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Improving Information for Policy Makers

# Abrupt Non-Linear Climate Change, Irreversibility and Surprise

by

**Stephen H. Schneider**

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## FOREWORD

This paper was prepared for an OECD Workshop on the *Benefits of Climate Policy: Improving Information for Policy Makers*, held 12-13 December 2002. The aim of the Workshop and the underlying Project is to outline a conceptual framework to estimate the benefits of climate change policies, and to help organise information on this topic for policy makers. The Workshop covered both adaptation and mitigation policies, and related to different spatial and temporal scales for decision-making. However, particular emphasis was placed on understanding global benefits at different levels of mitigation -- in other words, on the incremental benefit of going from one level of climate change to another. Participants were also asked to identify gaps in existing information and to recommend areas for improvement, including topics requiring further policy-related research and testing. The Workshop brought representatives from governments together with researchers from a range of disciplines to address these issues. Further background on the workshop, its agenda and participants, can be found on the internet at: www.oecd.org/env/cc

The overall Project is overseen by the OECD Working Party on Global and Structural Policy (Environment Policy Committee). The Secretariat would like to thank the governments of Canada, Germany and the United States for providing extra-budgetary financial support for the work.

This paper is issued as an authored “working paper” -- one of a series emerging from the Project. The ideas expressed in the paper are those of the author alone and do not necessarily represent the views of the OECD or its Member Countries.

As a working paper, this document has received only limited peer review. Some authors will be further refining their papers, either to eventually appear in the peer-reviewed academic literature, or to become part of a forthcoming OECD publication on this Project. The objective of placing these papers on the internet at this stage is to widely disseminate the ideas contained in them, with a view toward facilitating the review process.

Any comments on the paper may be sent directly to the author at:

Stephen H. Schneider
Department of Biological Scineces
Stanford University, Stanford, CA, USA
E-mails: shs@stanford.edu

Comments or suggestions concerning the broader OECD Project may be sent to the Project Manager:

Jan Corfee Morlot at: jan.corfee-morlot@oecd.org

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## 1.1 What is a "surprise"?

Strictly speaking, a surprise is an unanticipated outcome; by definition it is an unexpected event. Potential climate change, and more broadly, global environmental change, is replete with this kind of truly unexpected surprise 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.

In IPCC (1996), "surprises" are defined as rapid, non-linear responses of the climatic system to anthropogenic forcing (e.g., greenhouse gas increases), such as the collapse of the "conveyor belt" circulation in the North Atlantic Ocean or rapid deglaciation of polar ice sheets.

Unfortunately, most climate change assessments rarely consider low-probability, but high-consequence extreme events. Instead, they primarily consider scenarios that supposedly "bracket the uncertainty" rather than explicitly integrate unlikely events from the "tails of the distribution." Not even considered in the standard analytical works are structural changes in political or economic systems or regime shifts such as a change in public consciousness regarding environmental values. Although researchers may recognize the wide range of uncertainty surrounding global climate change, their analyses are typically surprise-free. Thus, decision-makers reading the "standard" literature will rarely appreciate the full range of possible outcomes, and thus might be more willing to risk adapting to prospective changes rather than attempting to avoid them through abatement than if they were aware that some potentially unpleasant surprises could be lurking (pleasant ones might occur as well, but many policymakers tend to insure against negative outcomes preferentially).

Events that are not truly unexpected are better defined as *imaginable abrupt events*. For other events—true surprises--although the outcome may be unknown, it may be possible to identify *imaginable conditions for surprise*. For example, if rate of change of $CO_2$ concentrations is one imaginable condition for surprise (i.e., more rapid forcing increases the chances for surprises), the system would be less rapidly forced if decision-makers chose as a matter of policy to slow down the rate at which human activities modify the atmosphere. To deal with such questions, the policy community needs to understand both the potential for surprises and how difficult it is for integrated assessment models, or IAMs (and other models as well) to credibly evaluate the probabilities of currently imaginable "surprises," let alone those not currently envisioned (Schneider, Turner and Morehouse Garriga, 1998).

## 1.2 "Emergent properties" of complex systems.

Most global systems are inherently complex, consisting of multiple interacting sub-units. Scientists frequently attempt to model these complex systems in isolation often along distinct disciplinary lines, producing internally stable and predictable behaviour. However, real-world coupling between sub-systems can cause the set of interacting systems to exhibit new collective behaviours -- called "emergent properties" – that are not clearly demonstrable by models that do not also include such coupling.

Furthermore, responses of the coupled systems to external forcing can become quite complicated. For example, one emergent property increasingly evident in climate and biological systems, is that of irreversibility or hysteresis -- changes that persist in the new post-disturbance state even when the original forcing is restored. This irreversibility can be a consequence of multiple stable equilibria in the coupled system -- that is, the same forcing might produce different responses depending on the pathway followed by the system. Therefore, anomalies can push the coupled system from one equilibrium to another, each of which has very different sensitivity to disturbances (i.e., each equilibrium may be self-sustaining within certain limits). The foregoing discussion is primarily about model-induced behaviours, but hysteresis has also been observed in nature (e.g., Rahmstorf, 1996).

Exponential increases in computational power have encouraged scientists to turn their attention to broadly focused projects that couple multiple disciplinary models. General Circulation Models (GCMs) of the atmosphere and oceans, for example, now allow exploration of emergent properties in the climate system resulting from interactions between the atmospheric, oceanic, biospheric, and cryogenic components.

In this section, I outline several examples of systems that exhibit complex, non-linear behaviour due to interactions between sub-systems of the climate system, including in one example, the socio-economic system. These include multiple stable equilibrium states of the thermohaline circulation (THC) in the North Atlantic Ocean and of the atmosphere-biosphere interactions in Western Africa.

A common view of the climate system and ecosystem structure and function is that of path independence (no memory of previous conditions). However, the multiple stable equilibria for both THC and for atmosphere-biosphere interactions in West Africa suggest a more complex reality. In such systems, the equilibrium state reached is dependent on the initial conditions of the system. Crossing thresholds can lead to unpredictable or irreversible changes. Furthermore, such complex processes have an implication for effective policymaking. Incorporating possibly damaging effects of changes in THC into modelling of climate change policy, for example, can significantly alter policy recommendations and lead to discovery of emergent properties of the coupled social-natural system (see Higgins et al 2002, from which much of this section is adapted).

### 1.3 Thermohaline circulation

The THC in the Atlantic brings warm tropical water northward, raising sea surface temperatures (SST) about 4°C relative to SSTs at comparable latitudes in the Pacific. The warm SSTs in the North Atlantic warm and moisten the atmosphere, thereby heating Greenland and Western Europe by roughly 5-8°C and increasing precipitation throughout the region (Stocker and Marchal, 2000, Broecker, 1997).

Temperature and salinity patterns in the Atlantic create the density differences that drive THC. As the warm surface waters move to higher northern latitudes, heat exchange with the atmosphere causes the water to cool and sink at two primary locations: one south of the Greenland-Iceland-Scotland (GIS) Ridge in the Labrador Sea and the other north of the GIS ridge in the Greenland and Norwegian Seas (Rahmstorf, 1999). Water sinking at the two sites combines to form North Atlantic Deep Water (NADW), which then flows to the southern hemisphere via the deep Western Boundary Current (WBC). From there NADW mixes with the circumpolar Antarctic current and is distributed to the Pacific and Indian Oceans, where it upwells, warms and returns to the South Atlantic. As a result, there is a net northward flow of warm, salty water to the surface of the North Atlantic.

Paleoclimate reconstructions and model simulations suggest there are multiple equilibria for the THC in the North Atlantic, including a complete collapse of circulation. These multiple equilibria constitute an emergent property of the coupled ocean-atmosphere system. Switching between the equilibria can occur as a result of temperature or freshwater forcing. Thus, the pattern of the THC that exists today could be modified by an infusion of fresh water at higher latitudes or through high-latitude warming and a concomitant reduction in the equator-to-pole temperature gradient (as models suggest for whole latitude bands, but not necessarily longitudinal sectors like the North Atlantic). These changes may occur if substantial climate change increases precipitation, causes glaciers to melt, or warms high latitudes more than low latitudes, as is often projected (IPCC 1996, 2001a).

Further research has incorporated this behaviour into coupled climate-economic modelling, characterizing additional emergent properties of the coupled climate-economic system (Mastrandrea and Schneider, 2001). Again, this coupled multi-system behaviour is not revealed by single-discipline sub-models alone; choices of model parameter values such as the discount rate determine whether emissions mitigation decisions made in the near-term will prevent a future THC collapse or not -- clearly a property not obtainable by an economic model *per se*.

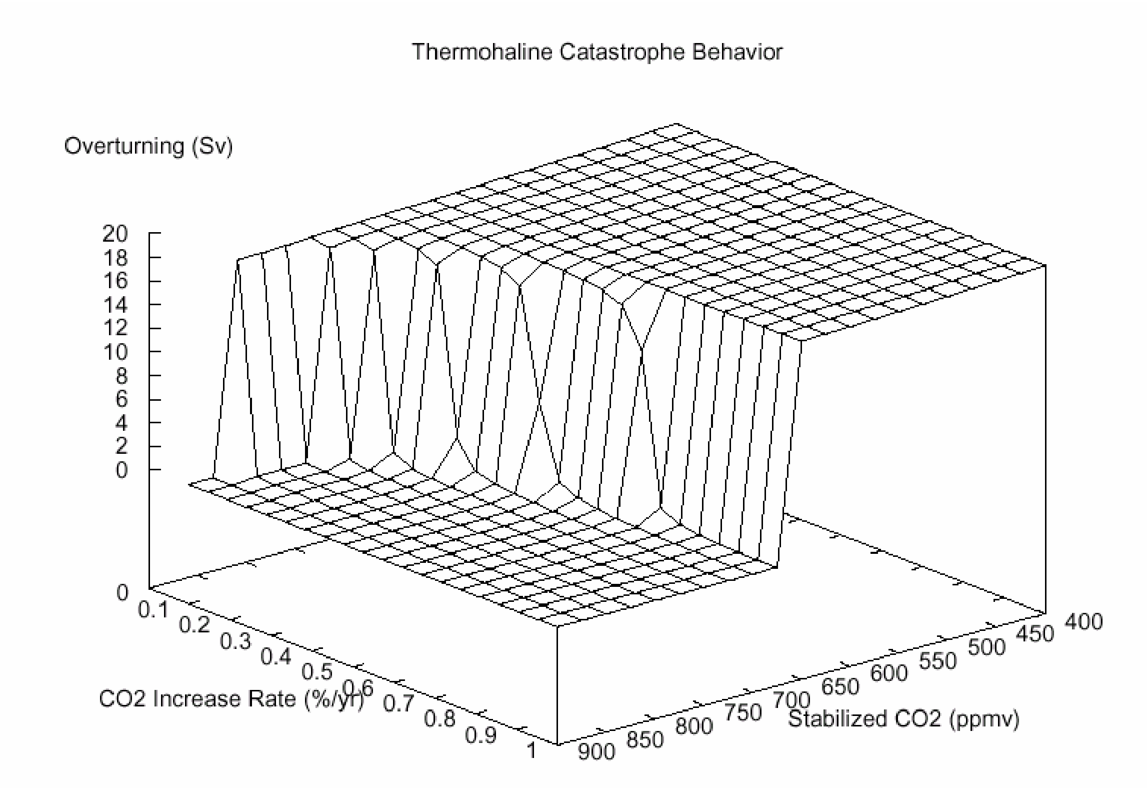
Rahmstorf (1996) presents a schematic stability diagram of THC, based on his modification of the conceptual model of salinity feedback developed by Henry Stommel. This diagram demonstrates three possible classes of THC equilibrium states under different levels of freshwater forcing, and the theoretical mechanisms for switching between them. These include two classes of deep water formation, one with sinking in the Labrador sea and north of the GIS ridge and one with sinking north of the GIS ridge alone, and one class of complete overturning shutdown. This formulation indicates that switching between stable equilibria can occur very rapidly under certain conditions. The paleo-climatic record supports this, suggesting rapid and repeated switching between equilibria, in a period of years to decades (Bond et al., 1997). Evidence indicates that during glacial periods, partial collapse of the continental ice sheets into the North Atlantic freed large amounts of fresh water through extensive iceberg releases (Seidov and Maslin, 1999), and that freshwater reduced the density of surface waters thus inhibiting sinking that drives the THC.

Complex general circulation models (GCMs) suggest that future climate change could cause a similar slowdown or even collapse in THC overturning (Wood et al., 1999, Manabe and Stouffer, 1993). The Simple Climate Demonstrator (SCD) developed by Schneider and Thompson (2000) incorporates a simple density-driven set of Atlantic ocean boxes that mimic the results of complex models, but is sufficiently computationally efficient that the SCD facilitates sensitivity analysis of key parameters and generates a domain of scenarios that show abrupt collapse of THC (figure 1). Model results (e.g., Stocker and Marchal, 2000, Schneider and Thompson, 2000 -- figure 1) suggest that both the amount of greenhouse gases entering the atmosphere as well as the rate of build-up will affect the THC overturning.

If warming reduces the ability of surface water to sink in high latitudes, this interferes with the inflow of warm water from the south. Such a slowdown will cause local cooling, which will re-energize the local sinking, serving as a stabilizing negative feedback on the slowdown. On the other hand, the initial slowdown of the strength of the Gulf Stream reduces the flow of salty subtropical water to the higher latitudes of the North Atlantic. This would act as a destabilizing positive feedback on the process by further decreasing the salinity of the North Atlantic surface water and reducing its density, further inhibiting local sinking. The rate at which the warming forcing is applied to the coupled system could determine which of these opposing feedbacks dominates, and subsequently, whether a THC collapse occurs.

Recent research efforts have connected this abrupt non-linearity to integrated assessment of climate change policy. William Nordhaus' DICE model (Nordhaus, 1994) is one example. It is a simple optimal growth model that, when given a set of explicit value judgments and assumptions, generates an optimal future forecast for a number of economic and environmental variables. It does this by maximizing discounted utility (satisfaction from consumption) by balancing the costs to the economy of greenhouse gas (GHG) emissions abatement (a loss in a portion of GDP caused by higher carbon energy prices) against the costs of damages from the build-up of atmospheric GHG concentrations. This build-up affects the climate, which in turn causes "climate damage," a reduction in GDP determined by the rise in globally averaged surface temperature due to GHG emissions. In some sectors and regions, such climate damages could be negative -- i.e., benefits -- but DICE aggregates across all sectors and regions (see, for example, the discussions in Chapters 1 and 19 of IPCC, 2001b) and therefore assumes that this aggregate measure of damage is always a positive cost.

**Figure 1. Equilibrium results of the SCD model under different forcing scenarios**



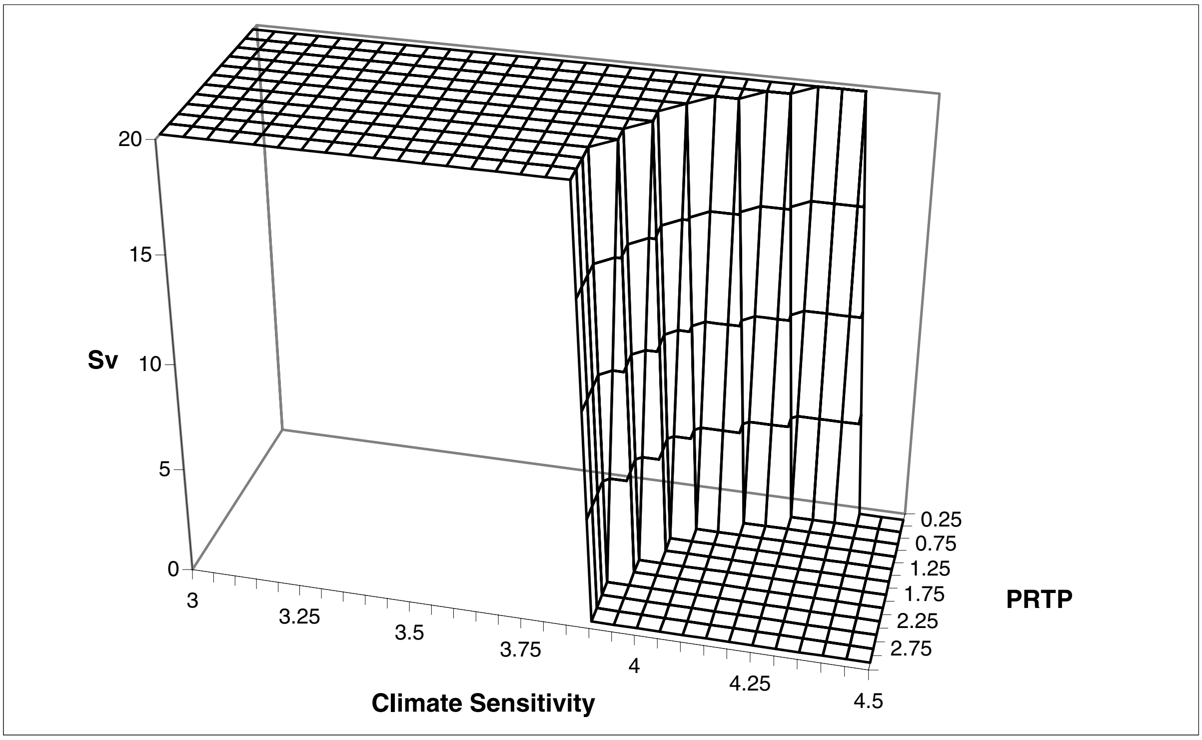
**Notes:** THC overturning in Sverdrups (1 Sv = 1 million $m^3$/s) is shown on the vertical axis as a function of the rate of carbon dioxide increase in the atmosphere and the stabilization concentration. Higher stabilization levels and more rapid rates of carbon dioxide increase make a THC collapse (abrupt change from "normal" -- 20 Sv -- to zero Sv) more likely.

*Source: Schneider and Thompson (2000)*

Mastrandrea and Schneider (2001) have developed a modified version of Nordhaus' DICE model called E-DICE, which contains an enhanced damage function that reflects the higher likely damages that would result when abrupt climate changes occur. When climate changes are smooth and relatively predictable, the foresight afforded increases the capacity of society to adapt. Damages will be lower under this scenario than for very rapid or unanticipated changes such as "surprises" like a THC collapse. Since the processes that climate models ignore by their high degree of aggregation require heroic parameterizations, their quantitative results can only be used as a tools for insights into potential qualitative behaviours. But to their credit, their results reveal emergent properties of the coupled climate-economy system that are not shown by separate single models of nature or society alone. However, when dealing with the abrupt non-linear behaviour of the SCD model (and other "surprise" scenarios), the E-DICE model produces a result that is qualitatively different from DICE with its lack of internal abrupt non-linear dynamics. As shown, a THC collapse is obtained for rapid and large $CO_2$ increases in the SCD model. An "optimal" solution of conventional DICE can produce an emissions profile that triggers such a collapse.

However, this abrupt non-linear event can be prevented when the damage function in DICE is modified to account for enhanced damages created by this THC collapse and THC behaviour is incorporated into the coupled climate-economy model.

**Figure 2. Cliff diagram of equilibrium THC overturning varying PRPT and climate sensitivity**



**Notes:** Showing that as pure rate of time preference (PRTP - proportional to discount rate) increases, the climate sensitivity threshold at which collapse of the THC occurs decreases. This is because higher discount factors imply lower present value for far future climate damages, which thus lead to smaller control rates on emissions. Lower control rates means more cumulative emissions and thus a greater risk of climate change sufficient to trigger abrupt non-linear responses like THC collapse in the future.

*Source: Mastrandrea and Schneider (2001)*

The coupled system contains feedback mechanisms that allow the profile of carbon taxes to increase sufficiently in response to the enhanced damages so as to lower emissions sufficiently to prevent the THC collapse in an optimization run of E-DICE. The enhanced carbon tax actually “works” to lower emissions and thus avoid future damages (Figure 2). Keller et al. (2000) support these results, finding that significantly reducing carbon dioxide emissions to prevent or delay potential damages from an uncertain and irreversible future climate change such as a THC collapse may be cost-effective. But the amount of near-term mitigation the DICE model “recommends” to reduce future damages is critically dependent on the discount rate. Thus, for low discount rates (less than 1.8% in one formulation), the present value of future damages creates a sufficient carbon tax to keep emissions below the trigger level for the abrupt non-linear collapse of the THC a century later. But a higher discount rate sufficiently reduces the present value of even catastrophic long-term damages so that abrupt non-linear THC collapse becomes an emergent property of the coupled socio-natural system. The discount rate is therefore the parameter that most influences the 22nd century behaviour of the modelled climate.

Although these highly aggregated models are not intended to provide high-confidence quantitative projections of coupled socio-natural system behaviours, I believe that the bulk of integrated assessment models used to date for climate policy analysis -- and which do not include any such abrupt non-linear processes -- will not be able to alert the policymaking community to the importance of abrupt non-linear behaviours. At the very least, the ranges of estimates of future climate damages should be expanded beyond that suggested in conventional analytic tools to account for such non-linear behaviours (e.g., Moss and Schneider, 2000).

### 1.4 Vegetation cover and climate dynamics

The potential for multiple equilibria in the coupled atmosphere-biosphere system has received increasing attention in recent years. As mentioned, several regions of the world appear to exhibit multiple stable equilibria, with the equilibrium realized depending on the initial conditions of the coupled system. Other regions appear to have a single stable equilibrium, at least under current conditions. This is relevant for policymakers, since if a region has exhibited multiple equilibria in the past, it could do so again in the future if forced to change by more recent disturbances like overgrazing or greenhouse gas build-ups.

Based on the results briefly reviewed below, the forest-tundra boundary appears to be a single stable equilibrium, at least at the scale relevant to the climate system. However, evidence suggests that certain regions in the sub-tropics indeed have multiple stable equilibria that depend upon initial vegetation distribution.

Several areas where multiple equilibria exist in the coupled atmosphere-biosphere system suggest a linkage between regional aridity and vegetation cover. For example, using a coupled global atmosphere-biome model, Claussen (1998), produces two separate equilibrium solutions for precipitation in North Africa and Central East Asia when initial land-surface conditions were different (but all other factors were the same).

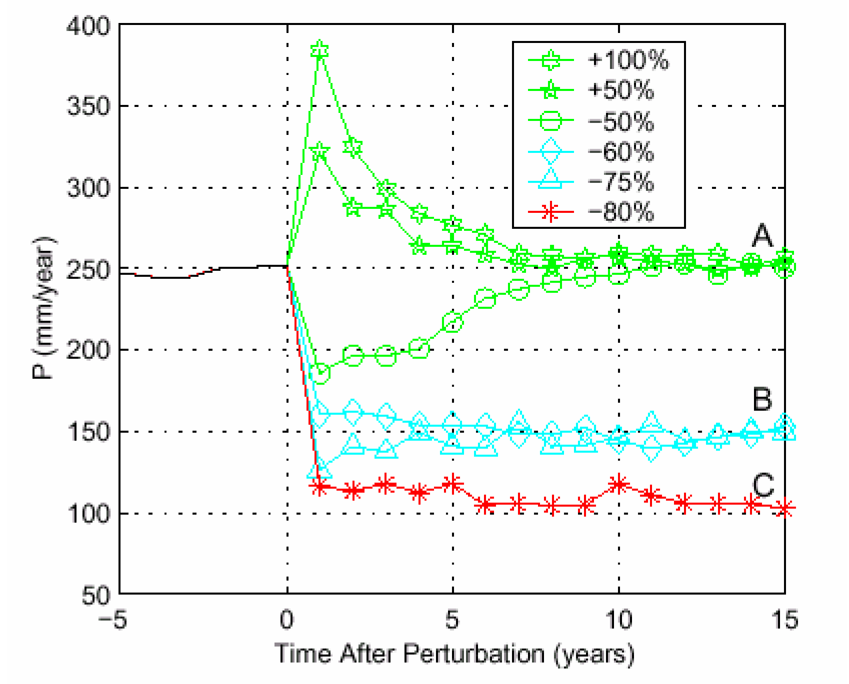
A similar study compared simulations with vegetation initialized as either forest or desert (Kleidon et al., 2000). The comparison between these “green” and “desert” worlds again illustrates that some regions are sensitive to the initial vegetation while other regions retain just one set of vegetation and precipitation conditions. In particular, regions of Africa, South Asia, and Australia produced different stable atmosphere-biosphere equilibria, depending on whether the initialized vegetation was forest or desert. This means that if the system is disturbed, it may not return to its original equilibrium, and thus a large enough disturbance could cause irreversible changes. In contrast, such simulations produce a single equilibrium for both the “green” and “desert” worlds in other regions, meaning that after a period of disturbance, they could be restored to their original conditions.

The Amazon is another candidate for multiple equilibria in the coupled climate-vegetation system. Kleidon and Heimann (1999) studied interactions between vegetation type, rooting depth, and climate in the Amazon basin. During the dry season, the water transpired by plants contributes substantially to atmospheric moisture, altering the partitioning of net radiation between sensible and latent heat fluxes and increasing relative humidity. In their simulation, Kleidon and Heimann found that vegetation type determines rooting depth, which partly determines the availability of soil moisture for evapo-transpiration. Comparison between simulations that differed in rooting depth revealed that the dry season is warmer and lasts longer when vegetation with a shallower rooting depth is present than when vegetation with deeper roots is initialized (Kleidon and Heimann, 1999).

Historical evidence suggests that two equilibria in the coupled vegetation and climate system may exist for the Sahel region of West Africa (10ºN-17.5ºN, 15ºW-15ºE) (Wang and Eltahir, 2000b), where an extended period of drought has persisted since the 1960s (Wang and Eltahir, 2000a).

Experiments (Wang and Eltahir, 2000a) suggest that this drought represents a change from a self-sustaining wet climate equilibrium to another self-sustaining dry equilibrium (Figure 3).

**Figure 3. Response of the coupled atmosphere-biosphere system to vegetation perturbations for the Sahel**



**Notes:** Model is a synchronously coupled biosphere-atmosphere model (as described by Wang and Eltahir, 2000b) that starts from a vegetation distribution for West Africa close to today's. Leaf area index shows a similar pattern as that shown here for precipitation. Three equilibria are obtained depending on the magnitude of the vegetation perturbation: (A) The coupled climate-vegetation system is stable to perturbations in which vegetation is degraded by 50 percent, or increased by 50, and 100 percent, thus vegetation and precipitation recover to pre-disturbance values. (B) Perturbations in which 60 and 75 percent of vegetation is degraded result in a second equilibrium in the coupled climate-vegetation system. (C) Perturbation in the form of 80 percent degradation of vegetation results in a third equilibrium.

*Source: Wang and Eltahir (2000b)*

Initially, a sea surface temperature (SST) anomaly altered modelled precipitation in the Sahel. As a consequence, the grassland vegetation shifted to that of a drier equilibrium state. Therefore, the combination of natural climate variability (i.e., SST anomaly) and the resulting change in land cover were both necessary to alter the availability of moisture for the atmosphere in the longer term, and to determine the equilibrium state (Wang and Eltahir, 2000b).

Wang and Eltahir (2000b), found that vegetation in their model is partly responsible for the low-frequency variability in the atmosphere-biosphere system characteristic of the Sahel and for the transition between equilibrium states. Rooting depth within the perennial grassland determines which equilibria the modelled system occupies at a given time. In the model, moist (i.e., favorable) growing seasons facilitate greater root growth of perennial grasses while dry (unfavorable) growing seasons lead to shallow root growth. Shallow roots lead to less evopotranspiration and less atmospheric moisture, causing a positive feedback (Wang and Eltahir, 2000b).

Similar modelling studies suggest that monsoon circulation in West Africa is sensitive to deforestation. However, the sensitivity of the monsoon circulation to changes in land cover depends critically on the location of the change in vegetation. Desertification along the Saharan border has little impact on the modelled monsoon circulation, while deforestation along the southern coast of West Africa results in a complete collapse of the modelled monsoon circulation with a corresponding reduction in regional rainfall (Zheng and Eltahir, 1998). This illustrates that relatively small areas of land cover might determine the equilibrium state of the atmosphere-biosphere system of an entire region.

Similar mechanisms have been hypothesized for the boreal forest/tundra boundary (Levis et al., 1999), but similar results were not obtained. Levis et al. (1999) examine the boreal forest/tundra boundary under current climate conditions to determine if multiple stable states in the atmosphere-biosphere system are possible. In one simulation, they initialize the model with the current boreal forest/tundra boundary, and in a second simulation, they initialize the model with boreal forest extended to the Arctic coast. In both simulations, the atmosphere-biosphere system converges to a single state, suggesting that for current conditions, there is a single stable equilibrium in the region -- at least for the processes in this model and at the scale of the continent.

The simulations performed by Claussen (1998) and Kleidon et al. (2000) are not specifically designed to test the forest-tundra boundary. However, their results are consistent with a single stable equilibrium at the forest-tundra boundary. Some caution is needed in interpreting these results in this manner because the two experiments compared 1) forest and desert; and 2) forest, grassland, dark desert, and light desert (as opposed to the forest and tundra specifically). However, the occurrence of a single equilibrium under the different initial vegetation conditions used by each suggests that the equilibrium of the atmosphere-biosphere system at the forest tundra boundary may not be sensitive to the vegetation initially present, at least not under current conditions.

But it also must be kept in mind that results from all such models depend on how the model aggregates processes that can occur at smaller scales than is implicit in the simulation; local variations in soils, fire regimes, and/or slope and elevation variability may all be neglected. The extent to which it is necessary to explicitly account for such processes, or to which such processes might influence conclusions about stability, remain a major debate point in all simulations that, for practical necessity, must parameterize the effects of processes occurring on small time and space scales. This suggests that using a hierarchy of models of varying complexity (and observations to test them) is the approach most likely to determine the implications of the degree of aggregation in various models. Most of the modelling studies briefly summarized above are suggestive of a potentially critical role that might be played by interactions between land cover and climate, but these are pioneering efforts, and a great deal more work will be needed to obtain more highly confident conclusions.

Six thousand years before present (around 4,000 B.C.), the Sahara was heavily vegetated, but over the following 1,000-2,000 years, an abrupt change in vegetation and climate occurred (Claussen et al., 1999). In model simulations, Ganopolski et al. (1998) found that an atmosphere-ocean-vegetation coupling was better able to represent the climate of the Sahara, with the addition of vegetation increasing precipitation four fold; evidence of a strong positive feedback between climate and vegetation distribution. Then, as orbital forcing caused a slow and steady decline in summer radiation, the modelled Sahara abruptly underwent desertification as a consequence of interactions between the orbital changes and the atmospheric and biospheric sub-systems (Claussen et al., 1999). These results suggest the Sahara of the mid-Holocene may have been prone to abrupt and irreversible changes but is currently in a single, quite stable equilibrium condition (i.e., desert).

Many factors complicate interpretation of model results such as these, however. Natural variability and ecosystem disturbance -- both human and natural -- are often not realistically incorporated into vegetation models. Whether different modelled equilibria remain stable under the more complicated conditions of the natural world requires additional exploration. Furthermore, natural ecosystems are rarely

-- if ever -- at equilibrium at the particular spatial and temporal scale of interest. Therefore, determining whether a particular region is switching between multiple equilibria as opposed to suffering the effects of an incomplete recovery from disturbance will require testing across a hierarchy of models incorporating different processes at different scales.

In addition, it is important to recognize that this review of multiple equilibria in the coupled climate-vegetation system is focused at the broadest scales of ecosystem structure and function as they relate to climate (e.g., albedo, transpiration, and roughness). At other biological scales (e.g., genetic, species, and population), different processes and characteristics may have multiple equilibria. For example, species or population extinction and loss of genetic diversity may occur without transitions in the climate system. Such changes clearly constitute different equilibria (e.g., with and without a particular species) that may be profoundly important biologically, but these different equilibria are not relevant at the scale of the climate system.

The key point of all these detailed examples is that the complexity of these non-linear interactions increases the likelihood that rapid climate changes could trigger abrupt responses, and that the harder and faster the system is disturbed, the higher the likelihood of such “surprises.”

# 2. INCORPORATING UNCERTAINTY AND SURPRISE INTO INTEGRATED ASSESSMENT MODELS (IAMS) OF CLIMATE CHANGE

## 2.1 Climate variability

A critical assumption of the standard assessment paradigm is that the probability of climate extremes such as droughts, floods, and super-hurricanes will either remain unchanged or will change with the mean change in climate according to unchanged variability distributions. As Mearns et al. (1984) have shown, however, changes in the daily temperature variance or the autocorrelation of daily weather extremes can significantly reduce or dramatically exacerbate the vulnerability of agriculture, ecosystems, and other extremely climate change-sensitive components of the environment. How such variability measures might change as the climatic mean changes is as yet highly uncertain, although an increase in extreme events is expected (see Table 1 from IPCC 2001 b). Variability in precipitation, most notably from an increase in high-intensity rainfall, is expected to rise. Karl and Knight (1998) have observed that about half of the 8 percent increase in precipitation in the U.S. since 1910 occurred in the top tenth percentile of rainfall intensity, in the form of the most damaging heavy downpours (see also, Wilby and Wigley, 2002). In addition, the El Niño/Southern Oscillation (ENSO) could well continue the trend of the past two decades and become a more frequent phenomenon, which will increase these aspects of climate variability relative to current conditions.

**Table 1. Projected Effects of Global Warming During the 21st Century**

| Projected Effect | Probability estimate | Examples of Projected Impacts with high confidence of occurrence (67 – 95% probability) in at least some areas |
|---|---|---|
| Higher maximum temperatures, more hot days and heat waves over nearly all land areas | Very likely (90-99%) | Increased deaths and serious illness in older age groups and urban poor<br>Increased heat stress in livestock and wildlife<br>Shift in tourist destinations<br>Increased risk of damage to a number of crops<br>Increased electric cooling demand and reduced energy supply reliability |
| Higher minimum temperatures, fewer cold days, frost days and cold waves over nearly all land areas | Very likely (90-99%) | Decreased cold-related human morbidity and mortality<br>Decreased risk of damage to a number of crops, and increased risk to others<br>Extended range and activity of some pest and disease vectors<br>Reduced heating energy demand |

Table 1 continued on next page

**Table 1. Projected Effects of Global Warming During the 21st Century (continued)**

| | | |
|---|---|---|
| More intense precipitation events | Very likely (90-99%) over many areas | Increased flood, landslide, avalanche, and mudslide damage<br>Increased soil erosion<br>Increased flood runoff increasing recharge of some floodplain aquifers<br>Increased pressure on government and private flood insurance systems and disaster relief |
| Increased summer drying over most mid-latitude continental interiors and associated risk of drought | Likely (67-90%) | Decreased crop yields<br>Increased damage to building foundations caused by ground shrinkage<br>Decreased water resource quantity and quality<br>Increased risk of forest fire |
| Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities | Likely (67-90%) over some areas | Increased risks to human life, risk of infectious disease epidemics and many other risks<br>Increased coastal erosion and damage to coastal buildings and infrastructure<br>Increased damage to coastal ecosystems such as coral reefs and mangroves |
| Intensified droughts and floods associated with El Niño events in many different regions | Likely (67-90%) | Decreased agricultural and rangeland productivity in drought- and flood-prone regions<br>Decreased hydro-power potential in drought-prone regions |
| Increased Asian summer monsoon precipitation variability | Likely (67-90%) | Increase in flood and drought magnitude and damages in temperate and tropical Asia |
| Increased intensity of mid-latitude storms | Uncertain (current models disagree) | Increased risks to human life and health<br>Increased property and infrastructure losses<br>Increased damage to coastal ecosystems |

*Source: IPCC (2001b)*

Projections for storms; including tropical cyclones, mid-latitude storms, tornadoes and other severe storms; are more controversial. Currently, the climate record is too noisy to detect clear evidence of increased hurricane intensities, but the theoretical understanding of the driving forces behind hurricanes strongly suggests that peak intensities should be higher in a warmer world (Emanuel, 1987; Walsh and Pittock, 1998). Increased climate extremes from human disturbances, although not possible to ascertain with high confidence given current data and methods for all important effects, is not a remote possibility (see Table 1). The right hand column, projected impacts, is predicated on the effects given in the left hand column actually occurring—that is, the impacts are contingent assessments, especially the confidence estimates, and do not incorporate the separate confidence estimates of the effects in the first column, whose probabilities are estimated in the central column.

## 2.2 Transient effects of climate change

Standard assessments before about 1995 modelled responses to a one-time doubling of $CO_2$ and analyzed the effects once the system reached equilibrium. Clearly, what happens along the path to a new equilibrium is of interest as well, especially in the event of abrupt change. Environmental or societal impacts resulting from abrupt changes are likely to be different from those that would occur with smoother, slower changes -- particularly for natural systems with slow adjustment mechanisms or human societies with less adaptive capacity. The long-term impact of climate change may not be predictable solely from a single steady-state outcome, but may well depend on the characteristics of the transient path. In other words, the outcome may be path-dependent. Any exercise which neglects surprises or assumes transitivity of the earth system -- i.e., a path *in*dependent response -- is indeed questionable, and should carry a clear warning to users of the fundamental assumptions implicit in it. Furthermore, rapid transients and non-linear events could well affect not only the mean values of key climate indicators, but also higher statistical moments, such as variability, of the climate (e.g., week-to-week variability, seasonal highs and lows, day-to-night temperature differences, etc). The fact that most climate scenarios generated over the past half dozen years are now transients is a clear improvement in technique relative to the previous standard use of one paradigm, that of $CO_2$ doubling. However, the reliability of time-evolving, regional climatic projections is difficult to assess, as the added complexity taxes our capacity to validate the new results. Therefore, considerable uncertainty will remain in all climate model projections for some time to come.

## 2.3 Rate of forcing matters

Even the most comprehensive coupled-system models are likely to have unanticipated results when forced to change very rapidly by external disturbances like land use (Pielke Sr, et al, 2002), $CO_2$ and aerosols. Some of those consequences could be harmful, others beneficial. Whether to hope for the beneficial ones or hedge against the harmful ones is the risk-management problem decision makers facing the climate issue will have to consider. Indeed, some of the transient coupled atmosphere-ocean models that project climate change hundreds of years into the future exhibit dramatic change to the basic climate state (Manabe and Stouffer, 1993). Other models remain stable. In order to develop a climate policy that will lower the risk of climate catastrophes, such as collapse of thermohaline circulation, policymakers need take into consideration rates of change in radiative forcing and possible consequences of rapid forcing for climate change beyond the 21st century, including very uncertain but highly consequential events like a THC collapse or multiple vegetation-precipitation equilibria.

## 2.4 Estimating climate damages

A critical issue in climate change policy is costing climatic impacts, particularly when the possibility for non-linearities, surprises and irreversible events is allowed. The assumptions made when carrying out such estimations largely explain why different authors obtain different policy conclusions. These issues are explored in the next several sections.

## 2.5 Historic losses as estimate of climate damages in monetary terms

We can anticipate costs associated with global change and place a preliminary value on some of the ecosystem services that could be affected. One way to assess the costs of climate change is to evaluate the historic losses from extreme climatic events, such as floods, droughts, and hurricanes.

Humanity remains vulnerable to extreme weather events. Catastrophic floods and droughts are cautiously projected to increase in both frequency and intensity with a warmer climate and with the influence of human activities such as urbanization, deforestation, depletion of aquifers, contamination of ground water, and poor irrigation practices (IPCC 2001a). The financial services sector has taken particular note of the potential losses from climate change. Losses from weather related disasters in the 1990s were eight times higher than in the 1960s (IPCC 2001b). Although there is no clear evidence that hurricane frequency has changed over the past few decades (or will change in the next few decades), there is overwhelming data showing that damages from such storms has increased astronomically. Attribution of this trend to changes in socio-economic factors (e.g., economic growth, population growth and other demographic changes, or increased penetration of insurance coverage) and/or to an increase in the occurrence or intensity of extreme weather events, as a result of global climate change, is uncertain and controversial (e.g., compare Vellinga et al. (2001) which acknowledges both influences and recognizes the difficulty in attribution, to Pielke Jr. and Landsea (1998), which dismisses any effects of climate change, at least for hurricane damages). Regardless of attribution, damage assessment of observed extreme events is one possible way in which we can relate the cost of more inland and coastal flooding, droughts, and possible intensification of hurricanes to the value of preventing the disruption of climate stability.

### 2.6 Valuing ecosystem services

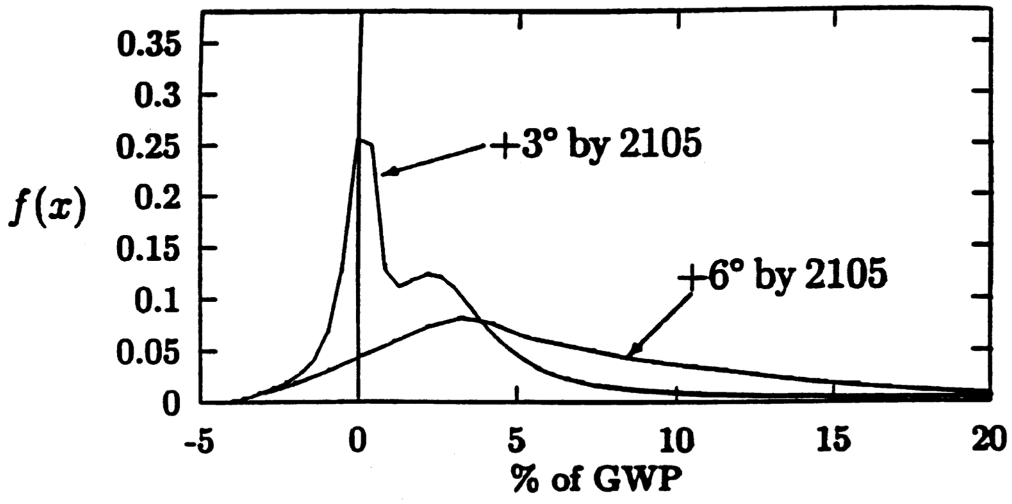
An assumption in cost-benefit calculations within the standard assessment paradigm is that "nature" is either constant or irrelevant. Since "nature" typically falls out of the purview of the market, cost-benefit analyses then ignore its non-market value. For example, ecological services such as pest control or waste recycling are omitted from most assessment calculations. Implicitly, this assumes that the economic value of ecological services is negligible or will remain unchanged with human disturbances. Recent assessments of the value of ecosystem services acknowledge the tremendous public good (i.e., free) provided, not to mention the recreational and aesthetic value. For example, a cost-assessment study in New York discovered that paying residents and farmers to reduce toxic discharges and other environmental disruptions in order to protect the Catskills, which provide a natural water purification service, produced a significant savings (on the order of billions of dollars) over building a new water treatment plant (Daily and Ellison, 2002).It is highly likely that communities of species will be disrupted, especially if climate change occurs in the middle to upper range projected (e.g., Root and Schneider, 2002; Leemans, this volume). Cost-benefit analyses have yet to capture the value of this occurring. That is one of the prime reasons the IPCC 2002b report (see, especially Chapter 1) stressed a risk-management approach to climate policy rather than a traditional cost-benefit framework in which too many relevant factors were simply left out.

### 2.7 Subjective probability assessments of potential climate change impacts in monetary terms

Asking experts to estimate the range and likelihood of potential climate damages provides a crude metric for assigning dollar values to climate damages, albeit subjective ones. Nordhaus (1994) conducted a survey of conventional economists, environmental economists, atmospheric scientists, and ecologists to assess expert opinion on estimated climate damages. Interestingly, the survey reveals a striking cultural divide across natural and social scientists in the study. The most striking difference in the study is that conventional economists believe that even extreme climate change (i.e., 6°C warming by 2090) would not impose severe economic losses. Natural scientists estimate the economic impact of extreme climate change to be twenty to thirty times higher than conventional economists' projections. Despite the magnitude in difference of damage estimates between economists and ecologists, the shape of the damage estimate curve was similar. The respondents indicate accelerating costs with higher climate changes. Most respondents, economists and natural scientists alike, offered subjective probability distributions that were "right skewed". That is, most of the respondents consider the probability of severe climate damage, or "nasty surprises", to be higher than the probability of moderate benefits, or "pleasant surprises"– (see Figure 4). Rougharden and Schneider (1999) demonstrate that adopting such "right skewed" probability distributions into integrated assessment models produces optimal carbon taxes several times higher than "point estimates". The long, heavy tails of the skewed distribution that Roughgarden and Schneider label "surprise" pull the median and mean of the distribution away from the mode.

It will not be easy to resolve the paradigm gulf between the relatively optimistic and pessimistic views of these specialists with different training, traditions and world views. One thing that is clear from the Nordhaus study is that the vast bulk of knowledgeable experts from a variety of fields admit to a wide range of plausible outcomes in the area of climate change, including both mild and catastrophic realizations. This is a condition ripe for misinterpretation by those who are unfamiliar with the multitude of probabilities most scientists attach to climate change, which stem from recognition of the many uncertainties in data and assumptions still inherent in climate models, climatic impact models, economic models or their synthesis via integrated assessment models. In a highly interdisciplinary enterprise like the integrated assessment of climate change, it is necessary to include a wide range of possible outcomes along with a representative sample of the subjective probabilities that knowledgeable assessment groups believe accompany each of those possible outcomes.

**Figure 4. Probability distributions (f(x)) of climate damages as a percentage of gross world product (market and non-market components combined)**



*Source: Roughgarden and Schneider, 1999. Data from Nordhaus, 1994*

**Notes:** Taken from an expert survey in which respondents were asked to estimate tenth, fiftieth, and ninetieth percentilesof climate damages for the two climate change scenarios shown.

## 2.8 Five numeraires

As was evident in the Nordhaus (1994) study, one reason for some of the differences between economists’ and natural scientists’ relative degrees of concern was the fraction of damages assigned to non-market categories. Roughgarden and Schneider (1999) analyzed the Nordhaus (1994) data set and found that most respondents who had estimated large damages placed the bulk of them in the non-market basket; the converse was true for those with low damage estimates. This raises a major issue about the dimensions of damages, which need even finer subdivision than the current binary market and non-market characterization. Schneider, Kuntz-Duriseti and Azar (2000) believe that the costs of climate change must be looked at in terms of the "Five Numeraires": Monetary loss, loss of life, quality of life (including coercion to migrate, conflict over resources, cultural diversity, loss of cultural heritage sites, etc.), species or biodiversity loss, and distribution/equity (e.g., the common scenario in which the cooler rich countries in the political "North" get improved crop yields while hotter, poorer countries in the political "South" get reduced crop yields with warming).

Any comprehensive attempt to evaluate the societal value of climate change should include, for example, such things as loss of species diversity, loss of coastline from increasing sea level, environmentally-induced displacement of persons, change in income distributions, and differential agricultural losses. The environment also possesses intrinsic worth without a clear market value, such as its aesthetic appeal, which suggests that it should be treated as an independent variable in utility. In a sense, this is what is meant by "existence value" – a priority is placed on preserving the environment, even if we don't intend to personally experience it. This is in addition to the "option value" of the environment, which we may want to preserve for our – and our grandchildren's -- possible personal use in the future. There is little agreement on how to place dollar values on any of these non-market impacts of climate change.

The point of this discussion is that it is essential for analyses of costs of climate change impacts or mitigation strategies to consider explicitly alternative numeraires and to be as clear as possible which are being used and what has been omitted. Moreover, before any aggregation is attempted -- e.g., cost-benefit optimization strategies -- authors should first disaggregate costs and benefits into several numeraires and then provide a "traceable account" (see Moss and Schneider, 2000) of how they were re-aggregated. Such transparency is essential given the normative nature of the valuation of various consequences characterized by the five numeraires.

## 2.9 Agency

The predominant approach to discounting is based on an infinitely lived representative agent (ILA) who maximizes utility from a future welfare stream subject to economic and environmental conditions, usually assumed to be known. The representative agent framework imposes strong assumptions regarding intergenerational fairness. An alternative modelling paradigm, the overlapping generations model (OLG), differentiates between individual time preference and intergenerational equity (whereas the distinction is suppressed in the ILA model) and endogenizes the choice of the discount rate (Howarth, 2000). A distinctive characteristic of OLG models (unlike infinitely lived agent models in most IAMs) is that the OLG framework explicitly models the existence of generations, who work and save when young and consume savings, or "dis-save," when old. Thus, the two modelling frameworks represent quite different conceptions of intergenerational equity. The policy recommendations derived from the OGM differ fundamentally from ILA model, and typically include but are not limited to, higher carbon emission abatement.

## 2.10 The discount rate

Discounting plays a crucial role in the economics of climate change, yet it is a highly uncertain parameter. Discounting is a method of aggregating costs and benefits over a long time horizon by summing across future time periods net costs (or benefits) that have been multiplied by a discount rate, typically greater than zero. If the discount rate equals zero, then each time period is valued equally (case of infinite patience). If the discount rate is infinite, then only the current period is valued (case of extreme myopia). The discount rate chosen in assessment models is critical, since abatement costs typically will be incurred in the relatively near term, but the brunt of climate damages will be realized primarily in the long term. Thus, if the future is sufficiently discounted, present abatement costs, by construction, will outweigh discounted future climate damages. The reason is, of course, that discount rates will eventually reduce future damage costs to negligible present values.

Consider a climate impact that would cost $1 billion 200 years from now. A discount rate of 5% per year would make the present value of that future cost equal to $58,000. At a discount rate of 10% per year, the present value would only be $5. Changes in this parameter largely explain why some authors, using large discount rates, conclude that $CO_2$ emission increases are socially beneficial -- i.e., are more economically efficient than cuts -- whereas others, using low or zero discount rates, justify substantial emission reductions, even when using similar damage functions (see Schneider and Kuntz Duriseti (2002), from which this section is adapted, for further discussion and more references).

It would seem that the appropriate discount rate would be a matter of empirical determination. However, the conflict involves a serious normative debate about how to value the welfare of future generations relative to current ones. Moreover, it requires that this generation estimate what kinds of goods and services future generations will value -- e.g., how they will choose to make trade-offs between a legacy of extra material wealth and greater loss of environmental services. Much of the debate centres around different interpretations of the normative implications of the choice of the discount rate (e.g., Arrow et al, 1996).

The *descriptive* approach chooses a discount rate based on observed market interest rates in order to ensure that investments are made in the most profitable projects. Supporters of this approach often argue that using a market-based discount rate is the most efficient way to allocate scarce resources used for competing priorities, one of which is mitigating the effects of climate change

The *prescriptive* approach emphasizes that the choice of discount rate entails a choice about how the future should be valued. Proponents of intergenerational equity often argue that it is difficult to find a convincing argument in favour of discounting the welfare of future generations. Why should the well-being of future people count less just because they don’t exist today?

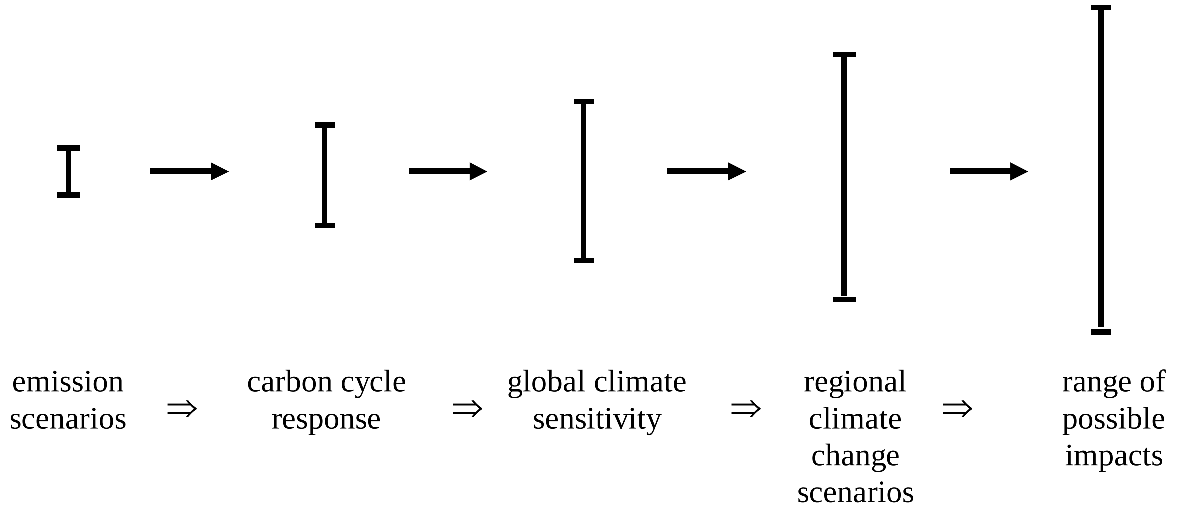
Although these two approaches are the most commonly used in IAMs of climate change, alternative discount methods have been proposed. There is empirical evidence to suggest that individuals exhibit "hyperbolic discounting," where discount rates decline over time, with higher (than market) discount rates in the short run and lower discount rates over the long term. This behaviour is consistent with the common finding that "human response to a change in a stimulus is inversely proportional to the pre-existing stimulus” (Heal, 1997). Hyperbolic discounting can be derived from both the descriptive and the prescriptive approaches. This can be modelled in IAMs with a logarithmic discount factor or by assuming that per capita income grows logistically over the next century, and since the discount rate is proportional to growth rates, declining discount rates are obtained (Azar and Sterner, 1996, Weitzman, 2000).

Furthermore, if climate change is really severe, such that future income eventually falls rather than grows, as is assumed in almost all IAMs, then the discount rate can be negative, provided that the rate of time preference is sufficiently low (see Arrow et al, 1996). In this case, future welfare should be valued *more* than the present. The complexity in the discounting issue stems not only from uncertainty in how to calculate the value of the future, but also from uncertainty over whether any particular choice of discount rates is appropriate for alternative value systems.

## 2.11 What is the probability of “dangerous” climate change?

But the problem for decision makers of assessing the likelihood of “dangerous anthropogenic interference with the climate system” is even more complicated than that. First of all, what is “dangerous” is a value judgment about the relative salience of various impacts, such as loss of income, lives, biodiversity, heritage sites and/or employment (the “five numeraires,” as it was labelled above). And, before such value judgments are even to be attempted, “dangerous climate change” involves, as illustrated in Figure 5, a cascade of uncertainties in emissions, carbon cycle response, climate response, and impacts. That is, we must we estimate future populations, future 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 modelling and, equally important, climate sensitivity estimated from climate models tested on paleoclimatic situations, as well as other "validation" exercises. Schneider (2001) showed that one could arrive at very different estimates of the probability of "dangerous" climate changes in 2100 because of the lack of specification by the IPCC of the independence of various scenarios or climate model sensitivities or their respective probabilities.

**Table 2. Range of major uncertainties typical in impact assessments showing the "uncertainty explosion"**



**Notes:** These ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic social and political impacts and policy responses. The only policy response implicit on this figure is adaptation, since the processes shown stop at impacts—in reality, perceptions of "unacceptable" risks could create abatement policies that would narrow the range of emission scenarios thus reducing the final impacts range. In that case, awareness of the large range of impacts might feedback on policies thus altering the emission scenarios so the cascade would be less "explosive".

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

Figure 5 shows the "uncertainty explosion" that occurs as each element of uncertainty is combined to encompass a comprehensive range of future consequences, including physical, economic, social and political impacts and policy responses. However, as noted in the caption of Fig 5, in a more complete model than that displayed above, arrows would cycle back from the last entry (impacts range) to the first uncertainty bar (emissions scenarios) since there would be a feedback loop of information from projected and/or experienced impacts that might modify human behaviour and thus alter the explosion of the uncertainty as depicted here. Such a model of rational response is why governments have created scientific groups like the IPCC to provide assessments of potential future risks so that policies can be fashioned to feed back on the scenarios in a way that might reduce the risks over time.

The IPCC Working Group 1 (IPCC 2001a) lead authors cascaded the 6 "equally sound" emissions "storylines" offered by SRES into radiative forcings that produce a wide temperature projection range via the use of 7 general circulation models (GCMs), which themselves represented a range of equilibrium climate sensitivities from 1.7 to 4.2 $^{o}$C warming for a doubling of $CO_2$ (and these 7 are a subset of 18 GCMs listed in Table 9.1 of the WG 1 Third Assessment Report with an even larger range of climate sensitivities to radiative forcing represented—see Schneider, 2001).

The result of combining the sensitivities of the 7 GCMs (via tuning a simple model to each GCM response) with the 6 illustrative scenarios from SRES is the very highly visible WG1 TAR-revised 2100 temperature projection of 1.4- 5.8 $^{o}$C further warming – a big jump from the 1- 3.5 $^{o}$C range of warming forecasted in the Second Assessment Report (see Key Findings) in 1996. This increase (from a high of 3.5 to a high of 5.8 $^{o}$C of warming by 2100) did not go unnoticed by policymakers!

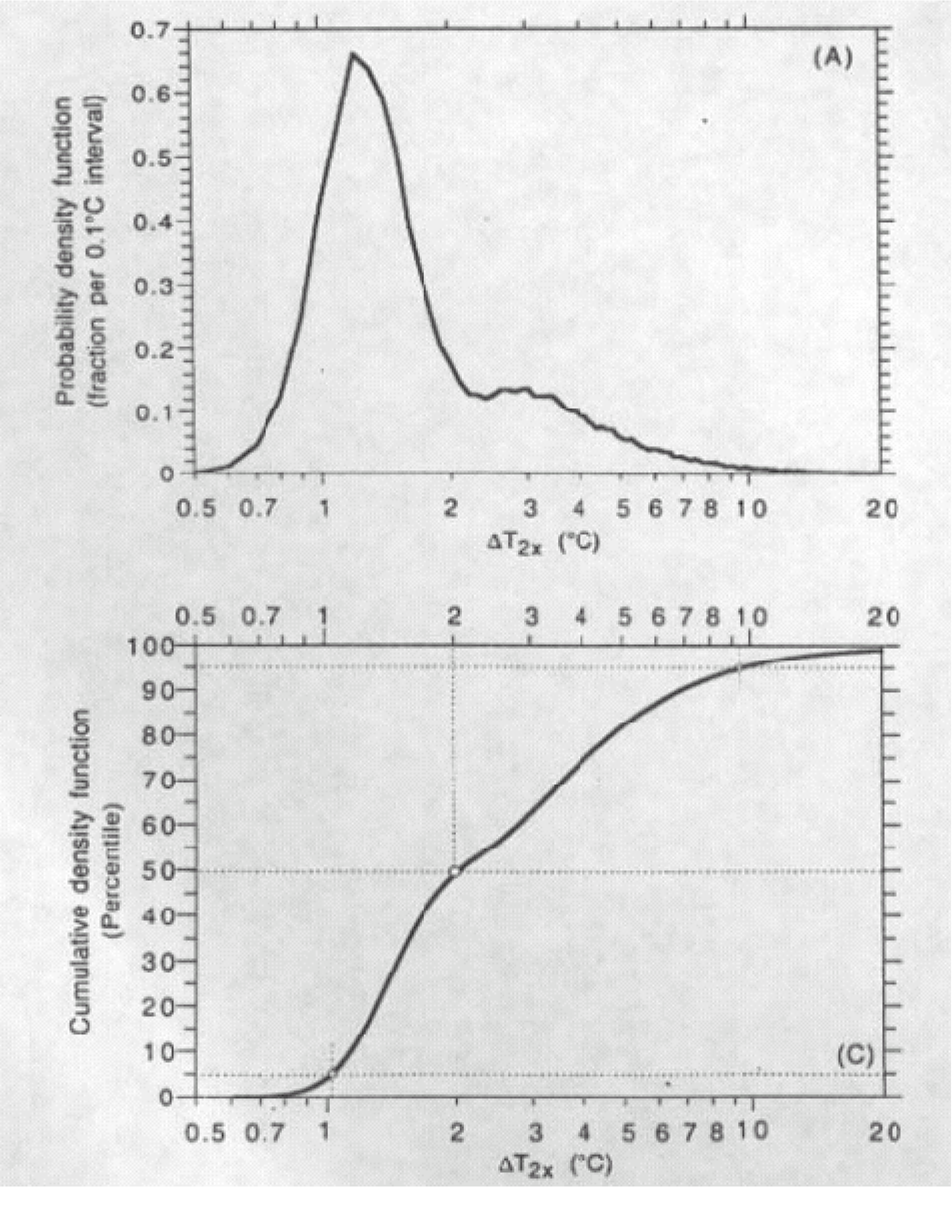
The problem with not having probabilities assigned to each SRES scenario or to each GCM climate sensitivity is that it is up to the policy analyst (or policymaker) to decide what he/she thinks the SRES team thought the probabilities were for each storyline, or what the WG1 authors thought the likelihood was for the sensitivity of each of the 7 GCMs selected. Unless assessors apply decision analytic elicitation (e.g., Morgan and Henrion, 1990; Morgan and Keith, 1995) or other techniques (e.g., Wigley and Raper 2001 or Forest et al, 2001 or Andronova and Schlesinger) to estimate more consistently the subjective likelihood of each scenario and GCM sensitivity, policymakers will eventually have to guess what the scenario generators or climate sensitivity assessors think are the joint probability distributions for outcomes.

Consider another simpler way to approach this problem of joint probability of temperature rise to 2100 and 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) -- Figure 6 -- shows that the 10 percentile value for climate sensitivity is 1.1 $^{o}$C for a doubling of $CO_2$ (i.e., 4 W/m$^2$ of radiative forcing). 1.1 $^{o}$C is, of course, below the1.5 $^{o}$C lower limit of the IPCC's temperature forecast for 2100. However, on Figure 6, this means that there is a 10 percent chance climate sensitivity will be 1.1 $^{o}$C or less -- that is, a 90% chance climate sensitivity will be 1.1 $^{o}$C or higher. The 50th percentile result -- that is, the value at which climate sensitivity is as likely to be above as below -- is 2.0 $^{o}$C. The 90th percentile value is 6.8 $^{o}$C, meaning there is a 90% chance climate sensitivity is 6.8 $^{o}$C or less, but there is still a very uncomfortable 10% chance it is even higher than 6.8 $^{o}$C -- a value well above the "top" figure in the IPCC range.

Using these three values for high, medium and low climate sensitivity can produce three alternate projections of temperature over time, once an emissions scenario is given. In the example I'll use shortly (from Root, Root and Schneider, in preparation), the three climate sensitivities just explained will be combined with two SRES storylines (see IPCC 2001a): A very high emissions scenario (A1FI -- the fossil fuel intensive scenario) and the high-tech scenario, where development and deployment of advanced technologies dramatically reduces the long term emissions (A1T). These make a good comparison pair since they almost bracket the high and low ends of the 6 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. 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. I'll use my own estimate of 3.5 $^{o}$C for this threshold since it was the highest number projected for the 2100 temperature rise in the Second Assessment Report and since the IPCC Working Group 2 TAR suggested that after "a few degrees," more serious climate change impacts could be anticipated.

Figure 7 presents the results. However, that is a very conservative number, since the IPCC noted that some "unique and valuable" systems could be lost at warnings any higher than 1$^{o}$C. In essence, the "threshold" for what is "dangerous" not only depends on the probability of factors like climate sensitivity or 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.

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

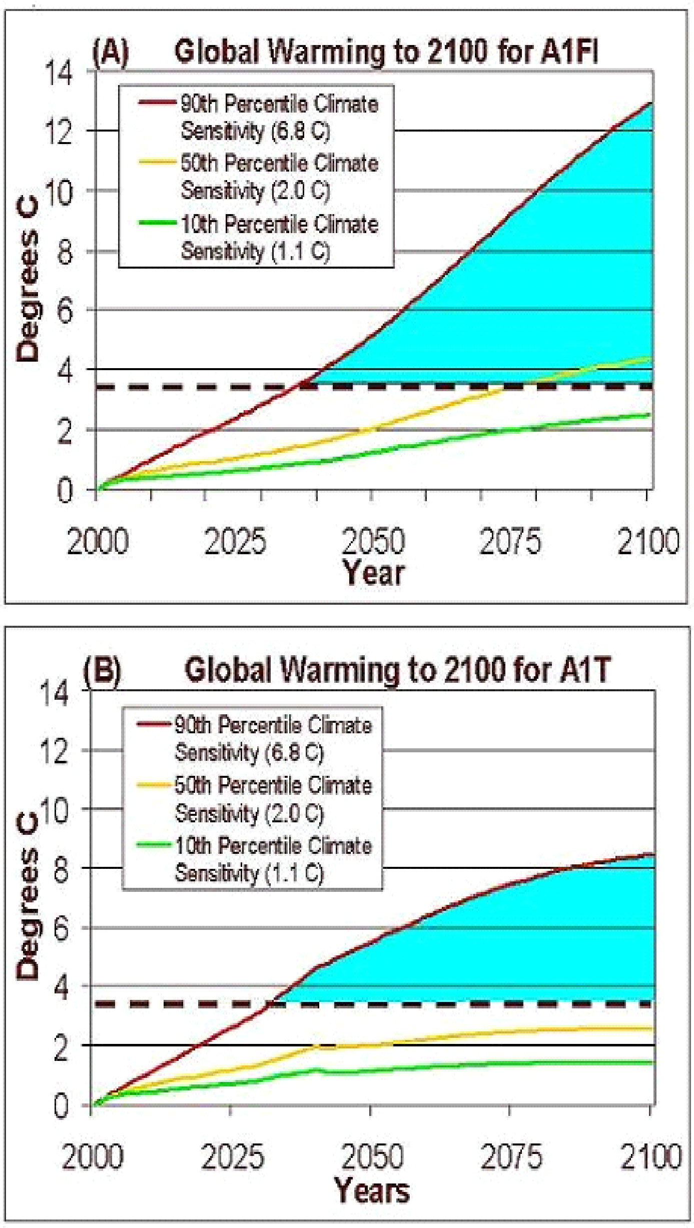


**Notes:** Estimated by matching a range of possible human radiative forcings to the climate system over the past several decades to the observed temperature changes. About half the values for climate sensitivity fall outside of the standard 1.5-4.5 °C "canonical" range in most climate assessments. The CDF suggest about a 15% chance that warming for a $CO_2$ doubling in equilibrium could be less than the lower limit in most assessments and about a 20% chance of warming above the 4.5 °C upper limit. Thus, uncertainties in this one factor, the climate sensitivity, imply climate impacts ranging from negligible to truly catastrophic.

*Source: Andronova and Schlesinger, 2001*

The most striking feature of both Figures 7A and 7B (A is for the A1FI scenario and B the A1T) is the top 90th percentile (red) line, which rises very steeply above the other two lines below. That is because of the peculiar shape of the probability density function for climate sensitivity in Figure 6 -- 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**



**Notes:** Three climate sensitivities -- 10th, 50th and 90th percentiles -- are read off the Andronova and Schlesinger estimate (Figure 6) and combined with the radiative forcings for two SRES scenarios, the fossil intensive (A1FI) and the advanced technology (A1T). These produce similar projections of warming for the first four to five decades of the 21st century, but diverge considerably – especially in the high-sensitivity 90th percentile case -- after mid-century. Two of the three A1FI lines exceed the threshold of 3.5 °C warming, indicated by the dashed horizontal line and the blue shaded area. Notice the blue area is much more dramatic in the fossil intensive scenario than the technological innovation scenario. In fact, at 2100, when the A1T curves are stabilizing (levelling off), the A1FI curves are still upwardly sloped -- implying yet greater warming in the 22nd century. Thus, for an examination of "dangerous" climate change potential, simulations well beyond 100 years are necessary since it is widely considered that warming above a few degrees C (see IPCC Working Group 2, TAR, Chapter 1 and Chapter 19) is likely to be much more harmful than for changes below a few degrees.

*Source: Root, Root and Schneider (in preparation)*

Also striking is that both the 10th and 50th percentile results for A1FI and A1T don't differ much in 2050, but then diverge considerably by 2100. This has led some to declare (erroneously, in my view) that there is very little climate difference across scenarios or even different climate models with different sensitivities. This is simply wrong, for although both A1FI and A1T have emissions and $CO_2$ concentration projections that are not very different for the first several decades of the 21st century, they diverge greatly after 2050, as does the temperature response. For the 90th percentile results, the temperature projections for both A1FI and A1T exceed the conservative "dangerous" threshold of 3.5 $^{o}$C at roughly the same time, around 2040, but the A1FI warming outstrips the A1T warming thereafter and is still steeply sloped in 2100, implying warming beyond 13$^{o}$C in the 22nd century -- a dramatic legacy of environmental change the people of this century would be leaving for distant posterity. Note the blue shaded areas on both the A1T and A1FI cases, which show when projections exceed the 3.5 $^{o}$C warming threshold. These areas of threshold exceedence also diverge greatly after 2050, with the A1T case stabilizing but the A1FI still expanding into the 22nd century.

This simple pair of figures (7A and 7B) shows via a small number of curves (6 in all) the amount of temperature change over time for three climate sensitivity probabilities (10$^{th}$, 50$^{th}$, and 90$^{th}$ 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. That is the next step that needs to be taken by the IPCC, although a group at MIT has already made an effort at it by using a series of different models and expert judgments to fashion a probability distribution for future climatic changes (Webster et al, Climatic Change, in press). That approach, I predict, will be the wave of the future for such analyses, but given the heavy model dependence of any particular such result, individual "answers" will remain controversial and assumption-bound for a considerable time to come.

The likelihood of threshold-crossing occurrences is thus 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 distributions that could easily be misinterpreted by integrated assessors or 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. For this reason, Moss and Schneider (2000) call for a "traceable account" of why any particular selections of climate sensitivities or emissions scenarios are made.

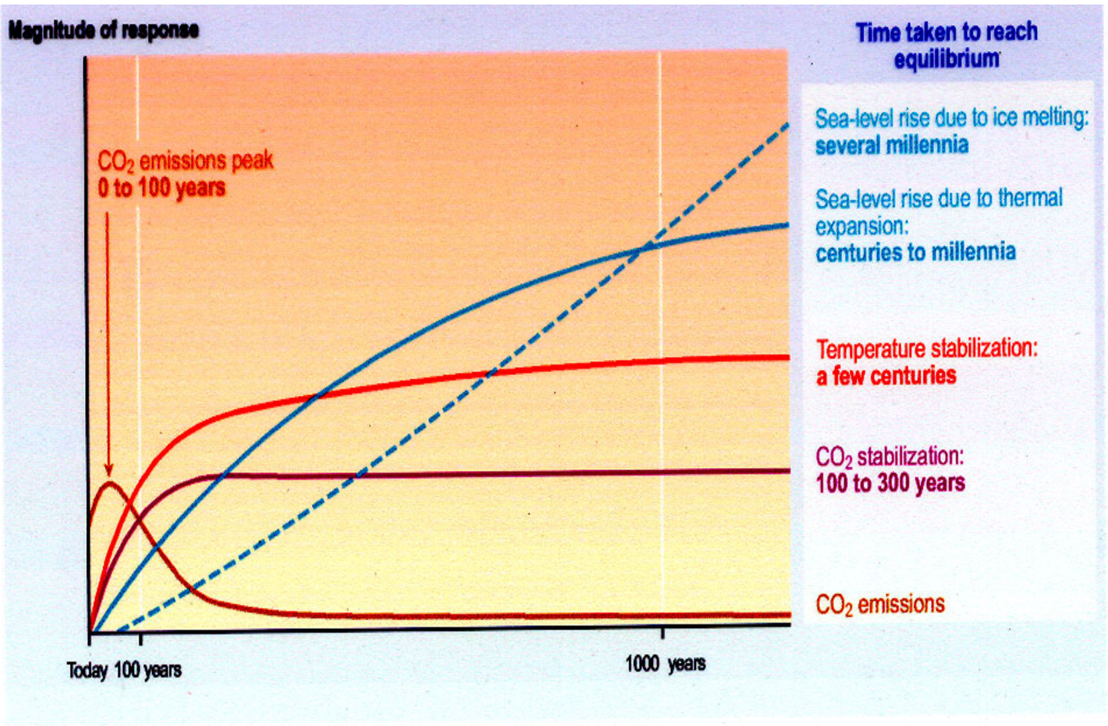
## 2.12 Irreversibility over long time horizons

Consider a specific example: Figure 8 (IPCC 2002c) shows a 1,000 year "cartoon" of effects that can play themselves out over a millennium, even for emissions decisions taken in the current century. Essentially irreversible millennial changes could be induced by "short-term" behaviour. The brown curve in Figure 8 represents fossil fuel era emissions -- about a century or two of dumping $CO_2$ and other greenhouse gases into the atmosphere. Cumulative emissions, the area under the brown curve, will determine the total increase in $CO_2$, which is represented by the purple curve. Note that the eventual $CO_2$ stabilization level takes a few centuries to reach, and, according to this IPCC assessment, remains stable for centuries at the final stabilized level determined from the cumulative emissions in the brown curve. So, even if humanity abandons fossil fuel emissions entirely in the 22$^{nd}$ century, essentially irreversible long-term increases in $CO_2$ concentrations are projected to remain for a millennium or more. There is dispute over whether the purple curve is truly a stable equilibrium or will descend gradually back toward its pre-industrial value of 280ppm, but in most analyses, the elevated concentration of $CO_2$ remains for centuries at least. Due to prolonged greenhouse gas elevation, the surface climate will continue to stay warm, as the red curve suggests, and it will likely take centuries before the temperature stabilizes at its new, warmer equilibrium--let alone begins to drop back. The scale of that equilibrium temperature increase depends on both the final stabilization level of $CO_2$ and the climate sensitivity -- how much the global average temperature rises for a doubling of $CO_2$.

Although the IPCC has routinely suggested that a good range for climate sensitivity is a 1.5 to 4.5 $^{o}$C rise for a doubling of $CO_2$, more recent studies suggest the range for climate sensitivity is quite bit larger. For example, Andronova and Schlesinger (1999) calculate that depending on how the climate has been forced by radiative disturbances from human activities over the past few decades -- themselves not well known -- the climate sensitivity could be as large as $10^{o}$ C! Similar results were obtained by independent methods by Forrest et al 2001(see their Figure 4). Such a dramatic rise would undoubtedly have very dangerous consequences (IPCC 2001b).

One threat of rising temperatures would be a continuous rise in sea level (as anticipated by Wigley, 1995). The blue solid curve on Figure 8 represents 1,000 years of "mixing" in the oceans, in which the warming at the water's surface is eventually mixed into every cubic meters of ocean, causing volumetric expansion. Thermal expansion of the oceans would continue until the oceans were well-mixed -- a time well known to be on the order of 1,000 years or more. Thus, even if humans invented cost-effective, zero carbon-emitting devices in "only" a century, the consequences of their cumulative emissions during the few centuries of the fossil fuel era (the area under the brown curve labelled $CO_2$ emissions) could still cause essentially irreversible consequences over a millennium or more. If any non-negligible discount rate were used to assess damages that far in the future, their present value would be very small. But, as mentioned in the discussion of prescriptive discount rates, there is an ethical question about whether a few generations of people should have the right to act in ways now that create quasi-permanent changes like rising sea levels over thousands of years.

**Table 3. CO2 concentration, temperature and sea level continue to rise long after emissions are reduced**



**Notes:** The fossil fuel era -- area under the brown curve labelled “CO2 emissions” -- may last “only” a few centuries, but implications for the stabilized increased greenhouse gas concentrations (purple curve) and surface temperature increase (red curve) for sea level rise could be essentially irreversible, with millennial-scale impacts (blue curves).

*Source: IPCC 2002c*

Finally, on Figure 8, there is a dashed blue curve, meant by the IPCC Synthesis Panel authors to represent melting polar glaciers like Greenland or West Antarctica. In addition to up to a meter of sea level rise over the next century or two from thermal expansion -- and perhaps a meter or two more over the five centuries after that -- significant global warming (more than a few degrees C -- IPCC 2001b) would likely trigger non-linear events like the deglaciation of major ice sheets near the poles. That would cause many more meters of sea level rise over many millennia, and once started might not be reversible on the time scale of thousands of years.

The implications of such very long-term potential irreversibility -- melting ice caps, the shut-off of thermohaline circulation, and extinction of species (e.g., NRC 2002; Root and Schneider, 2002), to name a few -- are precisely the kinds of non-linear events that would likely qualify as “dangerous anthropogenic interference with the climate system” under the UNFCCC 1992 Rio conference statement. Whether a few generations of people demanding higher material standards of living and using the atmosphere as an un-priced sewer to achieve such growth-oriented goals more rapidly is “ethical” is a value-laden debate that will no doubt heat up as greenhouse gas build-ups continue. A deeper appreciation by policymakers what is involved in appropriate discounting, applicability of broadened cost-benefit methods (despite the great remaining uncertainties), and references to the “precautionary principle” will undoubtedly be key to progress in this debate.

My own personal value position, given the vast uncertainties in both climate science and impacts estimations, is to enact (and act on) policies to slow down the rate at which we disturb the climate system. This can both buy us time to understand better what may happen -- a process that will take many more decades -- and lead to the development of lower-cost decarbonisation options. That way, the costs of mitigation can be reduced well below those that would otherwise be incurred if there were no policies in place to provide incentives to reduce emissions and invent cleaner alternatives. Slowing down the pressure on the climate system is the “insurance policy” against a number of potentially dangerous irreversibilities and abrupt non-linear events. The possibility and scope of such “surprises” will undoubtedly be debated frequently in the next decade or so, as more and more decision-makers come to understand that what we do in the next few generations may have indelible impacts on the next hundred generations to come.

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