topic of key vulnerabilities to climate change. A conceptual overview of “dangerous” climate change issues and the roles of scientists and policy makers in this complex scientific and policy arena are suggested, based on literature and recent IPCC work in progress. Literature on assessments of “dangerous anthropogenic interference” with the climate system is summarized, with emphasis on recent probabilistic analyses.

Introduction

“Europe’s summers to get hotter,” “The Arctic’s ominous thaw,” “Study shows warming trend in Alaskan Streams,” “Lake Tahoe Warming Twice as Fast as Oceans,” “Global Warming Seen as Security Threat,” “Global warming a bigger threat to poor,” “Tibet’s glacier’s heading for meltdown,” “Climate change affects deep sea life,” “UK: Climate change is costing millions.” These are just a few of the many headlines that crossed the wires in 2004, and they have elicited widespread concern, even in the business community. 2004 is thought to have been the fourth warmest year on record and the worst year thus far for weather-related disasters claims. Munich Re, the largest reinsurer in the world, recently stated that it expects natural-disaster-related damages to increase “exponentially” in the near future, and it attributes much of these damages to anthropogenic climate change. Thomas Loster, a climate expert at Munich Re, says: “We need to stop this dangerous experiment humankind is conducting on the Earth’s atmosphere.”

“Dangerous” has become something of a cliché when discussing climate change, but what exactly does it mean in that context? This paper will explore some basic concepts in climate change, how they relate to what might be “dangerous,” and various approaches to characterizing and quantifying “dangerous anthropogenic interference [DAI] with the climate system” [68]. It will also outline and differentiate the roles of scientists and policymakers in assessing what dangerous climate change entails. It will discuss current scientific attempts at assessing elements of dangerous climate change and will suggest ways in which such science can be translated into policy. It will also state explicitly that determination of “acceptable” levels of impacts or what constitutes “danger” are deeply normative, involving value judgments that must be made by decision makers, though scientist have a major role in providing analysis and context.

Climate Change: A Brief Primer

We will begin by stressing the well-established principles in the climate debate before turning to the uncertainties and more speculative, cutting-edge science debates. First, the greenhouse effect is empirically and theoretically well-established. The gases that comprise Earth’s atmosphere are semi-transparent to solar energy, allowing about half of the incident sunlight to penetrate the atmosphere to Earth’s surface. The surface absorbs the heat, heats up and/or evaporates liquid water into water vapor, and also re-emits energy upward as infrared radiation. Certain naturally-occurring gases and particles — particularly clouds — absorb most of the infrared radiation. The infrared energy that is absorbed in the atmosphere is re-emitted, both up to space and back down towards the Earth’s surface. The energy channeled towards the Earth causes its surface to warm further and emit infrared radiation at a still greater rate, until the emitted radiation is in balance with the absorbed portion of incident sunlight and the other forms of energy coming and going from the surface. That is what accounts for the 33 °C difference between the Earth’s actual surface air temperature and that which is measured in space as the Earth’s radiative temperature. Nothing so far is controversial. More controversial is

the extent to which non-natural (i.e., human) emissions of greenhouse gases have contributed to climate change, how much we will enhance future disturbance, and what the consequences of such disturbance could be for social and environmental systems—in short, the extent to which human alterations could risk DAI.

It is also well-known that humans have caused an increase in radiative forcing. In the past few centuries, atmospheric carbon dioxide has increased by more than 30 percent. The reality of this increase is undeniable, and virtually all climatologists agree that the cause is human activity, predominantly the burning of fossil fuels. To a lesser extent, deforestation and other land-use changes and industrial and agricultural activities like cement production and animal husbandry also contribute to greenhouse gas buildups. Most mainstream climate scientists agree that there has been an anomalous rise in global average surface temperatures since the time of the Industrial Revolution. Earth's temperature is highly variable, with year-to-year changes often masking the overall rise of approximately 0.7 °C that has occurred since 1860, but the twentieth century upward trend is obvious, as shown in Figure 1, below. Especially noticeable is the rapid rise at the end of the twentieth century. Indeed, the period from the 1980s onwards has been estimated to be the warmest period in the last 2,000 years. Mann and Jones, 2003 [35]; Mann, Bradley, and Hughes, 1998 [34]; and Mann, Bradley, and Hughes, 1999 [33] have attempted to push the Northern Hemisphere temperature record back 1,000 years by performing a complex statistical analysis involving some 112 separate indicators related to temperature. Although there is considerable uncertainty in the millennial temperature reconstruction, the overall trend shows a gradual temperature decrease over the first 900 years, followed by a sharp upturn in the twentieth century. That upturn is, of course, a compressed representation of the “real” (thermometer-based) surface temperature record of the last 150 years. Though there is some on-going dispute about details in the medieval period (e.g., [70]), many replicate studies confirm the basic picture of unusual warming in the past three decades compared to the past millennium [71].

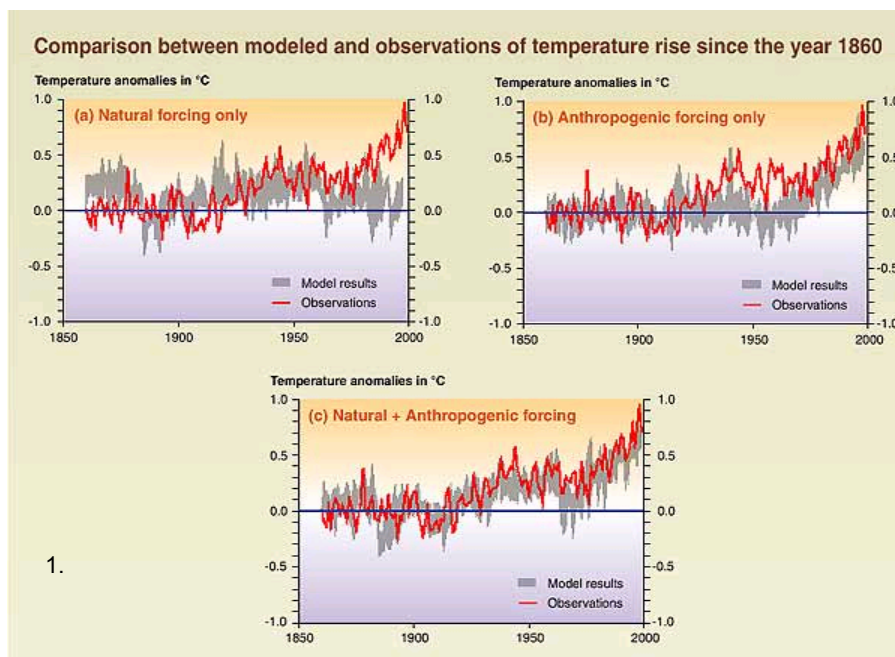


Figure 1 – Explaining temperature trends using natural and anthropogenic forcing.

It is likely that human activities have caused a discernible impact on observed warming trends. There is a high correlation between increases in global temperature and increases in carbon dioxide and other greenhouse gas concentrations during the era, from 1860 to present, of rapid industrialization and population growth. As correlation is not necessarily causation, what other evidence is there about anthropogenic CO₂ emissions as a direct cause of recent warming? As the data summarized in Figure 1 suggest, it looks increasingly like the answer is “yes.” The figure suggests that the best explanation for the global rise in temperature seen thus far is obtained from a combination of natural and anthropogenic forcings. Although substantial, this is still

circumstantial evidence. However, many recent “fingerprint analyses” have reinforced these conclusions (i.e., [58], [19], [48], [54], and [57]).

Climate Change Scenarios

Since the climate science and historical temperature trends summarized by the IPCC clearly show highly likely direct cause and effect relationships, we must now ask how climate may change in the future. Scientists, technologists, and policy analysts have invested considerable effort in constructing “storylines” of plausible human demographic, economic, political, and technological futures from which a range of emissions scenarios can be described, the most well-known being the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Emissions Scenarios (SRES), published in 2000. One grouping is the A1 storyline and scenario family, which describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and, in several variations of it, the rapid introduction of new and more efficient technologies. Major underlying themes are convergence between regions, capacity-building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A1 is subdivided into A1FI (fossil intensive), A1T (high-technology), and A1B (balanced), with A1FI generating the most carbon dioxide (CO₂) emissions and A1T the least (of the A1 storyline, and the second lowest emissions of all six marker scenarios). But even in the A1T world, CO₂ still at least doubles by 2100, as is true for *all* of the SRES scenarios.

For a contrasting vision of the world’s social and technological future, SRES offers the B1 storyline, which is (marginally) the lowest-emissions case of all the IPCC’s scenarios. The storyline and scenario family is one of a converging world with the same global population as A1, peaking in mid-century and declining thereafter, but with more rapid change in economic structures towards service and information economies, which is assumed to cause a significant decrease in energy intensity. The B1 world finds efficient ways of increasing economic output with less material, cleaner resources, and more efficient technologies. Many scientists and policymakers have doubted whether a transition to a B1 world is realistic and whether it can be considered equally likely when compared to the scenarios in the A1 family. Unfortunately, the IPCC did not discuss probabilities of each scenario (e.g., see the debate summarized by [14]). Figure 2 is illustrative of the SRES scenarios.

Climate Change Impacts

After producing the SRES scenarios, the IPCC released its Third Assessment Report (TAR) in 2001, in which it estimated that by 2100, global average surface temperatures would rise by 1.4 to 5.8°C. While warming at the low end of this range would likely be relatively less stressful, it would still be significant for some “unique and valuable systems” [25]. Warming at the high end of the range could have widespread catastrophic consequences, as a temperature change of 5 to 7°C on a globally averaged basis is about the difference between an ice age and an inter-glacial period occurring in merely a century [7]. In addition, if the IPCC’s projections prove reasonable, the global average rate of temperature change over the next century or two would likely exceed the average rates sustained over the last 10,000 years [63].

Based on these temperature forecasts, the IPCC has produced a list of likely effects of climate change, most of which are negative (see [25]). These include more frequent heat waves (and less frequent cold spells); more intense storms (hurricanes, tropical cyclones, etc.), and a surge in weather-related damage; increased intensity of floods and droughts; warmer surface temperatures, especially at higher latitudes; more rapid spread of disease; loss of farming productivity and/or movement of farming to other regions, most at higher latitudes; rising sea levels, which could inundate coastal areas and small island nations; and species extinction and loss of biodiversity. On the positive side, the literature suggests longer growing seasons at high latitudes and the opening of navigation in the normally ice-plagued Arctic. Weighing these pros and cons is the normative (value-laden) responsibility of policymakers, as discussed extensively below.

The IPCC also suggested that, particularly for rapid and substantial temperature increases, climate change could trigger “surprises”: rapid, non-linear responses of the climate system to anthropogenic forcing, thought to occur when environmental thresholds are crossed and new (and not always beneficial) equilibriums are reached. Schneider et al. (1998) [64] took this a step further, defining “imaginable surprises” – events that could be extremely damaging but are not truly unanticipated – which could include a large reduction in the strength or possible collapse of the North Atlantic thermohaline circulation (THC) system, which could cause significant

cooling in the North Atlantic region, with both warming and cooling regional teleconnections up- and downstream of the North Atlantic; and deglaciation of polar ice sheets like Greenland or the West Antarctic, which would cause (over many centuries) many meters of additional sea level rise on top of that caused by the thermal expansion from the direct warming of the oceans [59]. There is also the possibility of *true* surprises, events not yet currently envisioned [64]. However, in the case of true surprises, it is still possible to formulate “imaginable conditions for surprise”—like rapidly forced climate change, since the faster the climate system is forced to change, the higher the likelihood of triggering abrupt non-linear responses [28]. Potential climate change, and more broadly, global environmental change, faces both types of surprises because of the enormous complexities of the processes and interrelationships involved (such as coupled ocean, atmosphere, and terrestrial systems) and our insufficient understanding of them individually and collectively (e.g., [21]).

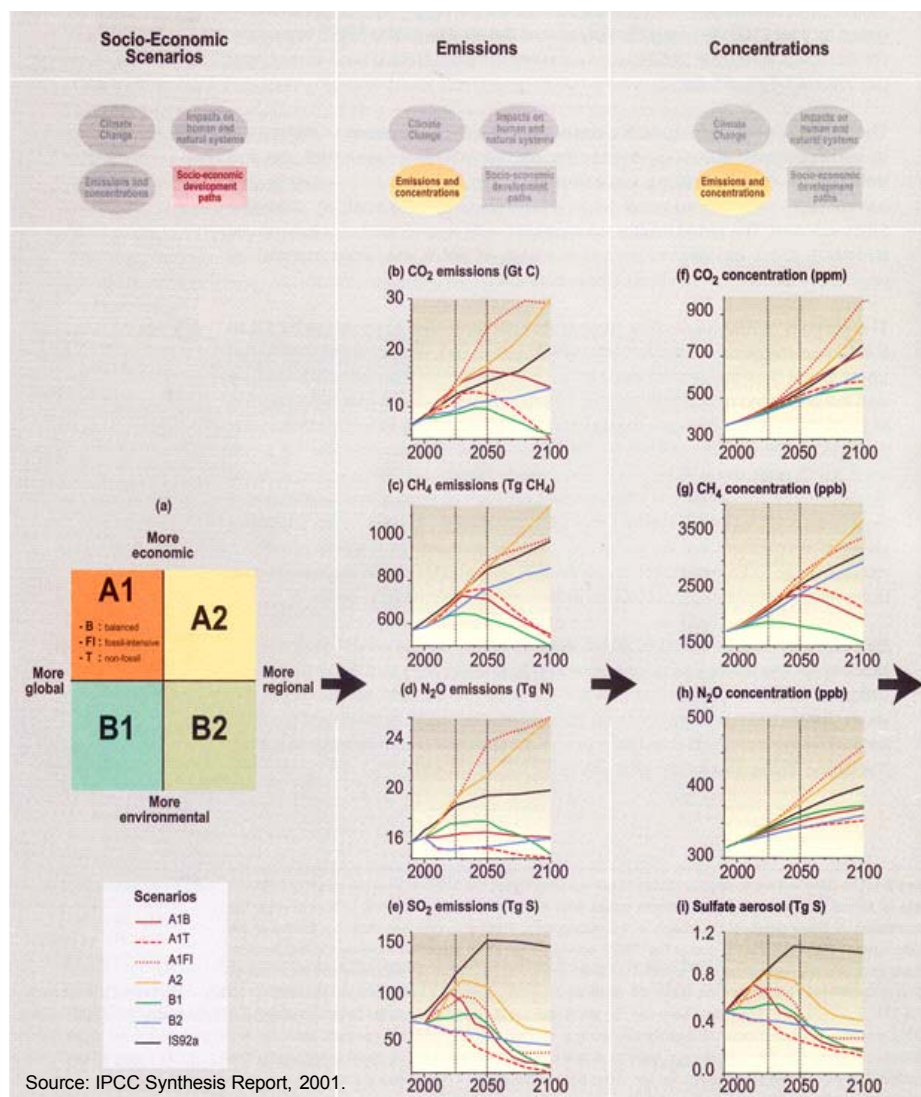


Figure 2 – SRES emissions scenarios.

Many systems have been devised for categorizing climate change impacts. IPCC (2001b) [25] has represented impacts as “reasons for concern,” as in Figure 3, below. These impacts are: risks to unique and threatened systems, risks associated with extreme weather events, the distribution of impacts (i.e., equity implications), aggregate damages (i.e., market economic impacts), and risks of large-scale singular events (e.g., “surprises”). Leemans and Eickhout (2004) [32] have also suggested including risks to global and local

ecosystems as an additional reason for concern, though this could be partially represented under the first reason for concern. The figure, also known as the “burning embers diagram,” shows that the most potentially serious climate change impacts (the red colors on the figure) typically occur after only a few degrees Celsius of warming.

Parry et al.’s (2001) [49] “millions at risk” work suggests another approach. The authors estimate the additional millions of people who could be placed at risk as a result of different amounts of global warming. The risks Parry et al. focus on are hunger, malaria, flooding and water shortage. Similarly, the 2002 Johannesburg World Summit on Sustainable Development (WSSD) came up with five key areas to target for sustainable development: water, energy, health, agriculture, and biodiversity (WEHAB). These categories, with the addition of coastal regions (as proposed by [51]), are also well-suited to grouping climate change impacts.

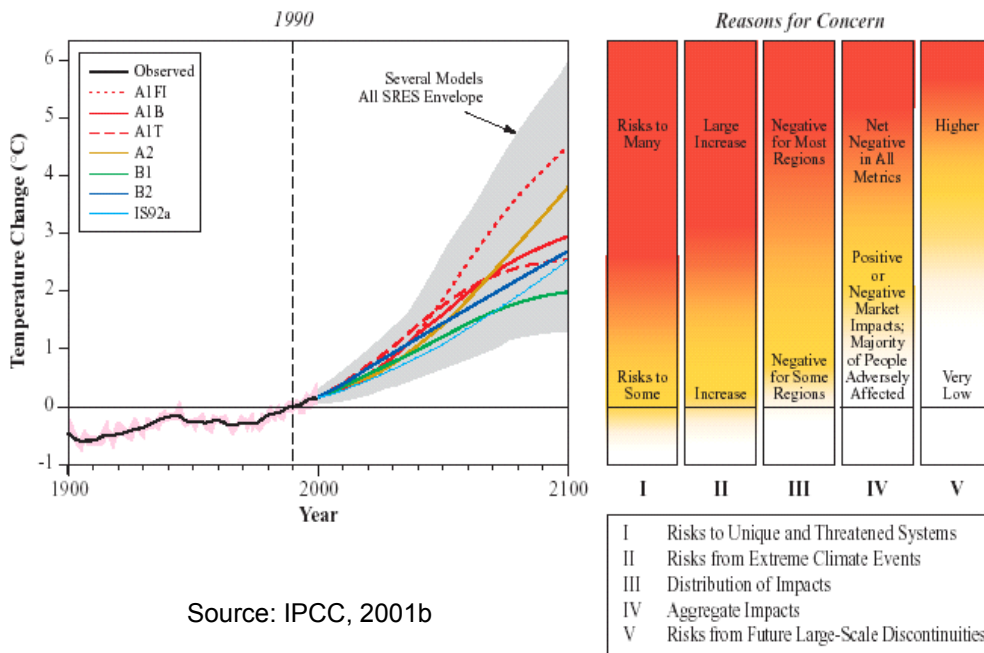


Figure 3 – IPCC reasons for concern about climate change impacts.

In looking at climate impacts from a justice perspective, Schneider and Lane (2005) [61] propose three distinct areas in which climate change inequities are likely to be significant: inter-country equity, intergenerational equity, and inter-species equity. (Schneider and Lane and others have also suggested intra-national inequity of impacts.) Another justice-oriented impacts classification scheme is Schneider et al.’s (2000) [62] “five numeraires”: market system costs in dollars per ton Carbon (C); human lives lost in persons per ton C; species lost per ton C; distributional effects (such as changes in income differentials between rich and poor) per ton C; and quality of life changes, such as heritage sites lost per ton C or refugees created per ton C. Lane, Sagar, and Schneider (2005) [31] propose examining not just absolute costs in each of the five numeraires, but *relative* costs as well in some of them:

...we should consider market-system costs relative to a country’s GDP, species lost relative to the total number of species in that family, etc. Expressing impacts through the use of such numeraires will capture a richer accounting of potential damages and could help merge the often-disparate values of different groups in gauging the seriousness of damages. In other cases, such as human lives lost, we believe that the absolute measure remains more appropriate.

It our strong belief that such broad based, multi-metric approaches to impacts categorization and assessment are vastly preferable to focusing solely on market categories of damages, as is often done by traditional cost-benefit analyses. One-metric aggregations can underestimate the seriousness of climate impacts. Evidence for this was gathered by Nordhaus (1994a) [41], who surveyed conventional economists, environmental economists, atmospheric scientists, and ecologists about estimated climate damages. His study reveals a striking cultural divide across natural and social scientists who participated in the study. Conventional economists surveyed suggested that even extreme climate change (i.e., 6°C of warming by 2090) would not likely impose severe economic losses, implying it is likely to be cheaper to emit more in the near term and worry about cutting back later, using additional wealth gained from near-term emitting to fund adaptation later on. Natural scientists estimated the total economic impact of extreme climate change, much of which they assigned to non-market categories, to be 20 to 30 times higher than conventional economists' projections. In essence, the natural scientists tended to respond that they were much less optimistic that humans could invent acceptable substitutes for lost climatic services (see[56]).

Because they typically only measure market impacts, traditional cost-benefit analyses are often considered skewed from a justice perspective. In a traditional CBA, the ethical principle is not even classical Benthamite utilitarianism (greatest good for the greatest number of people), but an aggregated market power form of utilitarianism (greatest good for the greatest number of dollars in benefit/cost ratios). Thus, an industrialized country with a large economy that suffered the same biophysical climate damages as an unindustrialized nation with a smaller economy would be considered to have suffered more by virtue of a larger GDP loss and would, in the aggregate-dollars-lost metric, be more important to "rescue" and/or rehabilitate, if possible. Even more problematic, what if an industrial northern country experienced a monetary gain in agriculture and forestry from global warming due to longer growing seasons, while at the same time—as much of the literature suggests—less developed southern countries suffered from excessive heating that amounted to a monetary loss of the same dollar value as the gain in the north? This could hardly be viewed as a "neutral" outcome despite a net welfare change of zero (derived from summing the monetary gain in the north and the loss in the south). Very few would view a market-only valuation and global aggregation of impacts in which the rich get richer and the poor get poorer as a result of climate change as an ethically neutral result.

Under the framework of the five numeraires and other systems that rely on multiple metrics, the interests of developing countries and the less privileged within nations would be given a greater weight on the basis of the threats to non-market entities like biodiversity, human life, and cultural heritage sites. Take the example of Bangladesh: Assume that rising sea levels (caused by climate change) lead to the destruction of lives, property, and ecosystems equivalent to about 80% of the country's GDP. While the losses would be indisputably catastrophic for Bangladesh, they would amount to an inconsequential 0.1% of global GDP [25], causing a market-aggregation-only analysis to classify the damage as relatively insignificant, though a reasonable interpretation of many would be that such a loss clearly qualifies as DAI. Those considering multiple numeraires, on the other hand, would argue that this is clearly unfair, as the loss of life, degraded quality of life, and potential loss of biodiversity are at least as important as aggregate market impacts.

“Dangerous” Climate Change

What, then, is “dangerous” climate change? The term was introduced in the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which calls for stabilization of greenhouse gases to “prevent dangerous anthropogenic interference with the climate system” [68]. The Framework Convention further suggests that: “Such a level should be achieved within a time frame sufficient

- to allow ecosystems to adapt naturally to climate change;
- to ensure that food production is not threatened and;
- to enable economic development to proceed in a sustainable manner.”

While it seems that some of the impacts of climate change discussed thus far suggest that dangerous levels of climate change may occur, the UNFCCC never actually defined what it meant by “dangerous”.

Many metrics for defining dangerous have been introduced in recent years, and most focus on the consequences (impacts) of climate change outcomes. From an equity perspective, it can be argued that any climate change that impacts more upon those who contributed the least to the problem is less just and thus arguably more dangerous – and could have repercussions that extend beyond environmental damages (to security, health, and economy, for example). Along similar lines, scientists defined “dangerous anthropogenic interference” at COP10 in Buenos Aires in December 2004 by assessing the key vulnerabilities with regard to climate change. In the IPCC TAR, “vulnerability” was described as a consequence of exposure, sensitivity, and adaptive capacity (Glossary, [25]). As proposed in Working Group 2’s working draft on Chapter 19 for the forthcoming IPCC Fourth Assessment Report (AR4), “key vulnerabilities” are defined as:

- (a) a valued property of the coupled human-natural system that is associated with large impact risks (such as the sensitivity of the thermohaline ocean circulation to anthropogenic climate change), or
- (b) an impact risk that is considered salient to specific sectors, regions or social groups (such as increased flood risks in coastal regions or the extinction of species). Key vulnerabilities describe those interactions between elements of the climate system, climate-sensitive resources and the services provided by them that may involve significant adverse outcomes that are considered in the literature to be significant enough in terms of their ecological, social, and economic implications to be relevant to the determination of DAI. [23]

(Please note, that all references to the current text or perspectives of Zero Order Drafts of the AR4 do not necessarily represent what will emerge from the many rounds in the next few years of review and governmental approvals of content. They cannot be quoted as IPCC results, and are only useful here to illustrate conceptual issues.)

The notion of key vulnerabilities was derived partly from the discussion on “concepts of danger” that occurred at the European Climate Forum’s (ECF) symposium on “Key vulnerable regions and climate change” in Beijing in October 2004 and was presented at COP 10. The ECF symposium identified three concepts of danger:

- **Determinative dangers** are, on their own, enough to define dangerous levels of climate change. The ECF’s list of determinative dangers resulting from climate change include: circumstances that could lead to global and unprecedented consequences, extinction of “iconic” species or loss of entire ecosystems, loss of human cultures, water resource threats, and substantial increases in mortality levels, among others.
- **Early warning dangers** are dangers already present in certain areas that are likely to spread and worsen over time with increased warming. These dangers could include Arctic Sea ice retreat, boreal forest fires, and increases in frequency of drought, and they could become determinative over time or taken together with other dangers.
- **Regional dangers** are widespread dangers over a large region, most likely related to food security, water resources, infrastructure, or ecosystems. They are not considered determinative, as they are largely confined to a single region. [12]

Dessai et al. (2004) [10] also focus on vulnerabilities as an indicator of dangerous climate change. They have separated definitions of danger into two categories: those derived from top-down research processes and those derived from bottom-up methods. The more commonly used top-down approach determines physical vulnerability based on hierarchical models into which are inputted different scenarios of socio-economic change, whereas the bottom-up approach focuses on the vulnerability and adaptive capacity of individuals or groups, which leads to social indications of potential danger like poverty and/or lack of access to healthcare, effective political institutions, etc.

While scientists have many ideas about what vulnerabilities may be considered dangerous, it is a common view of most natural and social scientists that it is not the direct role of the scientific community to define what “dangerous” means. Rather, it is ultimately a political question because it depends on *value judgments* about the relative salience of various impacts and how to face climate change-related risks and form norms for defining what is “acceptable” [60, 37]. In fact, the notion of key vulnerabilities itself is also a value judgment, and

different decision makers at different locations and levels are likely to perceive vulnerabilities and the concept of “dangerous” in distinct ways. Dessai et al. (2004) [10] explain the juxtaposition of science and value judgment by assigning two separate definitions for risk – internal and external. External risks are defined via scientific risk analysis of system characteristics prevalent in the physical or social worlds. Internal risk, on the other hand, defines risk based on the individual or communal perception of insecurity. In the case of internal risk, in order for the risk to be “real,” it must be experienced. Of course, these two definitions are intertwined in complex ways. Decision makers’ perceptions of risk are partly informed by the definitions and guidance provided by scientific experts, and societal perceptions of risk may also influence scientific research.

The Role of Science

Ultimately, scientists cannot make expert value judgments about what climate change risks to face and what to avoid, as that is the role of policy makers, but they can help policymakers evaluate what “dangerous” climate change entails by laying out the elements of **risk**, which is classically defined as **probability x consequence**. They should also help decision-makers by identifying thresholds and possible surprise events, as well as estimates of how long it might take to resolve many of the remaining uncertainties that plague climate assessments.

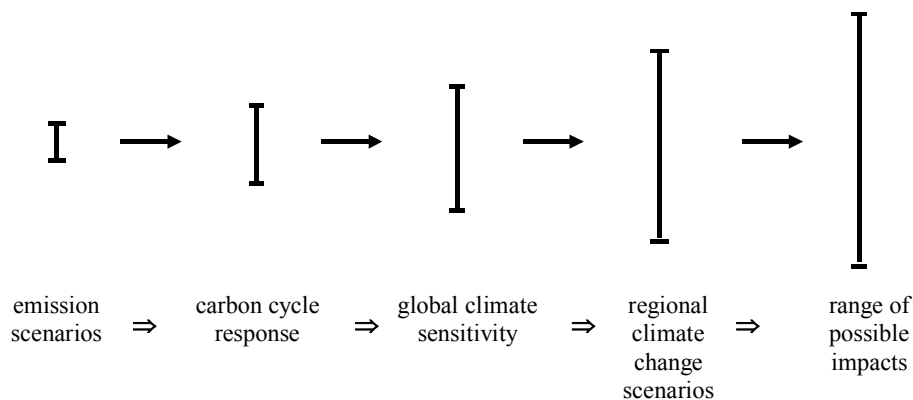
There is a host of information available about the possible consequences of climate change, as described in our discussion of the SRES scenarios and of the impacts of climate change, but the SRES scenarios do not have probabilities assigned to them, making risk management difficult. Some would argue that assigning probabilities to scenarios based on social trends and norms should not be done (e.g., [15]), and that the use of scenarios in and of itself derives from the fact that probabilities can’t be analytically estimated. In fact, most models don’t calculate objective probabilities for future outcomes, as the future has not yet happened and “objective statistics” are impossible in principle before the fact. However, modelers can assign subjective confidence levels to their results by discussing how well established the underlying processes in a model are, or by comparing their results to observational data for past events or elaborating on other consistency tests of their performance (e.g., [14]). It is our belief that qualified assessment of (clearly admitted) subjective probabilities in every aspect of projections of climatic changes and impacts would improve climate change impact assessments, as it would complete the risk equation, thereby giving policymakers some idea of the likelihood of threat associated with various scenarios, aiding effective decision-making in the risk-management framework.

Uncertainties

A full assessment of the range of climate change consequences *and* probabilities involves a cascade of uncertainties in emissions, carbon cycle response, climate response, and impacts. We must estimate future populations, levels of economic development, and potential technological props spurring that economic development, all of which will influence the radiative forcing of the atmosphere via emissions of greenhouse gases and other radiatively active constituents. At the same time, we also must deal with the uncertainties associated with probabilities generated with carbon cycle modeling, and, equally important, confront uncertainties surrounding climate sensitivity estimated from climate models tested on paleoclimatic situations, as well as perform other “validation” exercises.

Figure 4 shows the “explosion” that occurs as the different elements of uncertainty are combined. This should not be interpreted as a sign that scientists cannot assign a high degree of confidence to *any* of their projected climate change impacts, but rather that the scope of possible consequences is quite wide. There are many projected effects, on both global and regional scales, that carry high confidence estimates, but the figure suggests that there still are many impacts to which we can only assign low confidence ratings and others that have not yet been postulated—i.e., “surprises” and irreversible impacts.

One other aspect of Figure 4 needs mentioning: Current decision makers aware of potential future risks might introduce policies to reduce the risks over time—also known as “reflexive” responses—which would be equivalent to a feedback that affects the size of the bars on Figure 4 merely because the prospects for risks created precautionary responses. That possibility is partly responsible for the attitudes of some who are reluctant to assign probabilities—even subjective ones—to the components of Figure 4. If no probabilities are associated with scenarios, then the problem still remains for decision makers to weigh the importance of climate risks against other pressing social issues competing for limited resources.



Source: Modified after Jones, 2000, and the "cascading pyramid of uncertainties" in Schneider, 1983.

Figure 4 – Explosion of uncertainty.

Various classification schemes have been generated to categorize different types of uncertainties prevalent in scientific assessment (e.g., [76], [20], [64], [39], [55], [11], [36]). In the AR4, one classification scheme for uncertainties includes the following categories: lack of scientific knowledge, natural randomness, social choice, and value diversity [23].

The plethora of uncertainties inherent in climate change projections clearly makes risk assessment difficult. In this connection, some fear that actions to control potential risks could produce unnecessary loss of development progress, especially if impacts turned out to be on the benign side of the range. This can be restated in terms of Type I and Type II errors. If governments were to apply the precautionary principle and act now to mitigate risks of climate change, they'd be said to be committing a Type I error if their worries about climate change proved unfounded and anthropogenic greenhouse gas emissions didn't greatly modify the climate and lead to dangerous change. A Type II error would occur if serious climate change did occur, yet insufficient hedging actions had been taken as a precaution because uncertainty surrounding the climate change projections was used as a reason to delay policy until the science was "more certain". Researchers, understandably, often are wary of Type I errors, as they are the ones making the projections and don't like to be responsible for actions that turn out to be unnecessary. Decision makers, and arguably most individuals, on the other hand, might be more worried that dangerous outcomes could be initiated on their watch (Type II error), and thus may prefer some hedging strategies.

Vulnerability measurements

The climate science community has been asked to provide decision makers with information that may help them avoid Type 2 errors (e.g., avoid DAI). One way is through studies providing quantitative measures of key vulnerabilities. In contemplating quantitative values for *human* vulnerabilities, studies have addressed monetary loss [42, 43, 16, 30] and a wide range of population-related metrics, including loss of life [74], risk of hunger as measured by the number of people who earn enough to buy sufficient cereal [50], risk of water shortage as measured by annual per capita water availability [3], mean number of people vulnerable to coastal flooding [40], number of people prone to malaria infection or death [67, 69], and number of people forced to migrate as a result of climate change [9].

Non-human quantitative analyses have also been performed. They have calculated potential numbers of species lost [66], numbers of species shifting their ranges [48, 54], and absolute or relative change in range of species or habitat type. Leemans and Eickhout (2004) [32] note that after 1 to 2° C of warming, most species, ecosystems, and landscapes have limited capacity to adapt. Rates of climate change also influence adaptive capacity of social and (especially) natural systems.

Another quantitative measure of vulnerability is the five numeraires, discussed above, as it encompasses both human and non-human metrics of impacts. Each numeraire may be reported separately, or they can be aggregated. Any aggregation should be accompanied by a "traceable account" of how it was obtained [38].

Thresholds

Another important step toward achieving the goal of informing decision makers is identifying climate thresholds or limits. One classification scheme lists three categories of thresholds relevant in the context of Article 2 of the UNFCCC: systemic (natural) thresholds, normative (social) impact thresholds, and legal limits. A systemic threshold is a point at which “the relationship between one or more forcing variables and a valued system property becomes highly negative or non-linear” [23]. Normative thresholds have been divided into two categories by Patwardhan et al. (2003) [51]. Type I normative thresholds are “target values of linear or other ‘smooth’ changes that after some point would lead to damages that might be considered ‘unacceptable’ by particular policy-makers” [51]. Type II normative thresholds are “linked directly to the key intrinsic processes of the climate system itself (often non-linear) and might be related to maintaining stability of those processes or some of the elements of the climate system” [51]. Examples are presented in Table 1, below. Legal limits are manmade constraints like environmental standards placed upon certain factors that are thought to play a part in unfavorable outcomes. They can be influenced by normative thresholds, as well as cost and other factors.

Vulnerability	Global Mean Limit	References
Shutdown of thermohaline circulation	3 °C in 100 yr	O’Neill and Oppenheimer (2002) [44]
	700ppm CO ₂	Keller et al. (2004) [29]
Disintegration of West Antarctic ice sheet (WAIS)	2 °C, 450ppm CO ₂	O’Neill and Oppenheimer (2002) [44]
	2-4 °C, <550ppm CO ₂	Oppenheimer and Alley (2004, 2005) [46, 47]
Disintegration of Greenland ice sheet	1 °C	Hansen (2004) [17]
Widespread bleaching of coral reefs	>1 °C	Smith et al. (2001) [65]
		O’Neill and Oppenheimer (2002) [44]
Broad ecosystem impacts with limited adaptive capacity (many examples)	1-2°C	Leemans and Eickhout (2004) [32], Hare (2003) [18], Smith et al. (2001) [65]
Large increase of persons-at-risk of water shortage in vulnerable regions	450-650ppm	Parry et al. (2001) [49]
Increasingly adverse impacts, most economic sectors	>3-4°C	Hitz and Smith (2004) [22]
Source: IPCC Fourth Assessment Report, Chapter 19, Zero Order Draft.		

Table 1 – Proposed numerical values of “Dangerous Anthropogenic Interference.”

Extensive literature relating to Type II thresholds, also referred to as Geophysical and Biological Thresholds, has arisen in recent years. The literature has attempted to incorporate Type II thresholds into integrated assessment and decision-making, both on global scales (e.g., [1], [6], [75], [60], [21], [8], [59]) and on regional scales (e.g., [53]). The next step involves associating specific climate parameters with thresholds. For example, O’Neill and Oppenheimer (2002) [44] have given values of carbon dioxide concentration and global temperature change that they believe may be associated with Type II thresholds corresponding to the disintegration of the West Antarctic ice sheet (WAIS), collapse of thermohaline circulation, and widespread decline of coral reefs. Oppenheimer and Alley (2004) [46] also proposed a range of threshold values for disintegration of the WAIS, and Hansen (2004) [17] and Oppenheimer and Alley (2005) [47] discuss quantification of thresholds for loss of WAIS and Greenland ice sheets. Due to large uncertainties in models and in interpretation of paleoclimatic evidence, a critical issue in all of the above studies is whether the values selected correspond to actual geophysical or biological thresholds or simply represent convenient and subjective judgments about levels or risk.

Type I thresholds, perhaps more accurately called socioeconomic limits, generally don’t involve the large-scale discontinuities implied in the word “threshold,” with the exception of a possible collapse of an atoll society to cope with climate-change-induced sea level rise [9]. Again, there is extensive literature on Type I thresholds. Parry et al. (2001) [49], Arnell (2000) [4], Arnell et al. (2004) [5], Parry (2004) [50], and other studies view climate change impacts in terms of changes in the size of vulnerable populations, typically as a result of climate-change-induced food shortages, water shortages, malaria infection, and coastal flooding.

We present a simple example as another approach to the problem of joint probability of temperature rise to 2100 and the possibility of crossing “dangerous” warming thresholds. Instead of using two probability distributions, an analyst could pick a high, medium, and low range for each factor. For example, a glance at the cumulative probability density function of Andronova and Schlesinger (2001) [2] – included below – shows that the 10th percentile value for climate sensitivity is 1.1 °C for a doubling of CO₂. 1.1 °C is, of course, below the 1.5 °C lower limit of the IPCC’s estimate of climate sensitivity and the temperature projection for 2100. But this 10th percentile value merely means that there is a 10% chance climate sensitivity will be 1.1 °C or less – that is, a 90% chance climate sensitivity will be 1.1 °C or higher. The 50th percentile result – that is, the value that climate sensitivity is as likely to be above as below – is 2.0 °C. The 90th percentile value is 6.8 °C, meaning there is a 90% chance climate sensitivity is 6.8 °C or less, but there is still a very uncomfortable 10% chance it is even higher than 6.8 °C – a value well above the “top” figure in the IPCC range for climate sensitivity (4.5 °C).

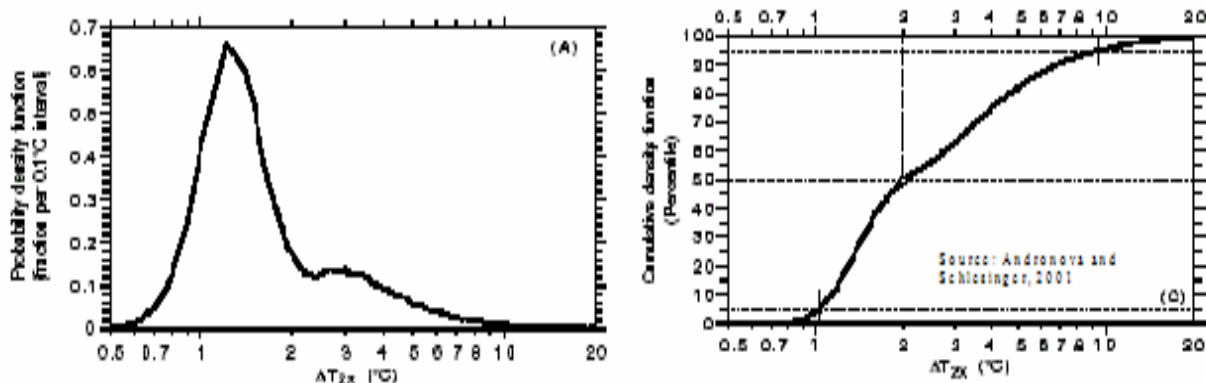


Figure 5 – Probability density function (A) and cumulative density function (C).

Using these three values (6.8 °C, 2.0 °C, and 1.1 °C) for high, medium, and low climate sensitivity can produce three alternate projections of temperature over time (using a simple mixed-layer climate model), once an emissions scenario is given. In the example below, these three climate sensitivities are combined with two of the SRES storylines: the fossil fuel intensive scenario (A1FI) and the high-technology scenario (A1T), where development and deployment of advanced lower carbon-emitting technologies dramatically reduces the long-term emissions. These make a good comparison pair since they almost bracket the high and low ends of the six SRES representative scenarios’ range of cumulative emissions to 2100, and since both are for the “A1 world,” the only major difference between the two is the technology component—an aspect decision makers have the

capacity to influence via policies and other measures. Therefore, asking how different the projected climate change to 2100 is for the two different scenarios is a very instructive exercise in exploring in a partial way the likelihood of crossing “dangerous” warming thresholds.

We’ll use a conservative estimate of 3.5 °C for this “dangerous” threshold since 3.5 °C was the highest number projected for the 2100 temperature rise in the IPCC’s Second Assessment Report (SAR) and because the IPCC Working Group 2 TAR suggested that after “a few degrees,” many serious climate change impacts could be anticipated. However, 3.5 °C is a very conservative number, since the IPCC noted that some “unique and valuable” systems could be lost at warmings any higher than 1-1.5 °C. In essence, the “threshold” for what is “dangerous” depends not only on the probabilities of factors like climate sensitivity and adaptive capacity, but on value judgments as to what is acceptable given any specific level of warming or damage—and who suffers the damage or pays the adaptation costs. The figure below presents the results.

The most striking feature of both figures A and B (A is for the A1FI scenario and B the A1T), below, is the top 90th percentile line, which rises very steeply above the other two lines below it. That is because of the peculiar shape of the probability density function for climate sensitivity in the cumulative probability density function figure, above – it has a long tail to the right due to the possibility that aerosols have been holding back not-yet-realized heating of the climate system.

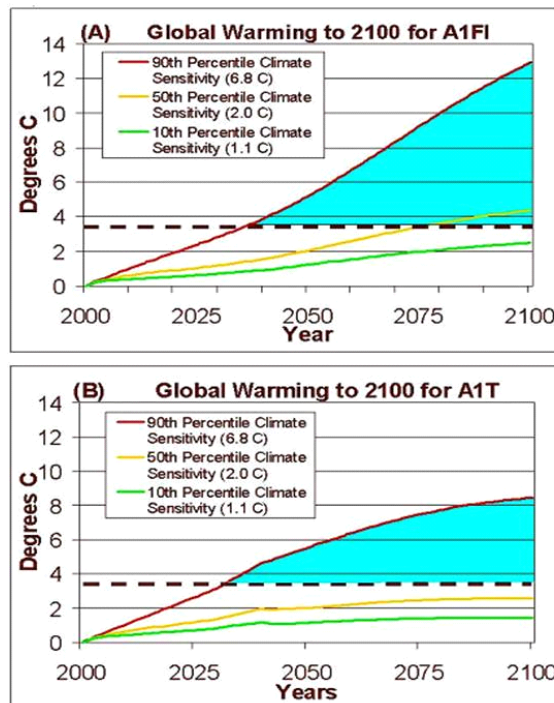


Figure 6 – Three climate sensitivities and two scenarios.

This simple pair of figures shows via a small number of curves the amount of temperature change over time for three climate sensitivity probabilities (10th, 50th, and 90th percentile). However, it does not give probabilities for the emissions scenarios themselves; only two are used to “bracket uncertainty,” and thus no joint probability can be gleaned from this exercise. The problem with this is that the likelihood of threshold-crossing occurrences is quite sensitive to the particular selection of scenarios and climate sensitivities used. This adds urgency to assessing the relative likelihood of each such entry (scenario and sensitivity) so that the joint distribution has a meaning consistent with the underlying probabilistic assessment of the components. Arbitrary selection of scenarios or sensitivities will produce conclusions that could easily be misinterpreted by integrated assessors and policymakers as containing expert subjective probabilistic analysis when, in fact, they do not until a judgment is formally made about the likelihood of each storyline or sensitivity.

Such joint probability analyses are the next step. A group at MIT has already made an effort at it (see [72]), as have Wigley (2005) [73], Rahmstorf and Zickfeld (2005) [52], and Mastrandrea and Schneider (2004) [37].

We will summarize here Mastrandrea and Schneider (2004) [37], which estimates the probability of DAI and the influence of climate policy in reducing the probability of DAI.

Climate Science and Policy Crossroads

In defining their metric for DAI, Mastrandrea and Schneider estimate a cumulative density function (CDF) based on the IPCC's "burning embers" diagram by marking each transition-to-red threshold and assuming that the probability of "dangerous" change increases cumulatively at each threshold temperature by a quintile, as shown by the thick black line in Figure 7. This can be used as a starting point for analyzing "dangerous" climate change.

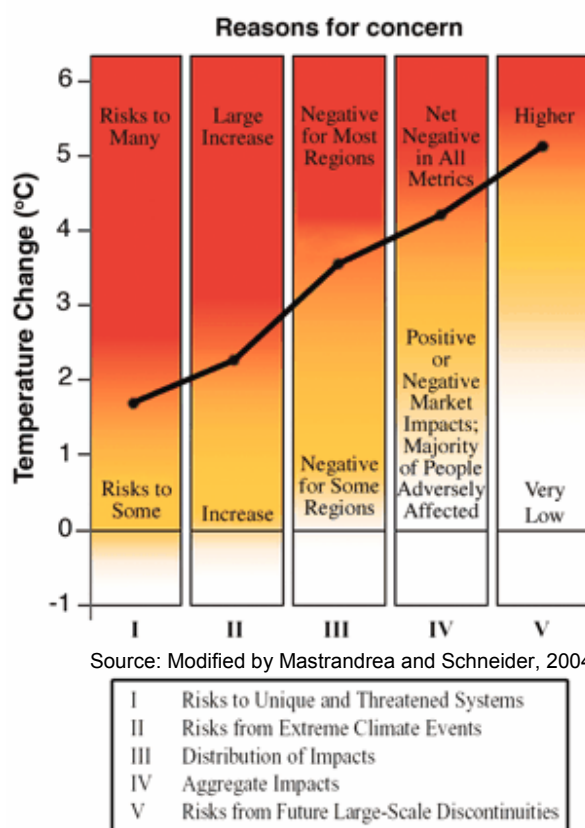


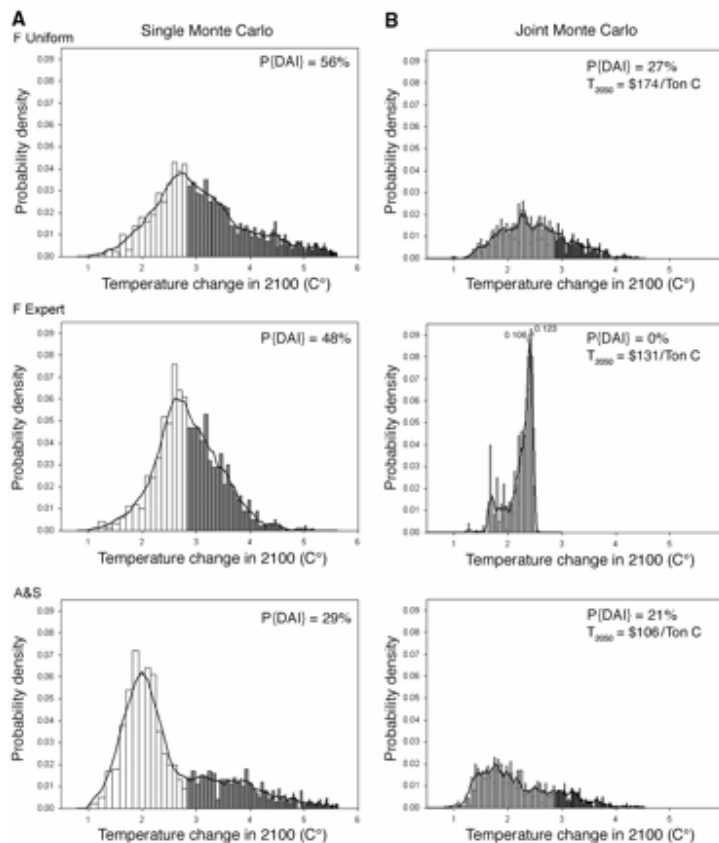
Figure 7 – Cumulative density function for “Dangerous Anthropogenic Interference.”

From Figure 7, Mastrandrea and Schneider identify 2.85°C as their median threshold for “dangerous” climate change, which may still be conservative. Mastrandrea and Schneider apply this median 2.85°C threshold to three key parameters – climate sensitivity, climate damages, and the discount rate – all of which carry high degrees of uncertainty and are crucial factors in determining the policy implications of global climate change. To perform these calculations, they use Nordhaus’ (1994b) [42] DICE model because it is well known and is a relatively simple and transparent integrated assessment model (IAM), despite its limitations. Using an IAM allows for exploration of the impacts of a wide range of mitigation levels on the potential for exceeding a policy-relevant threshold such as DAI. Mastrandrea and Schneider focus on two types of model output: i) global average surface temperature change in 2100, which is used to evaluate the potential for DAI; and ii) “optimal” carbon taxes.

They begin with climate sensitivity, typically defined as the amount that global average temperature is expected to rise for a doubling of CO₂ from pre-industrial levels. The IPCC estimates that climate sensitivity ranges between 1.5°C and 4.5°C, but it has not assigned subjective probabilities to the values within or outside

of this range, making risk analysis difficult. However, recent studies, many of which produce climate sensitivity distributions wider than the IPCC's 1.5 °C to 4.5 °C range, with significant probability of climate sensitivity above 4.5 °C, are now available. Mastrandrea and Schneider use three such probability distributions: the combined distribution from Andronova and Schlesinger (2001) [2], and the expert prior (F Exp) and uniform prior (F Uni) distributions from Forest et al. (2001) [13]. They perform a Monte Carlo analysis sampling from each climate sensitivity probability distribution separately, without applying any mitigation policy, so that all variation in results will be solely from variation in climate sensitivity. The probability distributions they produce show the percentage of outcomes resulting in temperature increases above their 2.85 °C “dangerous” threshold (Figure 8A).

Mastrandrea and Schneider's next simulation is a joint Monte Carlo analysis looking at temperature increase in 2100 with climate policy, varying both climate sensitivity *and* the climate damage function, their second parameter (Figure 8B). For climate damages, they sample from the distributions of Roughgarden and Schneider (1999) [56], which produce a range of climate damage functions both stronger and weaker than the



Source: Mastrandrea and Schneider, 2004.

Figure 8. Climate sensitivity-only and joint (climate sensitivity and climate damages) Monte Carlo analyses.

Notes: Panel A displays probability distributions for each climate sensitivity distribution for the climate sensitivity-only Monte Carlo analyses with zero damages. Panel B) displays probability distributions for the joint (climate sensitivity and climate damage) Monte Carlo analyses. All distributions indicate a 3-bin running mean and the percentage of outcomes above the median threshold of 2.85°C for “dangerous” climate change (P{“DAI”}), and the joint distributions display carbon taxes calculated in 2050 (T_{2050}) by the DICE model using the median climate sensitivity from each climate sensitivity distribution and the median climate damage function for the joint Monte Carlo cases. Comparing the joint cases with climate policy controls, b), to the climate sensitivity-only cases with negligible climate policy controls, a), high carbon taxes reduce the potential (significantly in two out of three cases) for DAI. (However, this case uses a PRTP of 0%, implying a discount rate of about 1%. With a 3% PRTP—a discount rate of about 6%—this carbon tax is an order of magnitude less, and the

reduction in DAI is on the order of 10%. See the supplementary on-line materials of Mastrandrea and Schneider, 2004 [37] for a full discussion.)

original DICE function. As shown, aside from the Andronova and Schlesinger climate sensitivity distribution, which gives a lower probability of DAI under the single (climate sensitivity-only) Monte Carlo analysis, the joint runs show lower chances of dangerous climate change as a result of the more stringent climate policy controls generated by the model due to the inclusion of climate damages. Time-varying median carbon taxes are over \$50/Ton C by 2010, and over \$100/Ton C by 2050 in each joint analysis. Low temperature increases and reduced probability of “DAI” are achieved if carbon taxes are high, but because this analysis only considers one possible threshold for “DAI” (the median threshold of 2.85 °C) and assumes a relatively low discount rate (about 1%), these results cannot fully describe the relationship between climate policy controls and the potential for “dangerous” climate change. They are given to demonstrate a framework for probabilistic analysis, and the highly model-dependent results are not intended to be taken literally.

Because the analysis above only considers Mastrandrea and Schneider’s median threshold (DAI[50%]) of 2.85°C, Mastrandrea and Schneider continue their attempt to characterize the relationship between climate policy controls and the potential for “dangerous” climate change by calculating a series of single Monte Carlo analyses varying climate sensitivity and using a *range* of fixed damage functions (rather than just the median case). For each damage function, they perform a Monte Carlo analysis sampling from each of the three climate sensitivity distributions discussed above. They then average the results for each damage function, which gives the probability of DAI at a given 2050 carbon tax under the assumptions described above, as shown in Figure 9, below. Each band in the figure corresponds to optimisation around a different percentile range for the “dangerous” threshold CDF, with a lower percentile from the CDF representing a lower temperature threshold for DAI. At any DAI threshold, climate policy “works”: higher carbon taxes lower the probability of future temperature increase, and thus reduce the probability of DAI. For example, if climate sensitivity turns out to be on the high end and DAI occurs at a relatively low temperature like 1.476°C (DAI[10%]), then there is nearly a 100% chance that DAI will occur in the absence of carbon taxes and about an 80% chance it will occur even if carbon taxes were \$400/ton, the top end of Mastrandrea and Schneider’s range. If we inspect the median (DAI[50%]) threshold for DAI (the thicker black line in Figure 9), we see that a carbon tax by 2050 of \$150-\$200/Ton C will reduce the probability of “DAI” to nearly zero, from 45% without climate policy controls (for a 0% PRTP, equivalent to a discount rate of about 1%).

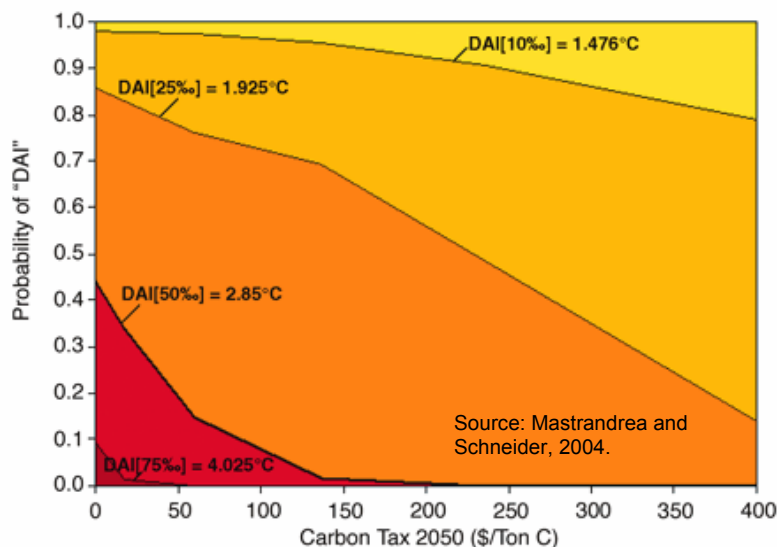


Figure 9 – Carbon taxes in 2050 and the probability of DAI.

Notes: Each band represents a different percentile range for the DAI threshold CDF—a lower percentile from the CDF representing a lower temperature threshold for DAI. At any threshold, climate policy controls significantly reduce the probability of DAI. At the median DAI threshold of 2.85°C (the thicker black line above), a 2050 carbon tax of >\$150/Ton C is necessary to virtually eliminate the probability of DAI.

Lastly, Mastrandrea and Schneider run Monte Carlo analyses varying climate sensitivity at different values for the PRTP, which illustrates the relationship between the discount rate and the probability of DAI at different temperature threshold values, as shown in Figure 10, below. As expected, increasing the discount rate shifts the probability distribution of future temperature increase upwards; a lower level of climate policy controls becomes “optimal” and thus increases the probability of DAI. At the median threshold of 2.85°C for DAI (the thicker black line in Figure 10), the probability of DAI rises from near zero with a 0% PRTP to 30% with a 3% PRTP. A PRTP of 3% is the value originally specified in Nordhaus’ DICE model. At PRTP values greater than 1%, the “optimal” outcome becomes increasingly insensitive to variation in future climate damages driven by variation in climate sensitivity.

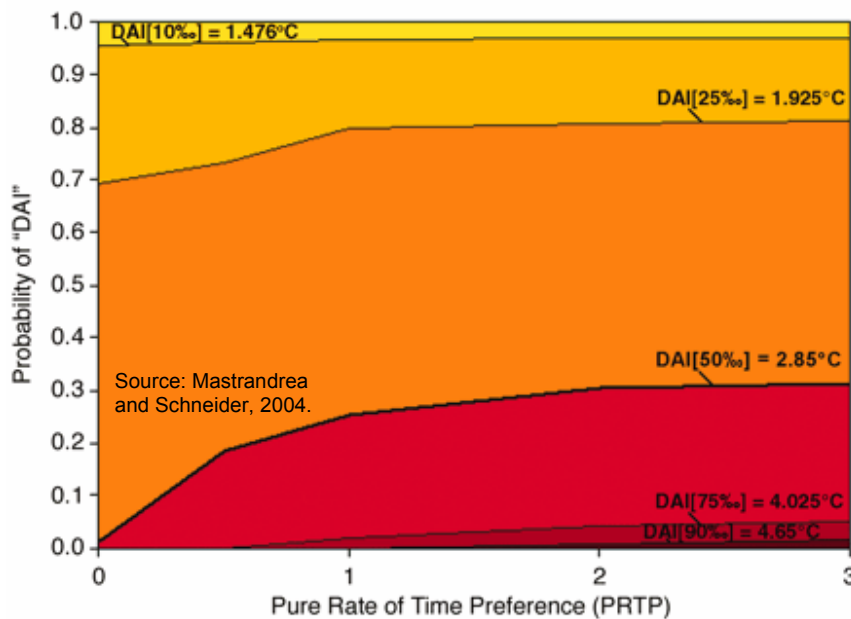


Figure 10 – PRTP and the probability of DAI.

Notes: Increasing the PRTP (and hence the discount rate) reduces the present value of future climate damages and increases the probability of “DAI.” At the median threshold of 2.85°C for “DAI” (thicker black line above), the probability of “DAI” rises from near zero with a 0% PRTP to 30% with a 3% PRTP, as originally specified in the DICE model.

While Mastrandrea and Schneider’s results using the DICE model do not provide us with confident quantitative answers, they still demonstrate three very important issues: (1) that DAI can vary significantly, depending on its definition; (2) that parameter uncertainty will be critical for all future climate projections, and most importantly for this volume on the benefits of climate stabilization policies; (3) that climate policy controls (i.e., “optimal” carbon taxes) can significantly reduce the probability of dangerous anthropogenic interference. This last finding has considerable implications for introducing climate information to policymakers. We agree with Mastrandrea and Schneider that presenting climate modeling results and arguing for the benefits of climate policy should be framed for decision makers in terms of the potential for climate policy to reduce the likelihood of exceeding a DAI threshold. While Mastrandrea and Schneider’s quantitative results should not be taken literally, the framework and methods for assessing DAI that they use should be taken seriously, as it is an effective method for conceptualizing climate change policy decisions.

The Value Judgments

Despite the uncertainties surrounding climate change probabilities and consequences, policymakers must still produce value judgments about what climate change risks to face and what to avoid. They must use all expert information available, like that above, to decide the relative allocation of limited resources on avoiding

potential DAI versus healthcare or education or a host of other worthy causes. It is our personal value judgment that hedging against first decimal place odds of DAI is prudent, and we hope that as climate science progresses and more information is available to policy makers, they will be more willing to risk Type I errors in the climate change arena and will enact effective abatement and adaptation measures. This view is partly motivated by Figure 11. Human actions over the next few generations can precondition climatic changes and impacts over the next millennium.

The figure shows a “cartoon” of effects that can play themselves out over a millennium, even for decisions taken within the next century. Such very long-term potential irreversibilities (significant increases in global annual average surface temperature, sea level rise from thermal expansion and melting glaciers, etc.) that the Figure depicts are the kinds of nonlinear events (exceeding Type 2 thresholds) that would likely qualify as “dangerous anthropogenic interference with the climate system” [37, 44, 7]. Whether a few dominant countries and/or a few generations of people demanding higher material standards of living and consequently using the atmosphere as an unpriced waste dump to more rapidly achieve such growth-oriented goals is “ethical” is a value-laden debate that will no doubt heat up as greenhouse gas buildups continue.

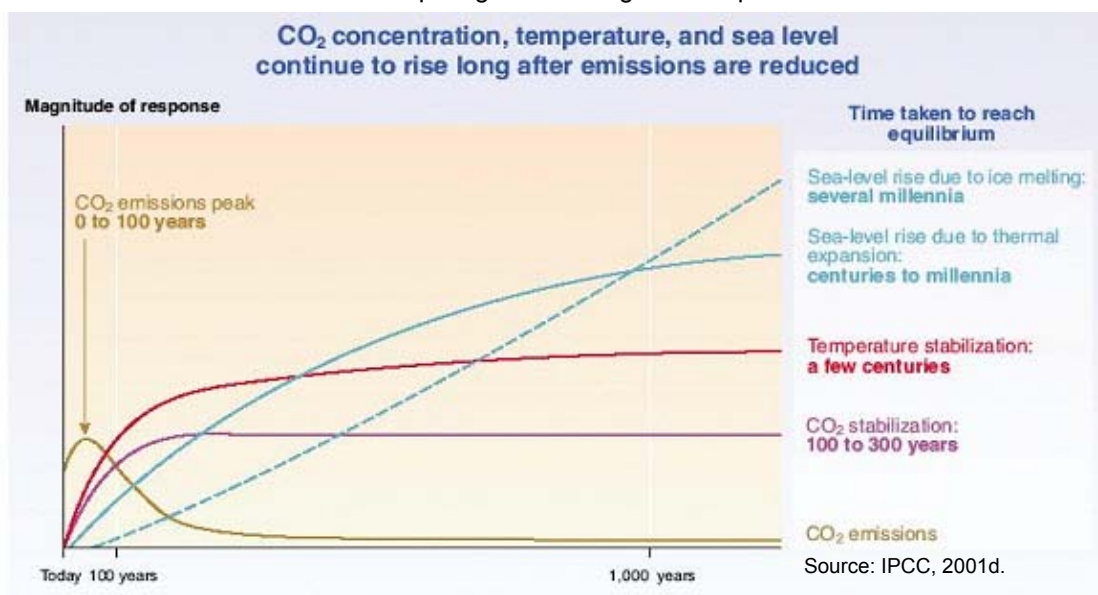


Figure 11 – Carbon dioxide concentration, temperature, and sea level rise.

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