ELSEVIER

Global Environmental Change 14 (2004) 245–258

GLOBAL ENVIRONMENTAL CHANGE

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Abrupt non-linear climate change, irreversibility and surprise

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Abstract

Any discussion of the benefits of greenhouse gas (GHG) mitigation measures should take into consideration the full range of possible climate change outcomes, including impacts that remain highly uncertain, like surprises and other climate irreversibilities. Real-world coupling between complex systems can cause them to exhibit new collective behaviours that are not clearly demonstrable by models that do not include such coupling. Through examples from ocean circulation and atmosphere–biosphere interactions, this paper demonstrates that external forcings such as increases in GHG concentrations can push complex systems from one equilibrium state to another, with non-linear abrupt change as a possible consequence. Furthermore, the harder and faster a system is perturbed, the higher the likelihood of such surprises—a conclusion that has significant bearing on the assessment of the potential benefits of the timing and stringency of GHG abatement measures. The paper concludes with a perspective on how to better incorporate uncertainty and surprise into integrated assessment models of climate change.
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Keywords: Surprise; Abrupt climate change; Thermohaline circulation; Irreversibility; Integrated assessment models

1. Introduction

Strictly speaking, a surprise is an unexpected outcome. In the context of climate change, a surprise would be said to have occurred if a climate change-induced phenomenon with a very low probability of happening became reality or if an event never before imagined took place. In IPCC (1996), "surprises" are defined as rapid, non-linear responses of the climatic system to anthropogenic forcing, such as a collapse of the "conveyor belt" circulation in the North Atlantic Ocean or rapid deglaciation of polar ice sheets. Potential climate change, and more broadly, global environmental change, is replete with such 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.

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." 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 climate change outcomes, and thus might be more willing to risk adapting to prospective changes rather than attempting to avoid them through abatement than they would be if they were aware that some potentially unpleasant surprises could be lurking. (Pleasant ones might occur as well, but many individuals and policy-makers, via insurance premiums, tend to insure against negative outcomes preferentially.) In fact, it is not even clear all such surprises are actually "low probability", just very uncertain at this point given the state of knowledge is still evolving.

Events that are not truly unanticipated are better defined as *imaginable abrupt events*. For other events–true surprises–while the outcome may be unknown, it may be possible to identify *imaginable conditions for surprise*. For example, if the rate of change of CO_2 concentrations is one imaginable condition for surprise (i.e., more rapid forcing increases the chances for surprises), we can deduce that the system would be less likely to undergo a "surprise" event if decision-makers

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0959-3780/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.gloenvcha.2004.04.008

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 (IAMs), and other models as well, to credibly evaluate the probabilities of currently imaginable "surprises", let alone those not currently envisioned (Schneider et al., 1998).

2. "Imaginable surprises": examples of abrupt non-linear response

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 sets of interacting systems to exhibit new collective behaviours—called "emergent properties"—that may not be clearly demonstrable by models that do not 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 level of 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 state to another, each of which has a 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).

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. With both of these systems, crossing thresholds can lead to unpredictable and/or irreversible changes. Such complex processes have implications for effective policy-making. Incorporating such possibilities into modelling of climate change policy, for example, can significantly alter policy recommendations and lead to the discovery of emergent properties of the coupled social–natural system (see Higgins et al., 2002, from which much of this section is adapted).

2.1. Thermohaline circulation

The Thermohaline Current (THC) in the Atlantic brings warm tropical water northward, raising sea surface temperatures (SSTs) about 4°C relative to SSTs at comparable latitudes in the Pacific. The SSTs in the North Atlantic warm and moisten the atmosphere, making Greenland and Western Europe roughly 5–8°C warmer than they would be otherwise 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. 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.

Palaeoclimate 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 freshwater 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).

Rahmstorf (1996) presents a schematic stability diagram of THC, based on his modification of the conceptual model of salinity feedback developed by Henry Stommel (1961, 1980). 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 palaeo-climatic record supports this, suggesting rapid and repeated switching between equilibria, over 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 freshwater through extensive iceberg releases (Seidov and Maslin, 1999), and that freshwater reduced the density of surface waters, thus inhibiting the sinking that drives the THC.

Complex general circulation models suggest that future climate change could cause a similar slow down 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 straightforward density-driven set of Atlantic ocean boxes that mimic the results of complex models, but the SCD is still sufficiently computationally efficient and is able to facilitate sensitivity analysis of key parameters and generate a domain of scenarios that show abrupt collapse of THC (Fig. 1). Model results (e.g., Stocker and Marchal, 2000; Schneider and Thompson, 2000—Fig. 1) suggest that both the amount of greenhouse gases (GHGs) 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 at high latitudes, this interferes with the inflow of warm water from the south. Such a slow down will cause local cooling, which will re-energize the local sinking and serve as a stabilizing negative feedback on the slow down. On the other hand, the initial slow down of the strength of the Gulf Stream reduces the flow of salty sub-tropical 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, continuing the inhibition of 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. Some coupled models of the atmosphere and oceans (e.g., Yin et al., 2004) do not produce a THC collapse from global warming, owing to some still-not-identified feedback processes in such models. That is why it is very difficult to assign any confident probabilities to the occurrence of a THC collapse—nor is it possible to rule it out at a high level of confidence either.

Recent research efforts have connected this abrupt non-linearity to integrated assessment of climate change policy. Nordhaus' (1994) DICE model 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 through maximizing discounted utility (satisfaction from consumption), by balancing the costs to the economy of 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

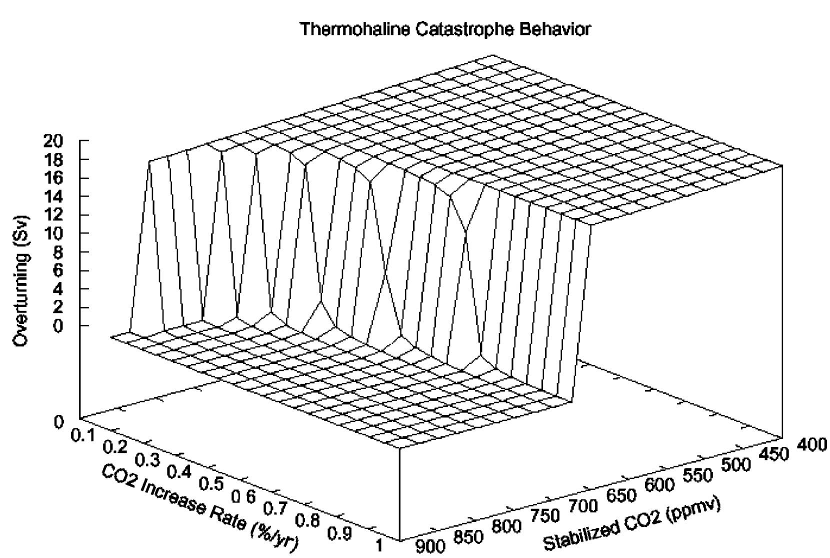

Fig. 1. Equilibrium results of the SCD model under different forcing scenarios. *Notes*: THC overturning in Sverdrups (1 Sv = 1 million m^3/s) is shown on the vertical axis as a function of the rate of carbon dioxide increase in the atmosphere and the stabilization concentration. Higher stabilization levels and more rapid rates of carbon dioxide increase make a THC collapse (abrupt change from "normal" -20 Sv to 0 Sv) more likely. *Source*: Schneider and Thompson (2000).

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—that is, 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.

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. 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, which lacks 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 (as in E-DICE) to account for enhanced damages created by this THC collapse and THC behaviour is incorporated into the coupled climate–economy model.

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 (Fig. 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 and E-DICE models "recommend" to reduce future damages is critically dependent on the discount rate, discussed below. For low discount rates (less than 1.8% in one formulation), the present value of future damages creates a carbon tax large enough to keep emissions below the trigger level for the abrupt non-linear collapse of the THC a century later. 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.

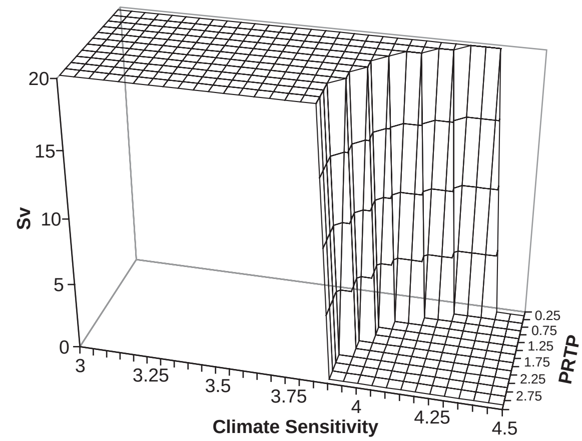

Fig. 2. Cliff diagram of equilibrium THC overturning varying PRPT and climate sensitivity. *Notes*: Figure shows that as PRTP (proportional to discount rate) increases, the climate sensitivity (how much global average temperature rises for doubling of CO_2 from present levels) threshold at which collapse 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 (see Fig. 1) of climate change sufficient to trigger abrupt non-linear responses like THC collapse in the future. *Source*: Mastrandrea and Schneider (2001).

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 IAMs used to date for climate policy analysis, few of which include any such abrupt non-linear processes, will not be able to alert the policy-making 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).

2.2. 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 policy-makers, 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 GHG build-ups.

Based on the results briefly reviewed below, the forest–tundra boundary appears to have 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).

Using average annual temperatures, total precipitation, and elevation as their independent variables, Siegel et al. (1995) come to similar conclusions. They find that varying temperature and precipitation levels caused noticeable variations in ecosystem areas and carbon storage in vegetation, but that the same conditions in different regions often supported different ecosystems. This may be explained by the fact that in their modelling, Siegel et al. found that mixed forest, semi-desert, and tundra ecosystems can dominate a region over a surprisingly wide range of temperature and rainfall levels.

A related study by Kleidon et al. (2000) compared simulations with vegetation initialized as either forest or desert. 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 among 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.

Historical evidence suggests that two equilibria in the coupled vegetation and climate system may exist for the Sahel region of West Africa (10°N–17.5°N, 15°W–15°E) (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 (Fig. 3).

Initially, an 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 of the equilibria the modelled system occupies at a given time. In the model,

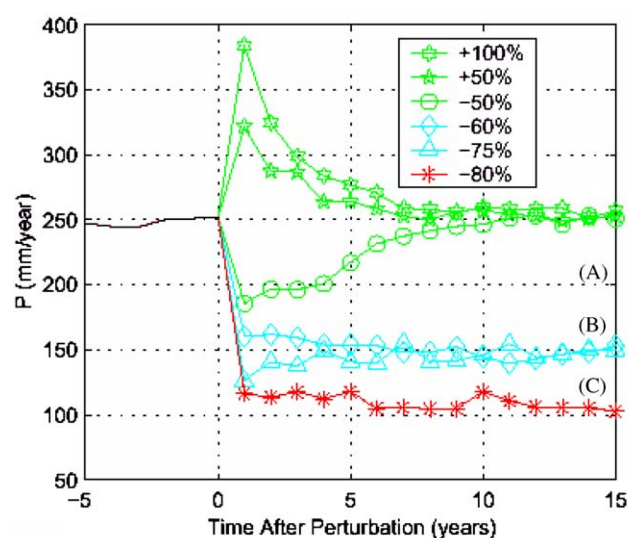

Fig. 3. Response of the coupled atmosphere–biosphere system to vegetation perturbations for the Sahel. *Notes*: Model is a synchronously coupled biosphere–atmosphere model (as described by Wang and Eltahir, 2000b) that starts from a vegetation distribution for West Africa close to today's. Leaf area 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% or increased by 50% and 100%. Thus, vegetation and precipitation recover to pre-disturbance values. (B) Perturbations in which 60% and 75% of vegetation is degraded result in a second equilibrium in the coupled climate–vegetation system. (C) Perturbation in the form of 80% degradation of vegetation results in a third equilibrium. *Source*: Wang and Eltahir (2000b).

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 evapo-transpiration and less atmospheric moisture, causing a positive feedback (Wang and Eltahir, 2000b).

Other 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. Zickfeld (her thesis, 2004) has hypothesized that multiple equilibria may exist in the Indian monsoon region as a result of GHG forcing.

Similar mechanisms for vegetation feedbacks have been put forward for the boreal forest–tundra boundary, 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.

The Sahara also appears to exhibit a single equilibrium. Six thousand years before present (around 4000BC), the Sahara was heavily vegetated, but over the following 1000–2000 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 substantially, which provided 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 that 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).

It must be also kept in mind that results from models such as these depend on how each 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.

Many factors complicate interpretation of model results. 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 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."

The key point of all these detailed examples is that even the most comprehensive coupled-system models are likely to have unanticipated results when forced to change very rapidly by external disturbances like changes in land use, CO_2 concentrations, and aerosol levels. 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. In order to develop a climate policy that will lower the risk of climate catastrophes, policy-makers 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.

3. Other limitations of the standard assessment paradigm

Most climate assessments also do an inadequate job of incorporating more near-term phenomena, including the transient effects of climate change as well as and impacts of changes in climate variability.

3.1. Transient effects of climate change

Standard assessments prior to 1995 modelled climatic responses to a one-time doubling of CO_2 and analysed 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. The long-term impact of climate change may not be predictable solely from a single steady-state outcome, but could very well depend on the characteristics of the transient path. In other words, the outcome may be path dependent. Any exercise that neglects surprises or assumes transitivity of the earth system—that is, 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.

3.2. 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, adopted from IPCC, 2001b). 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% increase in precipitation in the US since 1910 occurred in the top 10th 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 would increase these aspects of climate variability relative to current conditions.

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.

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 Increased heat stress in livestock and wildlife Shift in tourist destinations Increased risk of damage to a number of crops 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 Decreased risk of damage to a number of crops, and increased risk to others Extended range and activity of some pest and disease vectors Reduced heating energy demand
More intense precipitation events	Very likely (90–99%) over many areas	Increased flood, landslide, avalanche, and mudslide damage Increased soil erosion Increased flood runoff increasing recharge of some floodplain aquifers 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 Increased damage to building foundations caused by ground shrinkage Decreased water resource quantity and quality 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 Increased coastal erosion and damage to coastal buildings and infrastructure 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 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 Increased property and infrastructure losses Increased damage to coastal ecosystems

Source: IPCC (2001b).

In Table 1 above, the right-hand column, projected impacts, is predicated on the forecasted effects given in the left-hand column—that is, the impacts and their confidence estimates are contingent assessments and do not incorporate the separate confidence estimates of the effects in the first column, whose probabilities are estimated in the central column. The extent of the damages will depend on the path (when multiple equilibria are possible) and rate of climate change, as well as the level at which the climate actually stabilizes. In addition, the damage function will likely be non-linear in nature, affecting different countries to different degrees at different times, implying considerable inequities in the distribution of impacts (e.g., Schneider and Lane, 2004).

4. Incorporating non-linearities and surprises into damage estimates

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.

4.1. Historic losses as estimates of climate damages in monetary terms

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 increased 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 socioeconomic 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, among other events, to the value of preventing the disruption of climate stability.

4.2. 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 mostly ignore its value. For example, ecological services such as pest control and 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 (i.e., free) benefit 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 and Eickhout, 2004). Cost–benefit analyses have yet to capture the value of this occurring—and indeed, different groups would assign very different values to such damages. This is one of the prime reasons the IPCC (2001b) 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.

4.3. 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 between natural and social scientists in the study. The most conspicuous difference in the study is that conventional economists believe that even extreme climate change (i.e., 6°C of warming by 2090) would not impose severe economic losses and hence consider it cheaper to emit more in the near term and worry about cutting back later, using the extra wealth generated from delayed abatement to adapt later on. Natural scientists estimate the economic impact of extreme climate change to be 20 to 30 times higher than conventional economists do and often advocate actions to abate emissions now. 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 more climate changes. Most respondents—economists and natural scientists alike—offered subjective probability distributions that were "right-skewed". That is, most of the respondents considered the probability of severe climate damage, or "nasty surprises", to be higher than the probability of moderate benefits, or "pleasant surprises" (see Fig. 4). Roughgarden and Schneider (1999) demonstrate that adopting such "right-skewed" probability distributions in IAMs produces optimal carbon taxes several times higher than "point

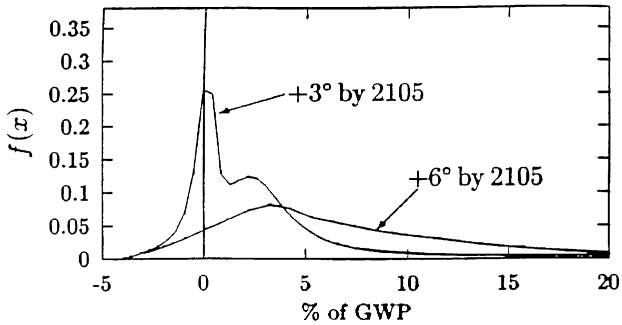

Fig. 4. Probability distributions ($f(x)$) of climate damages as a percentage of gross world product (market and non-market components combined). *Notes*: Taken from an expert survey in which respondents were asked to estimate 10th, 50th, and 90th percentiles of climate damages for the two climate change scenarios shown. *Source*: Roughgarden and Schneider (1999). Data from Nordhaus (1994).

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 scientists attach to climate change, which stem from the fact that there are many uncertainties in the data and assumptions inherent in climate models, climatic impact models, economic models, and their aggregation in IAMs (not to mention differences in personal opinion). In a highly inter-disciplinary field 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.

4.4. 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) analysed 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 sub-division than the current binary market and non-market characterization. Schneider et al. (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 and 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 impact 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 differences in agricultural effects. 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 do not 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.

It is essential for analyses of costs of climate change impacts and mitigation strategies to consider explicitly alternative numeraires and to be as clear as possible about which are being used and which have been omitted. Moreover, before any aggregation is attempted—for example, cost–benefit optimization strategies—authors should first disaggregate costs and benefits into several numeraires and then provide a ''traceable account'' of how they were re-aggregated (see Moss and Schneider, 2000). Such transparency is essential given the normative nature of the valuation of various consequences characterized by the five numeraires.

5. Discounting

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 will typically 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.

Discounting is often approached by considering a factor related to the discount rate, the pure rate of time preference (PRTP). Time preference expresses an individual's or group's preference on the timing of costs and benefits of an action. In general, there is a premium placed on present versus future benefits; people typically choose to reap benefits sooner and incur costs later. The PRTP is a measure of the strength of this preference and is proportional to the discount rate. The higher the PRTP, the more the present is valued over the future (and in the case of climate change, the less likely we are to spend money to reduce CO_2 and other GHG emissions now, given that the benefits would not be felt until the future) and vice versa. This is particularly alarming given that, as discussed by Frederick et al. (2002, p. 369), utility from current consumption is affected by past levels of consumption.

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—that is, 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—for example, how they will choose to make trade-offs between a legacy of extra material wealth and greater loss of environmental services. Such inter-temporal choices reflect many distinct considerations and often involve the interplay of several competing motives, especially when we are talking about choices made not by an individual but by a whole country or world full of them. 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 to discounting 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, only 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 inter-generational equity often contend 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 do not exist today? Time discounting is universal, but controversial, in economics and politics.

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", meaning a person's discount rate declines over time, with higher (than market) discount rates in the short run and lower discount rates over the long term. (For a review of evidence for hyperbolic discounting, see Frederick et al., 2002, pp. 360–362.) 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 prescriptive approaches and can be modelled in IAMs with a logarithmic discount factor or by assuming that per capita income grows logistically over the next century. Since the discount rate is proportional to growth rates, declining discount rates are obtained (Azar and Sterner, 1996; Weitzman, 2001).

Fortunately, the notion of declining discount rates over time is gaining acceptance in economics. For example, Pearce et al. (2003) explore why the discount rate may not be a fixed number, as is usually the case in economics, but rather a changing value that declines over time. They examine how people value the future in real life (hyperbolic discounting); what uncertainty about the future (either about interest rates or the economy in general) implies for discount rates; and social choice, in which both net benefits and sustainability requirements for future generations must be maximized, and they find that all three provide plausible justifications for a declining discount rate. Pearce et al. conclude that while none of these explanations is necessarily "the answer", it is unlikely that all three can simply be thrown out. Time-varying discount rates are supported by these phenomena, as well as a political one: "they help to resolve the long standing tension between those who believe the distant future matters and those who want to continue discounting in the traditional way'' (Pearce et al., 2003, p. 139).

Furthermore, if climate change is really severe, such that future income eventually falls rather than grows (the latter 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.

Thus far, our discussion of discounting has been anthropocentrically focused. However, the choice of discount rate will clearly affect species other than humans as well, which is troubling, as natural systems are expected to be less resilient than human systems in the face of climate change. If a high discount rate is chosen, it will likely bring about more rapid environmental change, which will in turn have greater, and most likely negative, impacts on other species, including habitat loss and eventually extinction, a serious irreversibility (e.g., Thomas et al., 2004). In addition to the inter-generational equity issues this choice of a discount rate presents, it also elicits questions of inter-species equity. Do humans have the right to force our choices on other species? Are we capable of fully considering all costs and benefits of our choice of discount rate? As stated by Peter Singer (1985), ''It does not follow, of course, that animals ought to have all the rights we think humans ought to have … It is equality of consideration of interests, not equality of rights'' that is the fundamental issue in inter-species equity (or lack thereof). This issue begs for additional research and consideration on the part of policy-makers.

6. Concluding remarks

The implications of such very long-term potential irreversibilities—melting ice caps, the shut-off of THC, and extinction of species, 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 United Nations Framework Convention on Climate Change (e.g., see Mastrandrea and Schneider, 2004, for a review and analysis of a probabilistic framework for addressing the UNFCCC mandate). Whether a few generations of people demanding higher material standards of living and using the atmosphere as an unpriced sewer to achieve such growth-oriented goals more rapidly is ''ethical'' is a value-laden debate that will no doubt heat up as GHG build-up continues. A deeper appreciation by policy-makers of what is involved in appropriate discounting, the application 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.

Already, some businesses are taking the reality of climate change seriously and are implementing, or at least considering, precautionary principles of their own. The insurance industry is particularly worried about potential increases in the costs of weather-related damages as a result of more climate change-induced extremes. As a result, many insurers are adopting their own policies for dealing with climate change. For example, in an earnest effort to address the climate change problem and protect its operations, Insurance Australia Group (IAG) is investing in research on climate, considering ways in which it can facilitate adaptation, and finding methods through which it and its customers can minimize their contributions to global warming (Coleman, 2003). Meanwhile, Swiss Re, one of the world's largest re-insurers, has taken measures to increase awareness of climate change risks and also to promote abatement and protection against future climate change. It has developed a voluntary emissions reduction program for American and European businesses, provided insurance to reduce risks associated with emissions trading, and assisted in abatement through asset management (by financing energy-efficient projects, for example), among other things (Walker, 2003). If more companies view climate change in this light and consider the five numeraires and the values associated with them, the more likely they will be to take steps to abate in the present rather than consider abatement to be a topic only for future agendas.

The same applies to the political realm. Thus far, hundreds of municipalities have circumvented state and federal governments and adopted climate plans of their own, pursuing actions such as installing energy efficient lighting or more efficient fleets of vehicles. Preliminary studies (e.g., Kousky and Schneider, 2003) have shown that such actions are generally cost-effective, with fairly short return-on-investment periods.

My personal value position, given the vast uncertainties in both climate science and impacts estimations, is to enact (and act on) policies that 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 decarbonization options. This 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. In the face of potential surprises and irreversibilities, we must not become trapped in conventional economic wisdom that suggests we should emit now and abate later; rather, we must take action now (see, for example, the arguments in Azar and Schneider, 2002). Slowing down the pressure on the climate system is our ''insurance policy'' against non-linearities, and irreversibilities like species extinction and the melting of large glaciers. Such non-linearities will undoubtedly be the topic of frequent debate 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.

References

Arrow, K.J., Cline, W., Mäler, K.G., Munasinghe, M., Squitieri, R., Stiglitz, J., 1996. Intertemporal equity, discounting and economic efficiency. In: Bruce, J.P., Lee, H., Haites, E.F. (Eds.), Climate Change 1995: Economic and Social Dimensions of Climate Change. Second Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 125–144.

Azar, C., Schneider, S.H., 2002. Are the economic costs of stabilising the atmosphere prohibitive? Ecological Economics 42, 73–80.

Azar, C., Sterner, T., 1996. Discounting and distributional considerations in the context of climate change. Ecological Economics 19, 169–185.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257–1266.

Broecker, W.S., 1997. Thermohaline circulation, the Achilles heel of our climate system: will man-made CO_2 upset the current balance? Science 278, 1582–1588.

Claussen, M., 1998. On multiple solutions of the atmosphere–vegetation system in present-day climate. Global Change Biology 4, 549–559.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., Pachur, H.J., 1999. Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. Geophysical Research Letters 26, 2037–2040.

Coleman, T.C., 2003. The impact of climate change on insurance against catastrophe, Insurance Australia Group, Draft.

Daily, G.C., Ellison, K., 2002. The New Economy of Nature: The Quest to Make Conservation Profitable. Island Press, Washington, DC, 260pp.

Emanuel, K.A., 1987. The dependence of hurricane intensity on climate. Nature 326, 483–485.

Frederick, S., Loewenstein, G., O'Donoghue, T., 2002. Time discounting and time preference: a critical review. Journal of Economic Literature XL (June), 351–401.

Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V., Petoukhov, V., 1998. The influence of vegetation-atmosphere–ocean interaction on climate during the mid-Holocene. Science 280, 1916–1919.

Heal, G., 1997. Discounting and climate change, an editorial comment. Climatic Change 37, 335–343.

Higgins, P.A.T., Mastrandrea, M., Schneider, S.H., 2002. Dynamics of climate and ecosystem coupling: abrupt changes and multiple equilibria. Philosophical Transactions of the Royal Society of London 357 (1421), 647–655.

Intergovernmental Panel on Climate Change, 1996. Climate change 1995—the science of climate change. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.). The Second Assessment Report of the IPCC: Contribution of Working Group I. Cambridge University Press, Cambridge, England, 572pp.

Intergovernmental Panel on Climatic Change (IPCC), 2001a. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Third Assessment Report of Working Group I. Cambridge University Press, Cambridge, England, 944pp.

Intergovernmental Panel on Climatic Change (IPCC), 2001b. Climate change 2001: impacts, adaptation and vulnerability. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Third Assessment Report of Working Group II. Cambridge University Press, Cambridge, England, 1032pp.

Karl, T.R., Knight, R.W., 1998. Secular trends of precipitation amount, frequency, and intensity in the USA. Bulletin of the American Meteorological Society 79 (2), 231–241.

Keller, K., Bolker, B.M., Bradford, D.F., 2000. Paper Presented at the Yale/NBER/IIASA Workshop on Potential Catastrophic Impacts of Climate Change, 24–25 July, Snowmass, CO.

Kleidon, A., Heimann, M., 1999. Deep-rooted vegetation, Amazonian deforestation, and climate: results from a modelling study. Global Ecology and Biogeography 8, 397–405.

Kleidon, A., Fraedrich, K., Heimann, M., 2000. A green planet versus a desert world: estimating the maximum effect of vegetation on the land surface climate. Climatic Change 44, 471–493.

Kousky, C., Schneider, S.H., 2003. Global climate policy: will cities lead the way? Climate Policy 3, 359–372.

Leemans, R., Eickhout, B., 2004. Another reason for concern: regional and global impacts on ecosystems for different levels of climate change, Global Environmental Change, this issue.

Levis, S., Foley, J.A., Brovkin, V., Pollard, D., 1999. On the stability of the high-latitude climate–vegetation system in a coupled atmosphere–biosphere model. Global Ecology and Biogeography 8, 489–500.

Manabe, S., Stouffer, R.J., 1993. Century-scale effects of increased atmospheric CO_2 on the ocean–atmosphere system. Nature 364, 215–218.

Mastrandrea, M., Schneider, S.H., 2001. Integrated assessment of abrupt climatic changes. Climate Policy 1, 433–449.

Mastrandrea, M., Schneider, S.H., 2004. Probabilistic integrated assessment of Dangerous climate change. Science 304, 571–575.

Mearns, L.O., Katz, R.W., Schneider, S.H., 1984. Changes in the probabilities of extreme high temperature events with changes in global mean temperature. Journal of Climate and Applied Meteorology 23, 1601–1613.

Moss, R.H., Schneider, S.H., 2000. Uncertainties in the IPCC TAR: recommendation to lead authors for more consistent assessment and reporting. In: Pachauri, R., Taniguchi, T., Tanaka, K. (Eds.), Third Assessment Report: Cross Cutting Issues Guidance Papers. World Meteorological Organisation, Geneva, Switzerland, pp. 33–51 (Available on request from the Global Industrial and Social Progress Institute at http://www.gispri.or.jp).

Nordhaus, W.D., 1994. Managing the Global Commons: The Economics of Climate Change. MIT Press, Cambridge, MA, 232pp.

Pearce, D., Groom, B., Hepburn, C., Koundouri, P., 2003. Valuing the future—recent advances in social discounting. World Economics 4 (2), 121–141.

Pielke Jr., R.A., Landsea, C.W., 1998. Normalized hurricane damages in the United States, 1925–1997. Weather Forecasting 13, 351–361.

Rahmstorf, S., 1996. On the freshwater forcing and transport of the Atlantic thermohaline circulation. Climate Dynamics 12, 799–811.

Rahmstorf, S., 1999. Decadal variability of the thermohaline circulation. In: Navarra, A. (Ed.), Beyond El Nino: Decadal and Interdecadal Climate Variability. Springer, New York, pp. 309–332.

Root, T.L., Schneider, S.H., 2002. Climate Change: overview and implications for wildlife. In: Schneider, S.H., Root, T.L. (Eds.), Wildlife Responses to Climate Change: North American Case Studies. National Wildlife Federation. Island Press, Washington, DC, pp. 1–56.

Roughgarden, T., Schneider, S.H., 1999. Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. Energy Policy 27, 415–429.

Schneider, S.H., Kuntz-Duriseti, K., 2002. Uncertainty and climate change policy, chapter 2. In: Schneider, S.H., Rosencranz, A., Niles, J.-O. (Eds.), Climate Change Policy: A Survey. Island Press, Washington, DC, pp. 53–88.

Schneider, S.H., Lane, J., 2004. Dangers and thresholds in climate change and the implications for justice, Chapter 2. In: Adger, N., et al., (Eds.), Justice in Adaptation to Climate Change. MIT Press, Cambridge, MA, submitted for publication.

Schneider, S.H., Thompson, S.L., 2000. A simple climate model used in economic studies of global change. In: DeCanio, S.J., Howarth, R.B., Sanstad, A.H., Schneider, S.H., Thompson, S.L. (Eds.), New Directions in the Economics and Integrated Assessment of Global Climate Change. The Pew Center on Global Climate Change, Washington, DC, pp. 59–80.

Schneider, S.H., Turner II, B.L., Morehouse Garriga, H., 1998. Imaginable surprise in global change science. Journal of Risk Research 1 (2), 165–185.

Schneider, S.H., Kuntz-Duriseti, K., Azar, C., 2000. Costing non-linearities, surprises and irreversible events. Pacific and Asian Journal of Energy 10 (1), 81–106.

Seidov, D., Maslin, M., 1999. North Atlantic deep water circulation collapse during Heinrich events. Geology 27, 23–26.

Siegel, E., Dowlatabadi, H., Small, M.J., 1995. A probabilistic model of ecosystem prevalence. Journal of Biogeography 22 (4–5), 875–879.

Singer, P., 1985. The Animal Liberation Movement [Essay]. Old Hammond Press, Nottingham, England (Available online at http://www.utilitarian.org/texts/alm.html).

Stocker, T.F., Marchal, O., 2000. Abrupt climate change in the computer: is it real? Proceedings of the National Academy of Sciences of the United States of America 97, 1362–1365.

Stommel, H., 1961. Thermohaline convection with two stable regimes of flow. Tellus 13, 224–230.

Stommel, H., 1980. Asymmetry of interoceanic freshwater and heat fluxes. Proceedings of the National Academy of Sciences of the United States of America 77, 2377–2381.

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

Vellinga, P., Mills, E., Berz, G., Huq, S., Kozak, L., Palutikof, J., Schanzenbächer, B., Shida, S., Soler, G., 2001. Insurance and other Financial Services, in IPCC. Third Assessment Report of Working Group II: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, pp. 417–450.

Walker, C., 2003. Testimony to the Senate Committee on Commerce, Science and Transportation—Hearing on the Case for Climate Change Action. One Hundred Eighth Congress, first session, 1 October. Senate Hearing #253. Available online at: http://commerce.senate.gov/hearings/testimony.cfm?id = 949&wit_id = 2674.

Walsh, K., Pittock, A.B., 1998. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. Climatic Change 39, 199–213.

Wang, G.L., Eltahir, E.A.B., 2000a. Ecosystem dynamics and the Sahel drought. Geophysical Research Letters 27, 795–798.

Wang, G.L., Eltahir, E.A.B., 2000b. Role of vegetation dynamics in enhancing the low-frequency variability of the Sahel rainfall. Water Resources Research 36, 1013–1021.

Weitzman, M.L., 2001. Gamma discounting. The American Economic Review 91 (1), 260–271.

Wilby, R.L., Wigley, T.M.L., 2002. Future changes in the distribution of daily precipitation totals across North America. Geophysical Research Letters 29 (7), 1135.

Wood, R.A., Keen, A.B., Mitchell, J.F.B., Gregory, J.M., 1999. Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model. Nature 399, 572–575.

Yin, J., Schlesinger, M.E., Andronova, N.G., Malyshev, S., Li, B., 2004. Is a Shutdown of the Thermohaline Circulation Irreversible? Nature, submitted for publication.

Zheng, X.Y., Eltahir, E.A.B., 1998. The role of vegetation in the dynamics of West African monsoons. Journal of Climate 11, 2078–2096.

Zickfeld, K., 2004. Modeling large-scale singular climate events for integrated assessment. Ph.D. Thesis, Potsdam University.