Are Uncertainties in Climate and Energy Systems a Justification for Stronger Near-term Mitigation Policies?

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Abstract

Defining long-run stabilization targets for atmospheric CO_2 is ultimately a political question since it depends on value judgments. However, because of the enormous uncertainties that surround projections of climate change, their impacts and mitigation costs, any proposed stabilization target is, quite expectedly, controversial. This uncertainty, some have argued, implies that climatic change might be of minor consequence; but, comparably likely, as others have suggested, climate change could as well have potentially catastrophic implications. Thus, since the climate science, impacts and policy analytic communities cannot rule out with high confidence the possibility of a variety of serious or even catastrophic outcomes, we argue that it is wise to keep many options open. Such flexibility also includes retaining low stabilization targets on the bargaining table for climate policy options. We show how uncertainties could demonstrate that near-term abatement can be both cost-efficient and necessary to reduce the risk of "dangerous" climate change. The cost of meeting low-stabilization targets are assessed in the context of conventional economic models and found to imply only a minor impact on the expected overall economic growth rates over the next century—achieving stringent targets like 450 ppm could represent only a few year's lost GDP growth rate in 2100 as compared to an order of magnitude economic expansion in the baseline case. Such "low cost climate insurance" might be politically quite acceptable once these relatively minor delay times were more widely known.

I. Introduction

Climate change is often considered one of the most serious environmental problems. This concern triggered the international negotiations that led to the United Nations Framework Convention on Climate Change (UNFCCC, UN, 1992). The convention calls for a "stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

But it should be kept in mind that the UNFCCC does not attempt to define the concept of dangerous interference with the climate system. Precise statements of what is "dangerous" are not possible, since (a) the degree of harm from any level of climate change is subject to a variety of uncertainties and (b) the extent to which any level of risk is "acceptable" or "dangerous" is a value judgment (Azar and Rodhe, 1997; Schneider et al., 2000). Science can provide estimates about expected climatic changes and associated ecological and societal impacts, but ultimately the question of what constitutes dangerous anthropogenic interference has to be settled in the political arena — given of course the best scientific assessments available about the likelihood of various potential outcomes.

In the mid-1990s, many governments, academics and environmental organizations were calling for more stringent international climate policies. These calls resulted in the Berlin Mandate, which required that targets and timetables be negotiated and set before the end of 1997, i.e., at the third meeting of the conference of the parties (COP3) in Kyoto.

However, Wigley, Richels and Edmonds (WRE, 1996) presented alternative emission trajectories towards various stabilization targets for atmospheric CO_2 (in the range 350-750 ppm) along which no significant abatement was seen as desirable over the next couple of decades. They argued that it would not only be possible, but also and more cost-effective, to defer emission abatement.[1] This challenged the *raison d'être* of the

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[1] More specifically they showed that it was possible to meet these stabilization targets without deviating from a prescribed baseline emission trajectory (that of IPCC IS 92a; see IPCC, 1992) for several decades and argued, using three economic and one physical argument, that it would be more cost-effective to follow

Berlin Mandate and the upcoming negotiations in Kyoto.

Although elimination of short term targets for abatement was never seriously discussed during the climate negotiations, the WRE paper influenced many economists' and U.S. policymakers' views on climate change and sparked an interest into research on more flexibility in international agreements on climate change (see e.g., Toman et al., 1999; and a special issue of Energy Journal (Weyant, 1999)).

It should be kept in mind that WRE stressed that their analysis "should not be interpreted as suggesting a '*do nothing*' or *'wait and see' policy*." Instead, they observed that all stabilization targets imply lower carbon emissions over the long run. This has importance for near-term energy investments since energy technologies are long lived. Research, development and demonstration today are required in order to develop carbon-free and energy-efficient technologies. They also concluded that any available 'no-regrets' options should be adopted immediately, and finally, the lower the stabilization target, the earlier is the need to start reducing the emissions. Clearly, the key issue now is not one of *do nothing* versus *do everything* but one of how much and what to do in the near-term given long run uncertainties about both climate impacts and abatement costs.

However, their view was misunderstood or misrepresented by some as an argument in favor of doing nothing now (e.g., Pearce 1996). Several major fossil fuel intensive companies used the findings in the WRE paper for lobbying against near-term reduction targets (see e.g., Masood, 1996). President Bush has invoked economic arguments against the Kyoto Protocol, some of which resemble these interpretations of WRE.

This paper will challenge the view that "dangerous anthropogenic climatic changes" can safely be avoided without serious consideration of substantial amounts of near-term abatement, and, will argue that such abatement may not at all be inconsistent with economic efficiency arguments. Moreover, it will show that substantial near-term abatement will not necessarily be prohibitively costly, despite some well-publicized claims to the contrary. Essentially, the arguments run as follows:

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their emission trajectories which arrived at the same long-term stabilization concentrations, but did not begin to apply significant abatement of emissions early on, unlike the stabilization scenarios of IPCC.

- There is still considerable uncertainty about the trajectory of the climate system, thereby allowing substantial concern to remain about low probability, catastrophic impacts, in particular if the climate is forced rapidly and strongly (IPCC, 1996a, p. 7). We do not dismiss the possibility of the converse — that substantial climate changes may not necessarily turn out to be "dangerous" — but the climate uncertainties also imply that in the near future the possibility of dangerous changes — even for atmospheric stabilization targets some might consider to be relatively low — cannot be ruled out with high confidence.
- The WRE emission trajectories suggest that also low stabilization targets could be met cost-effectively without significant near-term abatement. But the WRE trajectories were never cost-optimized. In parallel modeling efforts it was shown that for stabilization targets around 450 ppm or lower, early abatement is cost-efficient! Richels and Edmonds (1995), (using the MERGE and the ERB-model) write that "limiting concentrations at 400 ppm will require an early and rapid departure from business as usual." These emission trajectories are not cost-minimized, but the authors state that they have "attempted to identify an emissions path close to the least-cost solution." More subsequent runs by Manne and Richels (1997), however, confirm that "a more aggressive departure from the emissions baseline will be required" for targets in the range 450-550 ppm. For stabilization targets above say 600 ppm, very little near-term abatement is cost-effective in their modeling efforts. Similar results are also reported in IPCC Third Assessment Report (TAR) working group (WG) III, Chapter 2 (IPCC, 2001c, p. 153) where it is argued that "achievement of stabilization at 450 ppm will require emissions reductions in Annex 1 countries by 2020 that go significantly beyond their Kyoto commitments for 2008-2012." We do not at this point attempt to justify investments in such policies, only to point out that studies have been done for very low abatement targets.
- The larger the probability of abrupt non-linear or catastrophic climate changes — or the more "unique and valuable" systems that are threatened by climate changes of "only" a degree or two warming (e.g., see IPCC, 2001b, Chapter 19) the lower one can argue — depending on the characterization of "dangerous changes" — the stabilization target for efficient policies should be; and under such circumstances then more early abatement may well be demonstrated to be economically efficient.
- There is not only uncertainty about the stabilization target and the benefits of early stabilization, but also about the abatement costs themselves. In particular, there is a vigorous debate over how the energy system would respond to incentives to reduce CO_2 emissions. By initiating abatement policies sooner, firms and governments will learn more about how the energy system responds to such policies. This information will be useful when designing future abatement policies.
- Furthermore, learning by doing (LBD) and induced technological change (ITC) resulting from early abatement could substantially reduce the costs of abatement policies over time relative to current calculations that neglect prospects for technological development.

This paper is structured as follows: Section II reviews issues of uncertainty and multiple equilibria in the climate system and Section III reviews the sustainability approach to setting climate targets. Section IV discusses results of cost-benefit analysis of climate change policies with a focus on how uncertainty and the risk for low probability but catastrophic impacts affect the interpretation of the results. The results indicate that keeping the option of low stabilization targets open may be justified based on methodologies described both in Section III and IV.

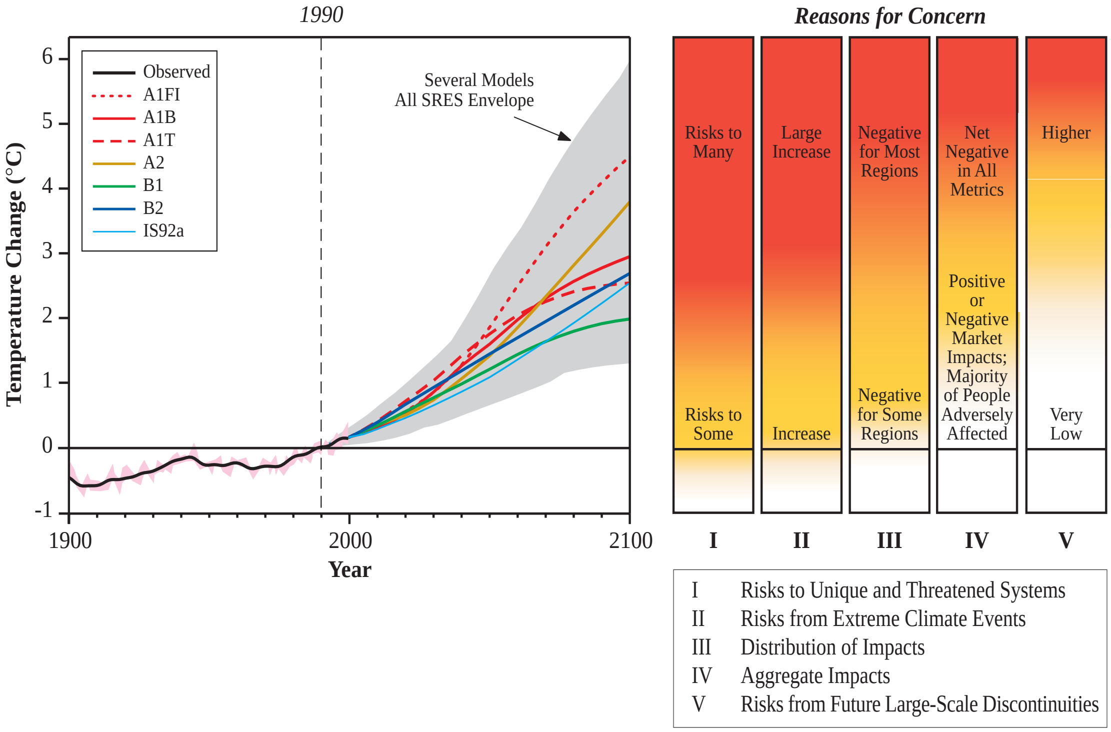
Section V briefly reviews simplifications in the models that have been used to state that no or only marginal early abatement is required. Improved modeling of these issues is likely to imply that more substantial early abatement may well be required—and certainly should be considered. These simplifications and assumptions include the omission of no-regrets options, the exclusion of the additional climate damages that would likely follow from the deferred abatement case, the rudimentary treatment (or outright omission) of technical change and energy systems inertia, the distributional consequences of both climate impacts and policies given delayed abatement, the political feasibility of less-abatement now, more-abatement later on, etc. Section VI discusses how much it might cost to meet various stabilization targets, and will attempt to put this into a different perspective than present value in dollars of some abatement policy, but rather frame the cost issue as the delay time to achieve roughly 500 percent growth in per capita income as a function of various abatement policies. Section VII concludes by analyzing the implications of climate and energy systems uncertainty on near-term policymaking and the Kyoto Protocol.

II. Uncertainty and Multiple Equilibria

Uncertainty surrounds every corner of the climate debate. Moreover, because of the complexity of the climate system, surprises can be expected (e.g., IPCC, 1996a, p. 7; IPCC, 2001b, Chapter 1). Low-probability and catastrophic events, as well as evidence of multiple equilibria in the climate system, are of key concern in the climate debate. So too are threats to unique and valuable systems and inequitable implications of unabated climate changes—see Figure 1 below (taken from IPCC, WG II, Summary for

Policymakers (SPM), IPCC, 2001b). There are great uncertainties in the impacts side as well as the climate system projections, all of which contributes some risk of dangerous events even for seemingly low stabilization targets.

Figure 1 **Reasons for Concern About Climate Change Impacts.**



Note: The risks of adverse impacts from climate change increase with the magnitude of climate change. The left part of the figure displays the observed temperature increase relative to 1990 and the range of projected temperature increase after 1990 as projected by IPCC, WG I (IPCC, 2001a) for scenarios from the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). The right panel displays conceptualizations of five reasons for concern regarding climate change risks evolving through 2100. White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems or low risks, and red means negative impacts or risks that are more widespread and/or greater in magnitude. (Please consult the IPCC, WG 2 TAR for more detailed explanations.)
Source: Figure 2, of the Summary for Policy Makers, IPCC, 2001b.

We will briefly review some issues related to uncertainty and complexity in the climate system. Subsequent sections will discuss how such uncertainties might influence decisions based on the sustainability approach (Section III) and cost benefit analysis of climate change (Section IV).

A. Uncertainty and Complexity in the Climate System: Two Examples of Emergent Properties of Coupled Socio-natural Systems

As complicated as each sub-system is by itself, the complexity of the coupled atmosphere-oceanic-ice-land-biota-society system (which comprises the full climate system) can lead to interactions that create behaviors (often known in complexity theory as "emergent properties") not evident by studying only one or two of the systems in isolation. Below, we offer two illustrative examples, evidence of multiple thermohaline circulation equilibria and interlinkage of surface vegetation change, hydrology and climate. Other examples of *radical* shifts in ecosystems in response to *gradual* changes in climate, nutrient loading, habitat fragmentation and biotic exploitation are given in a recent survey paper (Scheffer et al., 2001).

Thermohaline Collapse

The climate of Northern Europe is much warmer than other places at similar latitudes not benefited by the warm currents of the North Atlantic. This so called thermohaline circulation (THC) has not always been present, and in its absence dramatic cooling of the North Atlantic was coincident (Broecker, 1997). Some analysts think that sufficient greenhouse gas forcing applied sufficiently fast could trigger a collapse of the THC, with potential very long-term—virtually irreversible on a thousand year time scale—implications for Northern Europe (Stocker and Schmidtner, 1997 and Rahmstorf, 1999). A very recent calculation of the possibility of a THC collapse has been simulated by coupling a climate model capable of exhibiting abrupt non-linear dynamics with a conventional energy-economy model (Mastrandrea and Schneider 2001).

Paleoclimate reconstruction and model simulations suggest there are multiple equilibria for THC in the North Atlantic, including complete collapse of circulation. Switching between the equilibria can occur as a result of temperature changes or the injection of fresh water in the North Atlantic sector known as "freshwater forcing." Thus, the pattern of THC that exists today could be modified by an infusion of fresh water at higher latitudes or through high latitude warming. These changes may occur if climate change increases precipitation, causes glaciers to melt, or warms high latitudes more than low latitudes, as is often projected (IPCC, 1996a, 2001a).

Further research has incorporated this behavior into coupled climate-economic modeling, characterizing additional emergent properties of the coupled climate-economic system (Mastrandrea and Schneider, 2001). As we will soon demonstrate, uncertainty is emphasized since the choices of debatable model parameter values such as the climate sensitivity or discount rate determine whether emissions mitigation decisions made in the near-term will prevent a future THC collapse or not.

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—re-energizing 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 and thus 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 (e.g., see the "simple climate demonstrator" (SCD) model of Schneider and Thompson, 2000).

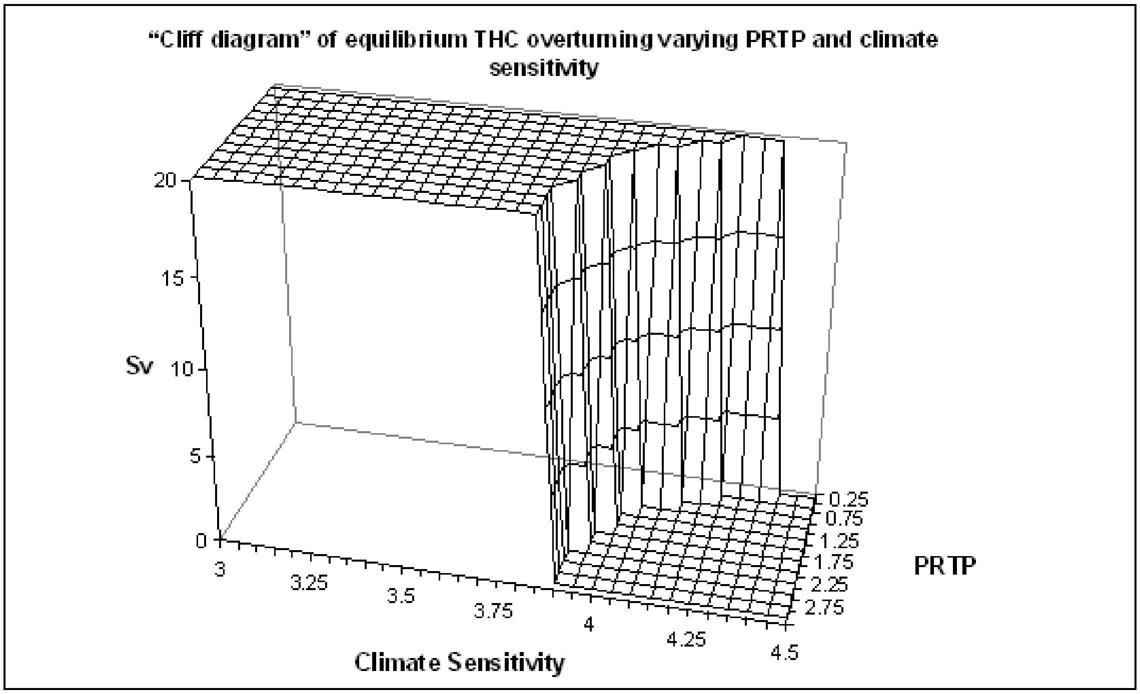
Recent research efforts have connected this abrupt non-linearity to integrated assessment of climate change policy. William Nordhaus' DICE model (Nordhaus, 1994) is a simple optimal growth model. Given a set of value judgments and assumptions, the model generates an optimal future forecast for a number 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 emissions abatement (a loss in a portion of GDP caused by higher carbon energy prices) against the costs of the buildup of atmospheric GHG concentrations. This buildup 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 IPCC, 2001b, Chapters 1 and 19, and Figure 1, this paper) and thus 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 they call E-DICE, containing an enhanced damage function that reflects the higher likely damages that would result when abrupt climate changes occur. If climate changes are smooth and thus relatively predictable, then the foresight afforded increases the capacity of society to adapt, hence damages will be lower than for very rapid or less anticipated changes such as abrupt unanticipated events—"surprises" such as a THC collapse. It is likely that, even in a distant future society, the advent of abrupt climatic changes would reduce adaptability and thus increase damages relative to smoothly varying, more foreseeable changes.

Since the processes that the models ignore by their high degree of aggregation require heroic simplifications often called "parameterizations," the quantitative results are only used as a tool for insights into potential qualitative behaviors. Because of the abrupt non-linear behavior of the SCD model, the E-DICE model produces a result that is also qualitatively different from DICE with its lack of internal abrupt non-linear dynamics. 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 sufficiently modified to account for enhanced damages created by this THC collapse and THC behavior 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. 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 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 (e.g., see Figure 2, from Mastrandrea and Schneider, 2001). Figure 2 is a "cliff diagram" showing the equilibrium THC overturning for different combinations of climate sensitivity and pure rate of time preference (PRTP) values. The normal THC is a steady circulation with flow rate of about 20 Sverdrups (Sv) (million cubic meters of water flowing per second). The climate sensitivity is the amount of global surface average temperature change that would eventually (i.e., in “equilibrium”, an idealization) occur if CO_2 were to double and be held fixed for many centuries. The higher the climate sensitivity, the more climate change will occur for any stabilization concentration target. As the PRTP decreases, “normal” circulation (i.e., 20 Sv—the system solution remains on top of the “cliff”) is preserved for disproportionately higher climate sensitivities since the lower PRTP leads to larger emissions reductions in E-DICE and thus it takes a higher climate sensitivity to reach the “cliff.” Thus, for low discount rates (PRTP of less than 1.8 percent in one formulation — see Mastrandrea and Schneider, 2001, their Figure 4) 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. That is, the THC continues to churn warm water to Northern Europe at nearly the typical rate of some 20 Sv. But a higher discount rate sufficiently reduces the present value of even potentially catastrophic long-term damages such that an abrupt non-linear THC collapse — the system “falls off the cliff” and the THC essentially ceases to perform its heat transferring function becomes an emergent property of the coupled socio-natural system — with the discount rate becoming the parameter that most influences the 22nd century behavior of the modeled climate.

Figure 2 **"Cliff diagram" of equilibrium Thermohaline Circulation in the North Atlantic Ocean (THC) overturning varying PRTP and climate sensitivity**



Notes: Two states of the system — "normal" (20 Sv of warm water flow to Northern Europe) and "collapsed" (0 Sv) THC — are seen here. The numbers are only for illustration as several parameters relevant to the conditions in which the THC collapse occurs are not varied across their full range in this calculation, which is primarily shown to illustrate the emergent property of high sensitivity to discounting in a coupled socio-natural model (e.g., from Mastrandrea and Schneider, 2001). One Sv is equal to one million cubic meters of water flowing per second and is the measure that is normally used to gauge the intensity of oceanic currents.

Although these highly aggregated models are not intended to provide high confidence quantitative projections of coupled socio-natural system behaviors, we 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 behaviors. Moreover, this model does not exhibit such abrupt collapse for very stringent stabilization scenarios. A few models have looked at very non-linear damages and these are described in Section IV. 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 behaviors (e.g., Moss and Schneider, 2000).

Vegetation Cover and Climate Dynamics

The potential for multiple equilibria in the coupled atmosphere-biota system has received increasing attention in recent years. 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 (e.g., see Higgins et al., 2002).

Regions with multiple equilibria may be characterized by a greater sensitivity of precipitation to either changes in total net surface radiation or to changes in the partitioning of net surface energy transfer between sensible and latent heat fluxes, as well as reflection of incoming radiation. Either or both can accompany vegetation change (Eltahir, 1996). Such regions include West Africa, where the strength of the tropical monsoon influences the vegetation distribution but also depends upon that vegetation (Eltahir, 1996, Zheng and Eltahir, 1997, Wang and Eltahir, 2000a, Zheng and Eltahir, 1998, and Wang and Eltahir, 2000b), and possibly the Amazon Basin, where the availability of water for precipitation may be dependent on rooting depth and the type of vegetation present (Kleidon and Heimann, 1999).

The boreal forest-tundra boundary, which influences albedo, is a third potential region where the atmosphere-biosphere system could have multiple equilibria. Boreal forest decreases albedo relative to tundra (i.e., snow covered treeless ground reflects much more energy than snow covered forests), thereby increasing total net surface radiation and temperature. Boreal forest also requires a longer growing season (i.e., higher temperatures) than tundra, suggesting the potential for positive feedbacks between vegetation and climate.

Indeed, simulations suggest that boreal forests raise both winter and summer temperature relative to tundra (Bonan et al., 1992). In part, this is due to the direct (local) effect of the albedo decrease over land during spring and fall. In part, the increase in summer temperature results from earlier sea-ice melting and the concomitant increase in summertime sea surface temperatures (SSTs), which is a distant scale feedback. Therefore, shifts in vegetation between forest and tundra constitute a positive feedback to changes in the climate system. Tundra (boreal forest) has a higher (lower) albedo, which decreases (increases) net radiation and temperature, thereby leading to conditions more favorable for tundra (boreal forest). If these feedbacks are sufficiently strong, multiple equilibria may be possible given different distributions of forest and tundra. Therefore, the climate-biosphere system could occupy either the colder-tundra state or the warmer-boreal forest state, depending on the initial distribution of vegetation or other factors such as fire disturbance regimes.

Based on the literature reviewed by Higgins et al., 2002, the forest-tundra boundary appears to be a single stable equilibrium, at least at the continental scale. However, evidence suggests that certain regions in the sub-tropics indeed have multiple stable equilibria that depend upon initial vegetation distribution, as will be briefly reviewed below.

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). Modeling 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.

Initially, a SST anomaly altered 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 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 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 (deep) roots lead to less (more) evapotranspiration and less (more) atmospheric moisture causing a positive feedback (Wang and Eltahir, 2000b). During subsequent years, the shallower (deeper) root systems are less (more) able to access soil moisture and thereby cause the atmosphere-biosphere system to remain in the drier (wetter) equilibrium.

Similar studies suggest that the monsoon circulation in West Africa is sensitive to deforestation — suggesting yet additional possible emergent properties of coupled socio-natural systems. However, the sensitivity of the monsoon circulation to changes in land cover depends critically on the location of the change in vegetation (Zheng and Eltahir, 1997). Desertification along the Saharan border has little impact on the monsoon circulation, while deforestation along the southern coast of West Africa results in a complete collapse of the monsoon circulation with a corresponding reduction in regional rainfall (Zheng and Eltahir, 1998). This illustrates that relatively small areas of land cover can determine the equilibrium state of the atmosphere-biosphere system of an entire region. Thus, a land use model would need to predict the time and space evolving nature of the human disturbance in order to find the emergent property of the coupled socio-natural system model.

Eltahir (1996) proposes a theory to more fully explain the occurrence of multiple equilibria such as these. The theory suggests that large-scale tropical circulation depends upon a gradient in moist static energy between the boundary layer above the ocean and inland. A large (small) gradient leads to strong (weak) monsoon circulation, and wet (dry) conditions in the Sahel. Perturbations in vegetation can alter the moist static energy gradient by altering total net surface radiation and also the amount of and partitioning between sensible and latent heat fluxes. But it also must be kept in mind that results from all such models depend on how the model aggregates over processes that can occur at smaller scales than is implicit in the simulation — e.g., local variations in soils, fire regimes, 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 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.

It will be very difficult to establish high confidence in any such non-linear coupled socio-natural systems simulations—just as it will be difficult to rule out such non-linear emergent properties with much confidence either. Thus, the risk management situation likely to be faced by international climate policy making bodies is a high degree of uncertainty with the possibility of abrupt climatic events occurring, even for seemingly stringent stabilization concentrations (e.g., below a doubling of the pre-industrial CO_2 equivalent).

These examples, the THC and the Sahel precipitation-vegetation regime, clearly demonstrate the potential sensitivity of highly non-linear systems even to gradual changes in external forcings, and illustrates that there are thresholds beyond which some states of the ecosystems can change radically — irreversibly for practical purposes — and potentially catastrophically, at least locally. Major remaining uncertainties still render the precise quantitative forcings at which a variety of such imaginable threshold-crossing events might be triggered difficult to defend with high confidence. But the very existence of such demonstrable non-linear thresholds strengthens the arguments for those who favor consideration of low stabilization targets and thus more stringent near-term abatement, since the less the system is disturbed the lower the likelihood of triggering threshold-crossing behaviors (as noted earlier in IPCC, 1996a, p. 7).

III. Uncertainty and the Sustainability Approach

There are basically two different approaches to setting targets for climate change, the so-called "sustainability approach" and "cost-benefit analysis" which will be discussed in the subsequent section (see also IPCC, WG II, 1996b). In cost-benefit analysis, all costs and benefits are, or should be, evaluated in monetary terms or some equivalence. The emission trajectory is then chosen so as to maximize the benefit-cost ratio.

In contrast to cost-benefit analysis, the sustainability approach[2] does not rely on a one-dimensional measure or numeraire according to which all impacts are measured — rather it is argued that the various reasons for concern, e.g., health impacts, changes in mortality rates, or environmental damage, should be expressed in their appropriate physical or biological units (e.g., see Figure 1 above and the discussion of the "five numeraires" in Schneider et al. (2000): market system costs in $/ton Carbon; human lives lost in persons/ton C; species lost per ton C; distributional effects in changes in income differentials between rich and poor per ton C; and quality of life changes, such as heritage sites lost per ton C or refugees created per ton C).

The emission target, or the stabilization target, is often based on comparisons with some physical or environmental parameters, chosen so as to reduce some adverse impacts. This can be done by selecting a rate or an absolute level of climate change that might allow for sufficient environmental and societal adaptation (Toth et al., 1997).

Those who advocate the sustainability approach claim support for their view on ethical arguments: How can we justify that the richest countries of the world emit greenhouse gases that are expected to cause most severe damage in the poorest countries of the world? Another key concern is the risk of low probability but catastrophic events. These arguments generally tend to be down-played in cost benefit analysis of climate change because of discounting (that makes future catastrophes marginally significant for present cost considerations) and a lack of explicit equity considerations (the assumption that benefits in one part of the world might compensate for damages some where else).

For reasons relating to the possibility of large scale unforeseen negative events, as well as impacts deemed more likely (see IPCC, 2001b), governments (e.g., the European Union, EU 2000[3]), several scientists (see e.g., Rijsberman and Swart (1990), the Scientific Advisory Council on Global Change to the Federal Government of Germany

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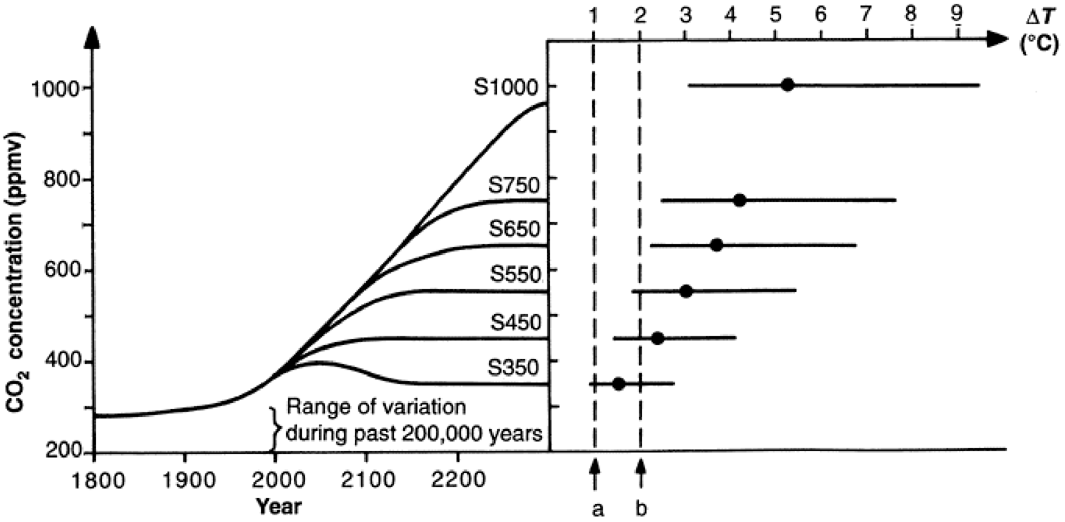
[2] The sustainability approach is sometimes also referred to as the Tolerable Windows approach (Toth *et al* 1997) and the Safe Landings Approach (Alcamo and Kreileman, 1996).

[3] It should be noted that the EU also adopted a maximum of 550 ppm CO_2 equivalent target. It can be seen from figure 1 that the concentration target and the temperature targets are compatible, but a 550-ppm concentration would require that the climate sensitivity is low. Thus, the EU negotiating positions and their energy policies need to be cognizant of the possibility that a more stringent concentration target than 550 ppm may be required. The Swedish government recently stated that it supports a global 550 ppm CO_2 equivalent target (which is roughly equivalent to a 450 ppm CO_2 target), and that it will work in favor of such a target.

(WBGU, 1995), Alcamo and Kreileman (1996), Azar and Rodhe (1997), and environmental organizations (e.g., Greenpeace (Hare, 1997)) have argued in favor of an upper limit on the increase in the global annual average surface temperature set at or around 2°C above pre-industrial temperature levels.

At present it is not possible to uniquely relate greenhouse gas concentrations and temperature. The present consensus among climate modelers is that a doubling of the CO_2-equivalent concentrations will increase global equilibrium annual average surface temperatures by 1.5-4.5°C (IPCC, 2001a).

Figure 3 **IPCC stabilization scenarios for atmospheric CO_2**



Notes: Left: IPCC stabilization scenarios for atmospheric CO_2. Right: Corresponding equilibrium changes in global mean temperature since pre-industrial times (central values plus uncertainty ranges from IPCC (1996a). Other greenhouse gases and aerosols combined have been assumed to add 1 W/m2. The dashed vertical lines denote (a) the estimated range of variability of the change between in global mean temperature during the past 1000 years and (b) the 2°C temperature considered as a long run climate policy target by the European Union. A temperature increase by 5-7°C corresponds to the sustained average change in global average surface temperature that takes place during the transition from an ice age to an interglacial.
Source*:* Azar and Rodhe (1997).

From Figure 3, we can see that the global temperature increase for an atmospheric CO_2 concentration of 550 ppm will only stay below 2°C if the climate sensitivity is in the very low end of IPCC's estimate.

Azar and Rodhe (1997) conclude that if the climate system is sensitive to CO_2 increases in the IPCC upper range, then a CO_2 concentration of 550 ppm will be sufficient to yield a global average temperature change of a magnitude approaching that which occurs during the thousands of years it takes to sustain the transition from an ice age (roughly 5-7^{o}C). It appears that to have a very high probability of keeping the global temperature changes within the range of natural fluctuations during the past few millennium (roughly 1^{o}C), the climate sensitivity has to be low and/or the atmospheric CO_2 concentration has to be stabilized at around 350 ppm (i.e., below current levels).

The policy challenge is whether the burden of proof must lie on those who argue that uncertainties which preclude confident prediction of the likelihood of exceeding any specific — 2^{o}C for Figure 3 — warming threshold should lead to a “wait and see” policy or on those who, citing precautionary principles, believe it is not “safe” and acceptable to risk changes in the global climate system that could substantially exceed the natural fluctuations during the past millennium. Indeed, IPCC, 2001b (SPM and Chapter 19) suggests that a major increase in the risk of climate damages occurs for warming above “a few degrees.” In fact, IPCC (2001b, Chapter 1) noted that the climate policy dilemma was one of risk-management tradeoffs, in which uncertainties prevent confident identification of “safe” thresholds, assuming a suitable set of value judgments could even be negotiated over what constitutes “safe” levels of change. However, and this is a primary message in this paper, until it has been widely accepted with much higher confidence that a temperature increase above 2^{o}C is “safe” or that the climate sensitivity is lower than the central estimate, the projections shown in Figure 3 suggest that the global climate policy community should not dismiss out of hand on cost-effectiveness grounds alone policies that make eventual stabilization in the range 350-400 ppm possible.

We do not intend to suggest that governments should adopt a specific stabilization target that should be adhered to over the next hundred years. On the contrary, approaches that frame climate policy as the world adopting a single stabilization target and trying to cost optimize emission trajectories towards that target is a highly incomplete analysis owing to the large numbers and kinds of uncertainties that attend almost every aspect of the climate problem. UNFCCC recognizes that steps to understand and address climate change will be most effective “if they are continually re-evaluated in the light of new findings in these areas” (UNFCCC 1992). In IPCC language: “The challenge now is not to find the best policy today for the next hundred years, but to select a prudent strategy and to adjust it over time in the light of new information" (IPCC, 1996a).

In our view, it is wise to keep many doors—analytically and from the policy perspective — open. This includes acting now so as to keep the possibility of meeting low stabilization targets open. As more is learned of costs and benefits in various numeraires and political preferences become well developed and expressed, interim targets and policies can always be revisited. But exactly how much near-term abatement and/or other technology policies that are required to keep the option of low stabilization within reach is, of course, very difficult to answer, in particular because the inertia of the energy system, let alone the political system, has proven difficult to model.

Research on sequential decision making under uncertainty include e.g., Manne and Richels (1992), Kolstad (1994, 1996a, 1996b), Yohe and Wallace (1996), Lempert and Schlesinger (2000), Ha-Duong et al. (1997), Narain and Fisher (2001), and Fisher (2001). The results of these studies are addressed in subsequent sections.

IV. Implications of Uncertainty on Integrated Assessments and Cost-Benefit Analysis of Climate Change

Several economic studies, most notably Nordhaus's pioneering DICE model (Nordhaus, 1994) have concluded that stringent measures to control emissions of CO_2 would be very costly even if the benefits of reducing the emissions (i.e., the avoided climatic changes) would be taken into account. Nordhaus, for instance, finds it optimal to allow the emission rates to increase threefold over present levels over this century. Several other studies find similar results, e.g., Manne et al. (1995) and Peck and Teisberg (1993).

However, these results have been challenged by a growing number of studies, e.g., Cline (1992), Azar and Sterner (1996), Roughgarden and Schneider (1998), Schultz and Kastings (1997), and Howarth (2000) who find that much stronger cuts in emissions are defendable on economic efficiency grounds alone. In particular, it has been shown that the outcome of the cost benefit analysis is very sensitive to the choice of discount rate. Some have argued that the rate of discounting should fall over time when intergenerational issues are addressed (e.g., Azar and Sterner 1996, Weitzman, 2001); others have analyzed the issues within the framework of overlapping generation models (see e.g., Howarth, 2000).

These diverging results can partly be attributed to choices for parameter values or even structural relationships that can be improved with more research (within economics, ecology and climate research). However, such improvements will not suffice to bridge all of the different results. Rather, some differences stem — ultimately — from disagreements on certain key parameters and modeling choices that are value-laden.

Layard and Walters (1978) open their textbook *Microeconomic Theory* by stating, “economics is making the best of things.” But the authors also remind us about the natural fallacy Hume warned about two centuries ago: one cannot deduce an "ought" from an “is.” Any "ought" is intrinsically linked to a value judgment. Thus, it has long been recognized that there is a strong normative component in (welfare) economics.

In the case of global warming, Grubb (1993) writes “it should be recognized that global impact costing studies inherently involve contentious value judgments, concerning which differing assumptions may completely reverse the conclusions.” Schneider (1997) stresses the importance of highlighting these value-laden assumptions in order to ensure that integrated assessment models of climate change (as well as other environmental problems) “enlighten more than they conceal.”

Azar (1998) identifies four crucial issues for cost-benefit analysis of climate change: the treatment of low-probability but catastrophic impacts, valuation of non-market goods, the discount rate, and the choice of decision criterion. He shows that (i) ethically controversial assumptions have to be made for each of these aspects, (ii) the policy conclusions obtained from optimization models, are very sensitive to these choices, and, finally, (iii) studies that find that minimal reductions are warranted have made choices that tend to reduce the importance of the most common arguments in favor of emission reductions.

The focus in our paper is on uncertainty and how that might affect the level and timing of mitigation policies. Several papers have tried to include learning, uncertainty and irreversibility effects in economic analysis of climate change. Kolstad notes, “the literature on irreversibilities tells us that with learning, we should avoid decisions that restrict future options" (Kolstad, 1996a, p. 2). He then sets off to look at greenhouse gas stock irreversibility versus capital stock irreversibility and concludes that the irreversibility of investment capital has a larger effect than the irreversibility of greenhouse gas accumulation. A similar result was obtained by Ulph and Ulph (1997). The intuitive explanation for this result is that while an investment in renewable energy cannot easily be reversed (if it proves that we do not really need to reduce the emissions), emissions are reversible in the sense that emitting one unit today can in principle be compensated for by emitting one ton less at some time in the future.[4]

However, this result is limited in scope. Kolstad (1996a, p. 14) recognizes that he has "not examined irreversible changes in the climate or irreversibilities in damage. Such irreversibilities are of real concern to many concerned with climate policy." In a separate paper, he writes, "of course, one may still wish to restrict emissions today to avoid low-probability catastrophic events" (Kolstad, 1996b, p. 232).

A. Including Risks of Catastrophes in Cost Benefit Analysis

The complexity of the climate system implies, we have noted, that surprises and catastrophic effects could well unfold as the climate system is forced to change, and that the larger the forcing the more likely there will be large and unforeseen responses.

Fisher (2001) and Narain and Fisher (2001) develop a model where the risks of catastrophic events are endogenous to how much greenhouse gases that are emitted. Under this assumption, they find, contrary to the results by Kolstad (1996a,b), that the climate irreversibility effect might actually be stronger than the capital investment irreversibility effect, not weaker. This set of theoretical analyses offer qualitative insights into the relative strengths of the different irreversibility arguments, but does not offer any quantitative "real world" numbers as regard optimal abatement levels.

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[4] Kolstad (1996) recognizes that this argument is only valid as long as it would not "be optimal to negatively emit in the future to correct over-emissions today." In most of the economic literature on climate change, it is assumed that emissions cannot be negative, but in principle they can. A biomass energy system with carbon sequestration and permanent disposal could remove CO_2 from the atmosphere, while at the same time delivering CO_2 free energy carriers (e.g., heat, electricity or hydrogen) to society. This would enhance the possibilities of climate risk management (see Obersteiner et al., 2001, and Azar and Lindgren, 2001).

Confident estimation of the probability and costs of true catastrophic surprises is by definition impossible. This means that they are very difficult, to say the least, to include in integrated assessments, or benefit-cost analysis of climate change. But the possibility of such events is an important driver for climate policy and must be considered. Moreover, even though we may not be able to envision the nature of a true surprise, we can fathom the conditions that would give rise to a greater likelihood of surprises—what Schneider et al. (1998) labeled “imaginable conditions for surprise.”

How then might we deal with low-probability high-impact events in cost-benefit analysis? Two different approaches emerge:

- Surprises and low-probability high impact events are excluded from the modeling effort (which is the most common approach), *but then it has to be clearly stated that the analysis has neglected one of the key concerns about climate change*. The policy conclusions that can be drawn from such analysis would then be very limited (unless a strong case can be made that the opposite holds true).
- Surprises and low-probability high impact events are included, but then we are confronted with major difficulties when assigning probabilities for the events and estimating their costs (since assigning dollar values for major environmental and social catastrophes across countries with very different levels of income is a difficult and perhaps not even meaningful). A few such studies do exist (e.g., Nordhaus 1994, Manne et al., 1995, Gjerde et al., 1999, Keller et al., 2000, and Mastrandrea and Schneider, 2001. The result of studies that include catastrophic impacts largely depends on the admittedly subjective probability assigned to a catastrophic event, and how it is valued in dollar terms, neither of which is possible to assess in objective non-controversial terms.

Nordhaus attempted to consider extreme events by assuming that global economic damage from climate change is proportional to the temperature change raised to the power of twelve (Nordhaus 1994, p. 115). This increases the optimal abatement level from 9 percent to 17 percent, a target stricter than the Kyoto protocol but nevertheless less ambitious than what some might expect given the extreme nature of the damage function. The reason is that the optimization is carried out under deterministic conditions. The optimizer (global policymaker) knows exactly where the very steep increase in costs begin and can therefore avoid taking action until it is needed to keep within the safe zone.

Cost-benefit optimization with a low probability high impact event has been analyzed in a study conducted by Energy Modeling Forum (Manne 1995). Uncertainty was assumed to be resolved by 2020, and very little near-term hedging was found to be optimal. One key reason for this result is that the probability for a catastrophic event was assumed to be rather low (0.25 percent, see IPCC, 2001c, p. 614).

Gjerde et al. (1999) conclude, "the probability of high-consequence outcomes is a major argument for cutting current GHG emissions." Mastrandrea and Schneider (2001) show that by including the risk of a complete shut down of THC in the Nordhaus DICE model, many very different "optimal emission trajectories" with much more stringent emissions controls are obtained, in particular if a low discount rate or very high enhanced damages are applied.

This literature is valuable because it demonstrates that perceptions of what is an "optimal" policy sensitively depends on structural assumptions and the numerical values of parameters that are difficult and sometimes impossible to pin down to narrow ranges (in some cases — the discount rate — they depend on value judgments and in other cases depend on physical phenomena that are difficult to predict — the threshold for THC collapse — confidently).

We do not dispute that benefit-cost analysis is an important tool that can be used to guide policymakers into making informed decisions concerning trade-offs in a resource-scarce world. But when applied to large scale, interregional and intergenerational problems with deep uncertainty and multiple measures of what is to be optimized, there is a considerable risk that this approach will mislead those not aware of the many limitations and implicit assumptions in most conventional cost-benefit calculations available in the climate literature. Our principal concern is that the seemingly value neutral language of benefit cost analysis — mathematics — will lead some policy makers into believing that value neutral policy conclusions can be drawn from seemingly objective analyses. Another concern is that the uncertainty about climate damages is so large that it renders any cost-benefit analysis (CBA) using a single climate damage function of little use. Roughgarden and Schneider (1998) have argued that a probability distribution must be used to incorporate the wide range of opinions in the literature about what climate damages might be (given some degree of climate change), which then provides as an output of the CBA a probability distribution of "optimal policies" rather than a misleading single "optimal" policy. In essence, this transforms the debate from one of using this analytical tool to prescribe a *specific* abatement amount, carbon tax or technology subsidy, but rather reframes the debate as a risk-management exercise where a *range of policy actions* could all be "optimal" depending on whether the high or low damage estimates turn out to be correct.

At present, it seems as if CBA analyses applied to the problem of global climate change, can justify largely any emission reduction targets (both marginal and substantial), the latter in particular if nasty surprises are taken into account.

V. Critical Issues and Choices in Models Used to Assess Timing of Abatement Policies

Clearly, any modeling of the global energy-economy system over the next hundred years is laced with assumptions and parameterizations that are very uncertain. But what are the critical assumptions in most top-down models that have analyzed the question of near-term emission abatement in light of long run stabilization targets? Below, we will describe a number of such assumptions and how they may affect the outcome of the models and the policy conclusions that can be drawn from them.

A. Uncertainty and Energy Systems Inertia

WRE expressed concern that a premature retirement of the existing capital stock would be expensive. They argue that deferring abatement would avoid, or at least reduce this cost, and make the transition to a low CO_2 emitting future less costly. But counterarguments can be raised. Capital is replaced continuously. If typical energy capital has a life time of say 40 years, it means that roughly 25 percent will be replaced every decade in steady state—and an even larger fraction for automobiles where there is larger potential for rapid energy efficiency improvements than in say power plants and the steel industry.[5] *A key observation here is that if we exploit this routine capital stock*

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[5] It is thus likely that the Kyoto protocol (even with US participation) could be met without significant premature retirement of existing capital stock, primarily as a result of the collapse of Soviet Union and the many built-in flexibility mechanisms. Annex-1 greenhouse gas emissions in 1998 were 6% below the 1990

turnover, we may avoid a renewed build-up of long-lived carbon intensive technologies, and thus a potential future premature retirement of capital stock (in particular if more rapid rates of future reductions are demanded to meet increasingly stringent abatement targets, see Grubb 1997).

Ha-Duong et al. (1997) used stochastic optimization techniques to determine the optimal hedging strategy under uncertain future carbon constraints under the assumption that there are costs also associated with not only the level of abatement but also the rate of change of the abatement level (the idea was that this would capture capital stock turn over issues). Uncertainty was assumed to be resolved by the year 2020. The findings in the paper by Ha-Duong et al. (1997) suggested that early abatement was economically efficient.

A similar approach was taken by Yohe and Wallace (1996), but they reached the opposite conclusion. The differing conclusions are largely determined by the choice of stabilization constraint. Ha-Duong et al. (1997) assumed an expected stabilization target at 550 ppm, with a symmetric probability around this goal (2.5 percent for 400 and 750, 10 percent for 450 and 700, 20 percent for 500 and 650, and finally, 35 percent for 550 ppm)[6], whereas Yohe and Wallace (1996) chose an uncertainty range as high as 550 - 850 ppm.

Some early abatement may thus be one way of avoiding, rather than causing, a premature replacement of the capital stock that was built in the hope that significant abatement might not prove necessary (at least if it turns out that low stabilization targets are warranted). Of course, as with all the tools we have discussed, major uncertainties are inherent in these citations as well. Nonetheless, the insights these authors provide through their analyses are worth consideration, even if the numerical results remain less than highly confident projections.

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levels (www.unfccc.de) and the Kyoto target is an overall 5% reduction, assuming US participation and no "Bonn sinks."

[6] Ha-Duong et al. used 400 ppmv as a ceiling, i.e., they did not allow any overshoots. It seems that the fundamental driver for their result is the introduction of this ceiling. Even a trivially small probability that we are not allowed to temporarily exceed the 400 ppmv target would force the model to an early departure from business-as-usual emissions.

B. Technological Change

WRE also argued that technical progress would bring down the cost of alternative technologies over time. This, they claimed, would make it more cost-effective to defer emission abatement to the future when it would be cheaper. Critics of this position argue that technological change is not simply an autonomous process that takes place regardless of policies chosen. Rather it is a result of a complex web of factors involving prevailing and expected prices, consumer values, taxes and regulations, and technology policies. R&D for less carbon intensive systems does not progress rapidly in a policy vacuum, but also depends on the creation of markets for emerging technologies and an expectation that the price of carbon will rise over time.

Grubb (1997) pointed out, "it is in steering the markets that governments can have the biggest impact on technology development." We need active training not relaxation, to get into shape to run a marathon. Austin (1997) notes, "it is ironic that proponents of delay place so little faith in near-term technological improvements driven by market and policy signals and so much faith in long-term technological improvement driven by nothing at all."

There is overwhelming evidence that overall energy policies are of critical importance for the development of alternative technologies (see Azar and Dowlatabadi, 1999). We need only to think of the fact that refrigerators became less energy efficient per unit of refrigerated volume between 1955 and 1970 (but this trend was reversed in response to the energy crises of the 1970s) and that energy efficiency improvements in engines have been eaten up by heavier cars and more powerful engines so that the overall energy use per km has gone up or remained roughly constant over the past 20 years in many countries. The rapid growth in wind and PV technology largely depends on government efforts to steer markets through subsidies, and recent advancements in fuel cell technologies have been driven by Californian air quality legislation. Thus, if the world would decide to defer, say, the first commitment period of the Kyoto Protocol 20 years ahead, it is more likely that private and government research, development, and demonstration on carbon efficient technologies would drop rather than increase. In light of declining R&D budgets for renewables, one may question how this sustained research that is supposed to make delayed abatement more cost effective is to come about in the absence of abatement policies. Government R&D spending in the OECD countries on renewables has dropped by more than 50 percent between 1980 and 1995. In the U.S. the drop was close to 60 percent (see Margolis and Kammen, 1999)

The most prominent other alternative to abatement policies is R&D subsidies targeted on decarbonizing technologies and the creation of niche markets (either through subsidies or specific legislation requiring that a certain percentage of the electricity market should be from renewable energy). However, economic justifications for such policies relative to more direct climate policies like a carbon tax are difficult to defend on efficiency grounds, unless there are clear pre-existing market inefficiencies that could be corrected by such subsidies (e.g., Schneider and Goulder, 1997). Since some component of market failures (e.g., spillovers or no-regrets) are likely to be part of the current energy system, Schneider and Goulder (1997) suggested that the most cost-effective policy may well be a combination of targeted technology development subsidies and abatement actions, not subsidies alone. In addition, creating markets for emerging technologies (e.g., through green certificates/renewable energy portfolios) may be equally important, but R&D is generally not seen as encompassing that action.

Although the divergence between WRE and their critiques was more related to the relative weight the different sides put on "market pull" versus "R&D push," it should be noted that these issues never entered into the climate policy models used to assess the WRE argument in any serious way. In most energy systems models, technological change is generally assumed to be exogenous (see Azar and Dowlatabadi, 1999, for a review of technical change in integrated assessment models). In these models, carbon-free technologies generally improve and become cheaper over time regardless of the amount of R&D, niche markets and carbon abatement policies.[7] Therefore one argument in favor of early abatement, i.e., that early abatement is necessary to develop the required technologies, is not well captured by most models (see Sanstad, 2000).

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[7] In the WRE world these options are already adopted in the baseline scenario. Although this is not explicit in the original WRE paper, it was a feature of subsequent modeling efforts developed to support the WRE conclusions. In the baseline scenario developed by Manne and Richels (1997), for instance, carbon free technologies capture roughly 40 percent of the global energy supply by the year 2050 and 70 percent by the year 2100.

An interesting exemption is the work by Mattsson and Wene (1997) and Goulder and Schneider (1999). Mattsson and Wene (1997) have endogenized learning by doing in optimization models and showed that early abatement is warranted because it buys down the costs of the technologies in the future. In the absence of such abatement, technological progress occurs only in conventional technologies.

By allowing energy R&D to compete with other economic sectors in a highly aggregated general equilibrium model of the U.S. economy, Goulder and Schneider (1999) — hereafter GS — postulate that a $25/ton carbon tax would likely dramatically redistribute energy R&D investments from conventional to non-conventional sectors, thereby producing induced technological changes (ITC) that lower long-term abatement costs — but by how much depends on a variety of complicated factors to be briefly described. Unfortunately, most integrated assessment models (IAMs) to date do not include any endogenous ITC formulation (or if they do, it is included in a very *ad hoc* manner). Thus insights about the costs or timing of abatement policies derived from IAMs should be viewed as quite tentative. However, even simple treatments of ITC or LBD (e.g. Grubb et al., 1995; Goulder and Schneider, 1999; Dowlatabadi, 1998; Goulder and Mathai, 1999, and Grubler et al., 1999) can provide qualitative insights that can inform the policymaking process, *provided* the results of individual model runs are not taken literally given the still *ad hoc* nature of the assumptions that underlie endogenous treatments of ITC in IAMs (or at least the economic components of IAMs).

GS demonstrate that there may be an opportunity cost from ITC. Even if a carbon tax were to induce increased investment in non-carbon technologies (which, indeed, does happen in the GS simulations), this imposes an opportunity cost to the economy by crowding out investments in conventional energy systems R&D and other sectors. The key variable in determining the opportunity cost is the fungibility of human resources. If all knowledge generating labor is fully employed, then increased R&D in non-carbon technologies will necessarily come at a cost of reduced research on conventional technologies. In other words, there would be a loss of productivity in conventional energy industries relative to the baseline case with no carbon policies. This imposes a cost that is paid early in the simulation. The benefits, lowered costs in non-conventional energy systems, are enjoyed decades later. With conventional discounting that means the early costs from the crowding out is likely to have more impact on present value calculations than the later benefits, which are heavily discounted (at 5 percent per year in GS) because they occur many decades hence. A similar effect might be realized, even when knowledge-generating labor is not fully employed simply due to transition costs. For example, engineers cannot switch from one industry to another without incurring a cost, e.g. from oil to solar power; in general, they require retraining. On the other hand, if there were a surplus of knowledge-generating workers available in the economy, then the opportunity costs of such transitions could be dramatically reduced. Similarly, if the carbon policy were announced sufficiently far in advance (e.g., 5-10 years), industries could more leisurely invest in training workers to have the necessary skills in non-carbon energy systems without massively re-deploying existing knowledge generators. This would offset much of the opportunity cost that GS calculate with the assumptions of fully employed R&D workers and no advanced notice of the carbon policy.

When GS ran a case with the assumption of no opportunity cost of R&D, which implies that there is a surplus of R&D resources in that economy that can be transferred without cost to creation of non-carbon based technologies, then ITC *positively* affects GDP — ITC is *efficiency improving* and thus is a below zero cost policy. However, for the standard idealized assumptions of (1) perfectly functioning R&D markets and (2) a scarcity of knowledge-generating resources (e.g., all capable engineers already fully employed) at the time the carbon tax is imposed without notice, the presence of ITC by itself is unable to make carbon abatement a zero cost option, and in the GS model can actually increase the *gross* costs to the economy of any specific, given carbon tax. But ITC also implies that more abatement is obtained per unit of carbon tax, so that the *net* cost per unit carbon reduction is lower with than without ITC. This also means that the carbon tax required to meet a specific carbon abatement target is lower with than without ITC.

Finally, as a general note of caution, policy-makers need to be aware of underlying and/or simplifying assumptions when interpreting any IAM results with or without treatments of ITC. Schneider (1997) offered the following list of caveats concerning ITC in general, and GS in particular:

- Questionable generality of the U.S. economy-oriented GS model for nondeveloped country economies;

- The returns on investment in energy R&D in GS are based on data from a past decade which might not be valid very far into the future;
- What is the extent to which R&D knowledge-generators (e.g., under-employed or not-yet-trained engineers) can be quickly made available to non-conventional energy sectors so that the opportunity costs of a redeployment of technologists from conventional energy sectors would be lessened;
- The degree and kinds of R&D market failures present can radically alter the conclusions relative to a perfectly functioning R&D markets assumption; and
- The possibility of multiple equilibria in which the quantity of energy provided may or may not be price sensitive during transitions to alternative equilibrium states.

C. Climate Damages Not Considered

WRE also invoked a physical argument in favor of abatement deferral. The emission budget for any stabilization target is somewhat larger the longer the emission reductions are deferred. This is because higher initial emissions lead to higher transient atmospheric concentrations, which, in turn, drive higher absorption rates into the ocean.[8]

But WRE also note that higher transient concentrations will lead to more rapid increases in global temperatures (before the ultimate stabilization target is reached). A more rapid forcing of the climate system would most likely cause larger damages and an increased risk of surprises (see Section II). WRE note that the potential economic benefits of delayed reductions must be balanced against the additional cost caused by the higher interim temperature, but confident quantification, in monetary terms — let alone other numeraires like species lost — of the difference in cost-damage estimated associated between the different trajectories leading to the same stabilization target, is very difficult, even though this is a typical exercise for many IAMs operating with explicit, but low- to medium-confidence (e.g., see Moss and Schneider, 2000) damage functions. Such estimates have thus largely been excluded from the analyses. Tol (1998), however, has provided a first estimate suggesting that additional climate damages associated with the

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[8] It is true that delaying emission reductions gives rise to a higher emission budget over the next couple of centuries, but the total emission budget leading to stabilization when equilibrium between the ocean and the atmosphere is established (this takes approximately 1,000 years) is independent of the path.

WRE trajectory towards 550 ppm (compared to the corresponding IPCC trajectory) are less than one-half of the benefits, but Tol quite forthrightly notes that “uncertainties are too large to draw this conclusion with any certainty.” Of course, it is difficult to assign high confidence to any estimates of these kinds (e.g., IPCC, 2001b, Chapters 1, 2 and 19).

D. Political Feasibility and Credible Signals

The economic arguments for postponing emission reductions have sometimes been misunderstood to imply that it is economically efficient to postpone reductions indefinitely. But, since there is an upper limit on the cumulative amount of CO_2 that we may emit for some specified target concentration, we have to start reducing the net emissions at some point. However, even if the economic arguments for deferral were convincing to all parties in the debate, one would still need to discuss the political feasibility of the proposed emission trajectories.

Suppose that we choose to defer emissions reductions until the year 2020, at which point substantial reductions would be needed. It is difficult to believe that policy makers at that time will feel bound by our decision to postpone all the effort to them. Rather, they may consider the pre-planned stabilization target too difficult to reach—citing premature retirement of their capital stock, for instance—and instead opt for a higher stabilization target and further delayed abatement. Deferring reductions has thus the disadvantage that it reduces the probability of reaching the pre-planned stabilization target. This aspect has also been formally modeled by Dowlatabadi (1996), who concludes, “under specific conditions, delay can lead to a sequence of control measures which increase the probability of non-compliance.”

Experience supporting this view can be found from the Swedish debate about nuclear power. In 1980 a referendum and a subsequent decision by the Parliament decided that Swedish nuclear reactors should be phased out by the year 2010. However, decisions to phase-out nuclear power have been delayed based on arguments similar to the WRE second and third argument. The longer Sweden deferred the initiation of the phase-out program (the more difficult it has become to meet the 2010 complete phase out date). Consequently, it seems unlikely that nuclear power will be phased out by the year 2010.

The analogy suggests that delay is likely to breed further delay and thus frustrate the implementation of policies. The only WRE argument that might support the willingness of political leaders of the future to accept stringent abatement requirements made for them by this generation of policymakers is if there really are low cost and available low-carbon energy systems in the future — but to induce the R&D needed to achieve this will likely, as we argued in the above section, require some combination of near-term direct subsidies and abatement policies.

E. Endogenizing Preferences and Values

Preferences and values are almost always assumed exogenous in economic analyses. However, values change and are endogenous to, amongst other things, decisions taken in the society. Arguing that a transition to a low carbon emitting energy system is necessary would encourage a greater social acceptance for, say, carbon taxes, than if decision-makers argue that it is "optimal" to postpone reductions. Early abatement increases awareness about the potential risks associated with carbon emissions. This awareness builds social acceptance for carbon taxes, energy efficiency standards or other policies and measures. An increasing acceptance implies a higher willingness to pay for renewables, which in turn means that the costs of the transition will be lower. All this takes time. Opting only for delay sends the wrong signals.

F. Other Considerations — What is in the Baseline?

The concepts of business as usual or baseline emissions are ambiguous for various reasons. For instance, a wide range of *near-term* policies could result in essentially the same near-term emission trajectory but produce very different long-term emission trajectories. A policy package that aims at restructuring the infrastructure for transportation, expanding natural gas distribution (and to make it compatible with future hydrogen distribution), and developing solar cells, would not produce any major near-term emission reductions, but would be instrumental for achieving more stringent reductions further into the future. Such a package could be warranted, but there is a risk that such a policy would be judged cost-inefficient based on the perception that no near-term abatement is cost-effective. It is for this reason important to distinguish between *actual emission reductions* and *action to reduce the emissions* (see Azar, 1996; Schneider and Goulder, 1997; Janssen and de Vries, 2000).

Another issue related to that of baseline ambiguities is that of “no regrets.” WRE clearly argued in favor of no-regrets policies in their article, but in their graph depicting emission trajectories, the suggested "optimal" emission trajectories followed a prescribed business as usual trajectory for several decades. In most, if not all, energy-economy models, markets are assumed to be in Pareto-equilibrium and therefore any abatement is by definition associated with a positive cost (and correspondingly the potential for no regrets is zero). But, there are indications that sizeable no-regrets options are available,[9] and cost-effectiveness considerations suggest that these should be seized earlier rather than later. One might also interpret these energy-economy models as if the no-regrets options are already in the baseline trajectory, but this can be misleading since the implementation of many "no regrets options" requires specific policies if they are to be tapped.

VI. Is the Cost of Stabilizing the Atmosphere Prohibitive?

Although the technical feasibility of meeting low atmospheric CO_2-stabilization targets has been demonstrated (see IIASA/WEC, 1995, LESS, IPCC, 1996b, Azar et al., 2000, and many for targets around 400 ppm), there is still concern about the economic costs of realizing such or similar targets. The more pessimistic economists generally find deep reductions in carbon emissions to be costly — and count in trillions of dollars. For instance, reaching 450 ppm would according to Manne and Richels (1997) cost the world between 4 and 14 trillion USD. Other top-down studies report similar cost estimates (see IPCC, 2001c, Chapter 8).

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[9] IPCC (1996b) writes that energy efficiency gains of perhaps 10-30 percent above baseline can be realized at negative to zero net costs. Other authors, e.g., Ayres (1994), have pointed to even larger potentials for cost-efficient energy efficiency improvements, but others are less optimistic. Regardless of one's

Yale economist William Nordhaus argued a decade ago, “a vague premonition of some potential disaster is insufficient grounds to plunge the world into depression” (Nordhaus, 1990). (We would agree, if the premise were true, which we will challenge shortly.) More recently, Linden claims that stabilization of the atmospheric concentrations of greenhouse gases “would essentially destroy the entire global economy,” (Linden, 1996). Or similarly, Hannesson in his textbook on petroleum economics argues, “if the emissions of CO_2 are to be stabilized or cut back at least one of two things must happen. Either the poor masses of the world will continue their toil in poverty or the inhabitants of the rich countries will have to cut back their standards of living to levels few would be willing to contemplate” (Hannesson, 1998). Statements along these lines may have contributed to the concern of former and present U.S. Presidents Bush that carbon abatement might “threaten the American way of life.”

The purpose of this section is not to judge the relative merits between bottom up and top down estimates of the costs of climate policies. Rather, we make the perhaps somewhat paradoxical observation that even the more pessimistic economic model results also support the conclusion that substantial reductions of carbon emissions *and several fold increases in economic welfare are compatible targets*. In this connection, Schneider (1993) in a comment on the Nordhaus 1992 DICE model, pointed out that DICE calculated that the “draconian” 20 percent emissions cut (that had been advocated at the time by a number of environmental groups and some governments) that DICE found costly and economically inefficient only delayed a century-long 450 percent per capita income growth from simulated year 2090 to about 2100 in the model. Schneider argued that a decade delay in achieving a phenomenal income growth was surely a politically palatable planetary “insurance policy” to abate half of global warming.

Extending this line of argument, we developed a simple model and estimated the present value (discounted to 1990 and expressed in 1990 USD) of the costs to stabilize atmospheric CO_2 at 350 ppm, 450 ppm and 550 ppm at 18 trillion USD, 5 trillion and 2 trillion USD respectively (see Azar and Schneider, 2002, assuming a discount rate of 5 percent per year). Obviously, 18 trillion is a huge cost. The annual output of the 1990

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assumption about the magnitude of these “no regrets options,” as well as equally cost-effective deployment of renewables, all parties agree that this potential should be tapped as soon as possible.

global economy amounts to 20 trillion (1990) USD/yr.[10] Seen from this perspective, these estimates tend to create the impression that we would, as the above critics suggested, have to make the draconian cuts in our material standard of living in order to reduce the emissions. To some, the cost-estimates are perceived as unaffordable and politically impossible.

However, viewed from another perspective a different picture emerges. GDP in the baseline, (i.e., without any emission abatement and without any damages from climate change) is assumed to grow by a factor of ten or so over the next 100 years, which is a typical value for these long run modeling efforts—we will not debate the plausibility of these growth expectations here, but merely show the consequences with and without climate stabilization policies. The cost associated with the 350 ppm target would only amount to a delay in achieving this 10-fold global GDP increase by 2-3 years. Thus meeting a climate target as stringent as 350 ppm would imply that global income would be ten times larger than today by April 2102 rather than 2100 in the no abatement policies scenario. This trivial delay in achieving a phenomenal growth expectation occurs even using the more pessimistic models, even without considering the ancillary environmental benefits of emission abatement and even without considering that climate change would be significantly reduced in the abatement scenario (see Figure 4).

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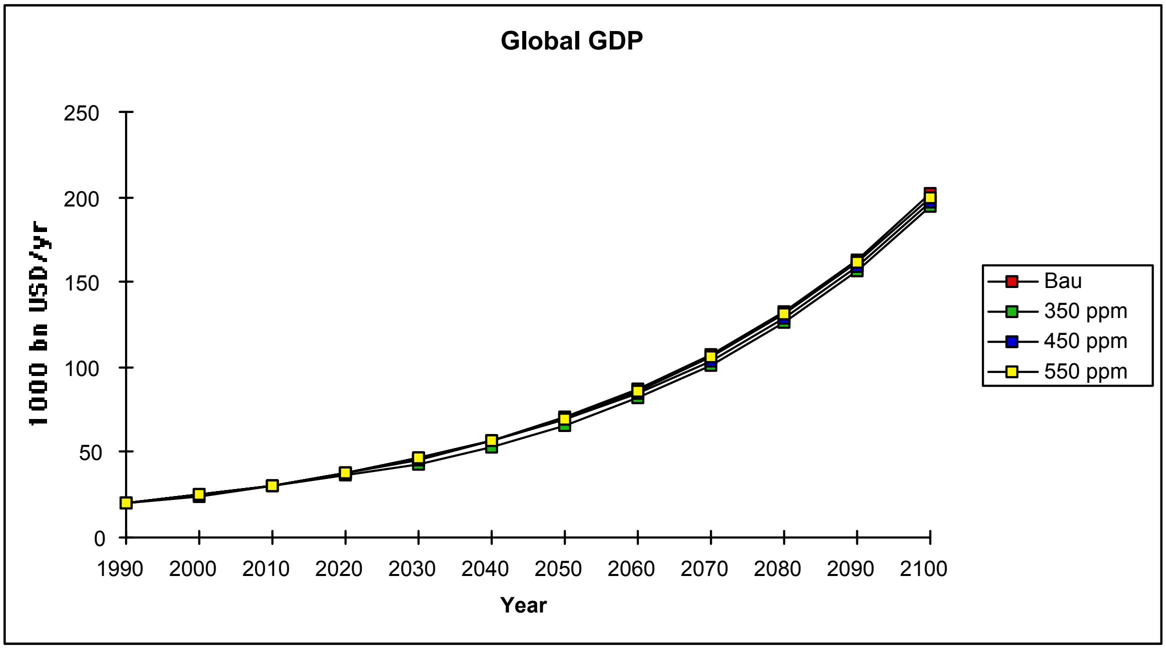
[10] We compare with the 1990 global economy since costs were discounted back to 1990 and expressed in 1990 USD. We chose 1990 in order to facilitate comparison with IPCC estimates, which are expressed in 1990 USD (see IPCC, 2001c, Chapter 8).

Figure 4 **Global income trajectories under BAU and in the case of stabilizing the atmosphere at 350 ppm, 450 and 550 ppm**



Notes: Observe that we have assumed rather pessimistic estimates of the cost of atmospheric stabilization (average costs to the economy assumed here are $200/tC for 550ppm target, $300/tC for 450ppm and $400/tC for 350ppm) and that the environmental benefits (in terms of climate change and reduction of local air pollution) of meeting various stabilization targets have not been included.
Source: Azar and Schneider (2002).

We believe representing the costs of stringent climate stabilization as a few years delay time in achieving a monumental increase in wealth should have strong impact on how policy makers, industry and the general public perceive the climate policy debate. Similar results can be presented for the Kyoto Protocol: the drop in GDP below baseline ranges between 0.05 percent and 1 percent for the different regions and different models (see IPCC, WG III, Chapter 8, IPCC, 2001c, p. 538). This translates into a drop in the growth rates for OECD countries over the next ten years that fall in the range 0.005-0.1 percent per year lower than baseline scenario projections. It should be kept in mind that the uncertainties about baseline GDP growth projections are typically much larger than the presented cost related deviations.

Further, with a growth rate of 2 percent per year in the absence of carbon abatement, the Kyoto protocol would imply that the OECD countries would get 20 percent per year richer by June 2010 rather than in January 2010 (assuming the high cost estimate). Whether that is a big cost or a small cost is of course a value judgement, but it is difficult to reconcile with the strident rhetoric of Lawrence B. Lindsey (2001), President Bush's assistant on economic policy, who states: “the Kyoto Protocol could damage our collective prosperity and, in so doing, actually put our long-term environmental health at risk.”

Finally, all this does not suggest that policies involving global emissions trading and/or carbon taxes would not be needed to achieve large cost reductions nor does it mean that the transition towards a CO_2-stabilized energy system below 500 ppm would be easy or will happen by itself (e.g., see Hoffert et al., 1998 for a sobering analysis of the departures needed from BAU to achieve such stabilization targets). On the contrary, such a transition would require the adoption of strong policies, e.g., carbon taxes, tradable emission rights, regulations on energy efficiency, transfer payments to deal with distributional inequities, enhanced R&D on new energy technologies, politically acceptable and cost-effective sequestration techniques etc. There will be winners and losers, and difficult negotiations will be required within and across nations to devise a cost-effective and fair burden sharing of transition costs. But, if further debate leads to the consensus judgement that preventing “dangerous” anthropogenic climate change implies stabilization of CO_2 concentrations below 500 ppm, then it should no longer be possible to use conventional energy-economy models to dismiss credibly the demand for deeply reduced carbon emissions on the basis that such reductions will not be compatible with overall economic development — let alone to defend strident claims that carbon policies will devastate the economy.

Hopefully, a broader recognition that reduced CO_2-emissions will at most only marginally affect economic growth rates by delaying overall economic expansion by only a few years in a century (and that with pessimistic cost assumptions, no ancillary benefits of climate policies, and no benefits for the averted climate changes), will increase the acceptability and willingness amongst politicians to adopt much stricter abatement policies than is currently considered politically feasible.

VII. Conclusions — Implications for the Kyoto Protocol and Beyond

Climate change is widely considered as one of the most potentially serious environmental problems the world community has to confront. This concern has materialized into a UN Framework Convention on Climate Change that calls for stabilization of atmospheric greenhouse gas concentrations below "dangerous" levels. As a way of initiating the process towards this ultimate objective, the world's industrialized countries, except U.S., have agreed to adopt near-term emission reduction targets.

Wigley et al. (1996), as well as a number of economists, have argued that the long-term stabilization target could be met more cost-effectively by reducing less now and more later on. Taken to the extreme this view has been misrepresented as if we should not reduce anything at all now, and compensate that by more stringent reductions later on. The lower costs would largely be derived from the fact that future costs are discounted, and that postponing emission reduction will give us time to develop new and more advanced energy technologies and plan the restructuring of the energy system so that premature retirement of the existing energy capital is avoided. Optimization models looking at the interaction between the economy and the energy system have been used to demonstrate such conclusions numerically.

But these modeling results are sensitive to the ultimate stabilization target. If a low stabilization target is chosen, stringent near-term abatement is found cost-efficient. If a high stabilization target were chosen, less early abatement would be required. Thus, optimal near-term policies depend on considerations about the long-term target. It would have been very interesting if optimization models with perfect foresight over the next hundred years had found similar near-term policies regardless of the stabilization target. They do not. Therefore, any judgment about the cost-efficiency of near-term abatement targets is contingent on the (too often implicit) choice of ultimate stabilization target.

However, this stabilization target is uncertain and controversial. We know with high confidence that there are certain climate impacts that will cause negative impacts on society, such as a rising sea levels, but given the complexity of the climate system unexpected impacts cannot be ruled out. Some of them might be more serious than the high confidence changes. It is likely that views and decisions about the ultimate stabilization targets will change over time. Clearly, new knowledge and information, and resolution of uncertainty will drive this process. But it will also be driven by each generation's values and sense of responsibility towards nature, future generations, the distribution of "winners and losers" of both climate impacts and policies, and perceptions about what "dangerous climatic change" means.

And, equally important, prevailing greenhouse gas concentrations in the atmosphere will have a strong impact on each generation's debate over which stabilization target society should opt for. The higher the concentration, the more difficult it is to convince policy-makers that a low target should be chosen. The main reason why 550 ppm is being discussed now is that governments and policy analysts see it as feasible, in contrast to say 400 ppm. It is our conviction that targets that have been discarded as impossible, such as 350 ppm, might still be on the agenda today had carbon abatement and/ or low-carbon technological development been initiated in 1970.

In the real world, climate policies are carried out under uncertainty about the climate system and the cost and possible rate of changes of the energy system. Therefore, hedging strategies are often proposed as the most reasonable policies (e.g., Lempert and Schlesinger, 2000). Given that climate change is generally considered likely to become a serious social and environmental problem, and then some early climate policies are prudent. The question is thus not if something should be done, but what, how much, and who pays.

Optimization models can be used to analyze hedging strategies. We may assume a certain probability distribution that different stabilization targets have to be met, and that this distribution is resolved by 2020, or any other year. Under these assumptions we may calculate the optimal near-term policies given uncertainty about the stabilization target. But, even the probabilities and the resolution year are uncertain, and neither is it possible to assign a high degree of confidence within the spheres of natural or social sciences. For that reason, energy-economy optimization models cannot help us to determine a single cost-efficient near-term policy. At best they can produce a subjective probability distribution of possible "optimal" policies, depending on the probabilities of many assumptions internal to their structure (e.g., Roughgarden and Schneider, 1999).

Rather, given all the uncertainty about the climate and the energy system, we suspect that real world climate policy implies that each generation will have to fight its own battle about how much to reduce its own emissions. It is an evolving process in which both uncertainty about the climate system and the energy system unfolds along the path. The target will be constantly moving. Postponing emission abatements to future generations is in the real world equivalent to avoiding an opportunity to reduce the emissions now without any guarantee of an increase in emission abatement in the future. Why would future generations be more inclined to reduce their emissions more if we reduce them less, or not at all? [11]

It is in light of this analysis that the international process that produced the Kyoto Protocol as well as the development of it should be seen. The Kyoto Protocol requires that emissions from Annex 1 countries should be reduced by 5 percent between 1990 and 2010, and although no targets have been negotiated for subsequent commitment periods, it is widely understood that Kyoto is but a first step towards more stringent targets. For example, all three IPCC Assessment Reports have noted the need for 50 percent or greater cuts below most business as usual scenarios by mid to late 21st Century to stabilize atmospheric CO_2 concentrations below a doubling of pre-industrial values, and the Third Assessment Report has clearly noted that eventually *all net carbon emissions must go to zero* to prevent continuous buildup of CO_2 concentrations in the 22nd Century and beyond. However, some analysts have assumed that this initial reduction target from the Kyoto process should apply also for the next 100 years despite the fact that there is no support in the Protocol for such an interpretation, see the Special Issue of Energy Journal (Weyant, 1999). Comparisons of this fictitious "Kyoto forever" were made with a case where Kyoto was not enforced, but more reductions were carried out subsequently so that the climate implications by 2100 were essentially the same as those in the "Kyoto forever." In this way it was "proven" that "Kyoto forever" is not cost-efficient, and we

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[11] A standard economist response to this would typically be that by avoiding emissions reductions now, we would be making people richer in the future, and therefore at least economically more well situated to accept climate policy initiatives. But not reducing the emissions means that we can get even more locked into carbon intensive capital, and perhaps making future generations thus less inclined to abate carbon. Further, the difference in GDP growth rates between an abatement scenario and a business as usual scenario is marginal (see section 6). Overall, the relation between willingness to abate carbon seems not to

were taught that also Kyoto was not cost-efficient. Some have even argued that Kyoto (but essentially referring to "Kyoto forever" which is something else than the real Kyoto Protocol) is pointless because it might entail costs of hundreds of billions of dollars with only marginal changes in global temperatures by 2100 — less than a decade delay in achieving whatever warming would have occurred in the absence of the "Kyoto forever" fictitious protocol.

It is clear that these types of analyses have had an impact on U.S. politics, but it is a fundamental misunderstanding behind the idea of Kyoto. The Protocol is just the first step of an evolving process. More stringent policies can be expected, much in the same way as the Montreal Protocol continuously sharpened reduction requirements on ozone depleting substances — but the responsibility for doing this lies with forthcoming political leaders and future generations. As noted, the IPCC has long made it clear that cuts of 50 percent or more below most baseline scenarios are needed in the 21st century to achieve even modest stabilization goals like 600 ppm, so the "Kyoto forever" scenario is essentially a massive climate change scenario that is a very small departure from the CO_2 tripling or quadrupling baseline scenarios typically projected for 2100 and beyond (e.g., IPCC Synthesis Report, 2002, Question X). Although the bulk of the departure from typical baseline emissions may indeed be more prudent to delay into the future, that is no fair argument to project the first step (a Kyoto-like agreement) as the only step for 100 years and then declare inefficiency and defeat. Assuming that the Kyoto targets will remain as is over the next 100 years, and then to use that as an argument against the Kyoto Protocol that has been negotiated to hold for only a decade, borders on intellectual dishonesty, [12] since no climate scientist has ever argued that "Kyoto forever" can do more than a marginal decrease in climate change to 2100 and beyond. Kyoto Forever is simply a cost-ineffective prescription for large and sustained climate changes, but no Kyoto is a

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be so strongly correlated to income. Although India seems less inclined to adopt carbon abatement policies than Europe, Europe is more willing than U.S. and Canada who are richer.

[12] Nordhaus and Boyer (1999) argue that extending the Kyoto Protocol 100 years into the future is "the environmental objective embodied in the Kyoto Protocol," (p. 100). They conclude that the Kyoto Protocol is "highly cost-ineffective with the global temperature reduction achieved at a cost of almost 8 times the cost of a strategy which is cost-effective in terms of 'where' and 'when' efficiency." Also Lomberg (2001) argues along similar lines—and is critiqued by Schneider (2002).

prescription to further delay beginning the process of moving toward the more stringent climate regimes that will be needed in the decades ahead if stabilization concentrations below 600 ppm are to be achieved.

We are gratified that Nordhaus, 2001, recognized that as a political strategy to jump start the process, at least, implementing a flexible version of the Kyoto Protocol makes sense to him.

For those in favor of stringent climate policies, the argument that we should defer emission abatement and do more in the future, will thus only be confronted by the view that we should do both. Those citing WRE arguments for delayed abatement would say that the budget for emission abatement is limited, but the counterargument would be that although the budget is limited, arguments could also be made over how large it *should be*. The fact that we will act today is rather unlikely to imply that weaker climate policies will be carried out in the future.

If low stabilization targets were so expensive to meet that it would not be possible to meet other worthy social and environmental objectives (e.g., clean water and energy systems, particularly in LDCs), then we would join the argument that higher targets should be accepted at the outset. But, we have shown, by extrapolating results from conventional top-down economic models, that phenomenal economic growth worldwide and low stabilization targets are compatible goals (see Section VI). In the baseline, world income typically grows by a factor of ten or so over the next hundred years, but with carbon abatement policies taking us towards 350, 450 or 550 ppm, this increase in income would be delayed by at most a few years (for each target). This does not mean that we think that the costs are not important. We readily concede that there are many other "worthy causes" that could argue likewise that investments in their behalf would only produce a small delay in achieving large economic growth factors a century hence. But the climate problem is so laced with large uncertainties — including abrupt non-linear events with catastrophic potential (e.g., THC collapse) — and the possibility of many irreversibility occurrences (e.g., species extinctions or flooded heritage sites) — that we consider it a compelling case for strong consideration for hedging actions. Plus, as noted in IPCC (2001c), "ancillary benefits of climate policies can improve clean air and energy systems, helping to meet sustainable development objectives and climate stabilization goals simultaneously." Thus, after having assessed the benefits and costs of emission reduction, and acknowledging the many uncertainties in every stage of the analysis—many of which we have emphasized in this paper — it is nonetheless our value judgment that the extra "climate safety" afforded by a few years delay in a factor five of per capita income growth over 100 years is an insurance premium in planetary conservation well worth its price.

We believe that it is a prime task for the global community to act now so as to keep low stabilization targets (say 400 ppm CO_2, or 450 CO_2 equivalents) within reach — but we wouldn't argue against a few decade overshoot above the long run target during the transition. That low stabilization target — even with a small overshoot — requires early abatement and carbon abatement policies. As more is learned of the risks to social and natural systems, and political preferences become better developed and expressed, targets and policies can always be revisited and either lower or higher targets can be fashioned. What cannot necessarily be fashioned is a reversal of abrupt non-linear climatic changes or impacts that present analyses consider possible. The very large uncertainties thus allow the possibility of at least some "dangerous anthropogenic interference in the climate system" at relatively low stabilization targets like 500 ppm. Thus, we believe near-term abatement and the consideration of actions for moving toward low stabilization concentrations, with rethinking as new information comes in, should not be foreclosed by arguments based on most existing integrated assessment models, given the well known limitations in the structural and value-laden assumptions in these very preliminary tools.

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