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Climate Policy 1 (2001) 433–449

CLIMATE POLICY

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Integrated assessment of abrupt climatic changes

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Received 9 February 2001; received in revised form 6 June 2001; accepted 25 August 2001

Abstract

One of the most controversial conclusions to emerge from many of the first generation of integrated assessment models (IAMs) of climate policy was the perceived economic optimality of negligible near-term abatement of greenhouse gases. Typically, such studies were conducted using smoothly varying climate change scenarios or impact responses. Abrupt changes observed in the climatic record and documented in current models could substantially alter the stringency of economically optimal IAM policies. Such abrupt climatic changes — or consequent impacts — would be less foreseeable and provide less time to adapt, and thus would have far greater economic or environmental impacts than gradual warming. We extend conventional, smooth IAM analysis by coupling a climate model capable of one type of abrupt change to a well-established energy–economy model (DICE). We compare the DICE optimal policy using the standard climate sub-model to our version that allows for abrupt change — and consequent enhanced climate damage — through changes in the strength (and possible collapse) of the North Atlantic thermohaline circulation (THC). We confirm the potential significance of abrupt climate change to economically optimal IAM policies, thus calling into question all previous work neglecting such possibilities — at the least for the wide ranges of relevant social and climate system parameters we consider. In addition, we obtain an emergent property of our coupled social–natural system model: "optimal policies" that do consider abrupt changes may, under relatively low discount rates, calculate emission control levels sufficient to avoid significant abrupt change, whereas "optimal policies" disregarding abrupt change would not prevent this non-linear event. However, there is a threshold in discount rate above which the present value of future damages is so low that even very large enhanced damages in the 22nd century, when a significant abrupt change such as a THC collapse would be most likely to occur, do not increase optimal control levels sufficiently to prevent such a collapse. Thus, any models not accounting for potential abrupt non-linear behavior and its interaction with the discounting formulation are likely to miss an important set of possibilities relevant to the climate policy debate. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Emergent properties of coupled socio–natural systems; Integrated assessment; Abrupt non-linear climate change; Thermohaline circulation; Discount rate; Climate policy analysis

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PII: S1469-3062(01)00038-9

1. Introduction: context of the use of integrated assessment models for climate policy analysis

Integrated assessment models (IAMs) have become increasingly important tools in interdisciplinary climate policy analysis. As instruments of analysis, IAMs allow study of the behavior of coupled systems — which may have emergent properties that are not revealed by simulations with each disciplinary sub-model alone. However, many such early-generation models are limited by restrictive assumptions (Schneider, 1997) relative to the nature of the complex systems they attempt to simulate. First generation IAMs applied to the climate problem calculate optimal emission control rates — often via the imposition of a tax on carbon — given some standard set of population, technology and energy systems scenarios. The impacts of a climate change scenario on the economy are usually treated via a climate damage function, through which a given amount of climate change — some degree of global warming — is translated into a consumption loss, often a percentage reduction in gross domestic product (GDP). This loss of consumption leads to a loss of utility — usually the quantity to be maximized in IAMs. Most of these first IAMs consistently produced economically optimal solutions with very modest near-term mitigation.

Such coupled models typically employ simple climate sub-models that produce only smoothly-varying climate change scenarios. The translation of gradual warming into climate damage omits a significant source of potential climate damage — abrupt non-linear climate changes. If climate changes are smooth then the capacity of society to adapt is higher. Changes that are gradual and more foreseeable lead to lower damages compared to very rapid changes such as abrupt unanticipated events or “surprises”. Many large-scale environmental systems have been shown to possess multiple equilibria and the potential to switch rapidly between them, as well as hysteresis behavior (Higgins et al., 2001). One example is the multiple stable equilibria of the thermohaline circulation (THC) of the North Atlantic, creating the possibility of rapid and irreversible (in the near-term) ocean circulation changes, with significant detrimental effects. Because of the time lag between emissions and impacts, and the abrupt nature of such an event, seemingly “optimal” near-term policy behavior that does not account for the possibility of abrupt changes could precondition a catastrophic collapse of this ocean current system by the 22nd century. The simple climate models used in first generation IAMs are not equipped to represent such changes, nor are most economy models coupled to them [1]. This study addresses these deficiencies, and sketches some preliminary policy implications.

These same themes are present in the study of decision making under uncertainty. Working Group III of the IPCC TAR (IPCC, 2001c) presents the results of seven models from an Energy Modeling Forum project (Manne, 1995) on hedging strategies for low-probability, high-consequence climatic scenarios under uncertainty resolved (i.e. the uncertainty is replaced with knowledge) in 2020. These models employ cost–benefit analysis and show little abatement until after uncertainty about the occurrence of high damages is resolved — low near-term abatement. However, when abrupt non-linear changes are involved, a wait-and-see approach may lead toward an undesirable outcome: by the time the threatening outcome is clearly identified, it may then be extremely expensive or even impossible to avoid. Working Group III also describes research (Ha-Duong et al., 1999) that supports such concerns by showing decoupling from

[1] For example, these models often assume perfect foresight of all future time periods. We introduce a wide range of increased damages due to abrupt climatic change within this formulation, noting that damages will be greater without such artificial foresight. Taking this one step further, elimination of perfect foresight may increase optimal control rates by enhancing precautionary savings behavior (Kuntz-Duriseti, 2001; Lippman and McCall, 1981; Blanchard and Mankiw, 1988).

current emissions trends if the interplay between the inertia of the economic system and uncertainty over the required magnitude of emissions abatement is considered, a very similar situation.

We demonstrate the potential importance of abrupt non-linear climate damages with a modeling exercise coupling a simple IAM to a simple climate–ocean model capable of representing one form of abrupt non-linear climate change — weakening or collapse of THC. Owing to this simplicity, our quantitative results are only meant to be illustrative of principles we believe should be taken into consideration by the policy community.

2. The DICE model

William Nordhaus' dynamic integrated climate and economy (DICE) model (Nordhaus, 1992) has been a widely used IAM because of its relative simplicity and transparency. It couples a simple globally and seasonally-averaged two-box climate model (Schneider and Thompson, 1981) with an economic model of similar complexity. The coupled climate–economy system is solved as a simple optimal growth model that maximizes discounted utility from consumption in all considered time periods with perfect foresight (a traditional social welfare function). The model determines the optimal forecast for future emissions reductions by balancing the costs of reducing emissions with the costs of climate change, represented by a climate damage function.

Since its creation, many papers have demonstrated the sensitivity of the DICE model results to changing structural assumptions (Schultz and Kasting, 1997; Roughgarden and Schneider, 1999). This paper relaxes a simplification of most conventional IAMs via the addition of a sub-model that includes abrupt, non-linear climate changes. The DICE model makes no attempt to incorporate certain non-linear behaviors found in more complex general circulation models (GCMs) (Manabe and Stouffer, 1999) or observed in nature (Broecker, 1997). The original DICE climate model is capable only of smooth temperature changes — no discontinuities in the slope of the time-evolving changes — given a smooth CO_2 increase scenario. However, when forced by certain smooth emissions scenarios, GCMs can display abrupt non-linear responses, in particular the weakening or collapse of the thermohaline circulation (THC) of the North Atlantic Ocean that warms northern Europe by as much as 10°C (Broecker, 1997). Such abrupt non-linear changes could rapidly change the rate of temperature increase in as little as a decade, could cause regional surface temperatures to alter much more rapidly than global averages, or could even produce a regional temperature decrease while the rest of the world warms (Schneider and Thompson, 2000)[2]. Several simulations suggest that this circulation is sensitive both to the level at which greenhouse gases are stabilized in the future and also to the rate of increase of such concentrations in the atmosphere (Stocker and Schmittner, 1997).

This paper explores the implications of incorporating abrupt non-linear climate behavior associated with reduction and/or collapse of THC into the DICE model by creating the Enhanced DICE model, or E-DICE. Only a few previous studies have considered rate-dependent damages from global warming (Peck and Teisberg, 1994; Toth et al., 1997), the possibility of abrupt climate change (Toth et al., 1997), and specific abrupt climate change damages from ocean circulation changes (Keller et al., 2000a,b).

[2] Paleoclimatic data suggest that THC collapse has occurred many times, particularly in glacial periods when episodes of icebergs discharged into the North Atlantic provided a cap of low salinity, low density melt-water that facilitates the formation of sea ice, reduces the strength of the sinking of surface water and in turn, inhibits the Gulf Stream and its extension into northwestern Europe (Broecker et al., 1985; Seidov and Maslin, 1999).

While Keller et al. address the incorporation of ocean circulation changes, as do we, our approach differs in that we couple a physical climate–ocean model to the optimal growth DICE model, whereas Keller et al. tabulate data from a more complex climate–ocean model, but do not directly couple the economy model to a physical model. Our approach allows us to find salient emergent properties of the coupled system, since internal feedback processes can interact between our sub-models using an iterative coupling technique.

3. The E-DICE model

The E-DICE model we develop extends the DICE model to incorporate potential damages from changes in THC overturning rate by modifying the original DICE climate damage function. We add a term ε to the exponent of the damage function, creating a more non-linear, "hockey stick"-like function (see Appendix A). Fig. 1 compares the DICE damage function with a representative E-DICE damage function. Since this "top down" damage function formulation is not based on more mechanistic "bottom up" analyses, we use a range of plausible assumptions to test the sensitivity of this IAM to an array of abrupt events and display its results compared to standard results using a smooth climate change model without the added parameter for abrupt damages.

The E-DICE model determines values for ε by exchanging information with an enhanced climate model that simulates THC. This model, the simple climate demonstrator (SCD) (Schneider and Thompson, 2000), was developed as an extension of an original two-box climate model (Schneider and Thompson, 1981) (the conventional climate model in DICE). The SCD model retains suitable simplicity for use in integrated assessment while demonstrating the major features of global warming simulations performed by recent GCMs — specifically the response of THC to anthropogenic CO_2 emissions. The present circulation strength is thought to be (with considerable observational uncertainty) roughly 20

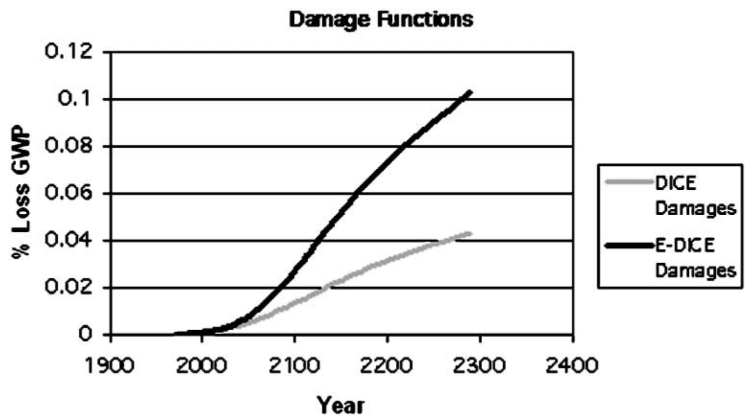

Fig. 1. Comparison of DICE and E-DICE damage functions. The E-DICE damage function here corresponds to an ϵ of 0.98, a mid- to high-range value. The temperature profile used to generate the DICE damage curve is that of the original DICE optimal solution (3% PRTP). E-DICE was run with a maximum THC enhanced damage of 10% GWP, a rate of time preference of 1.8%, an initial THC overturning rate of 15 Sv (1 Sv = 1 million m^3/s), and a climate sensitivity of 4.5°C for an equivalent doubling of CO_2.

Sverdrups (Sv), where 1 Sv = 1 million m^3/s. It is well-known from many modeling studies that the strength of the overturning circulation initially decreases with increasing CO_2, and for small and slowly developing emissions scenarios the strength recovers, whereas for large and/or rapid forcing the overturning may cease entirely — the so-called thermohaline catastrophe. SCD reproduces this established behavior.

Details of the behavior of SCD and the steps in an E-DICE/SCD run are outlined in Appendix A.

4. Results with Nordhaus discounting

The output of the canonical DICE model produces optimal carbon taxes for the future. Here, that analysis is expanded to include enhanced damages from THC reduction: the E-DICE/SCD runs. Fig. 2 compares the optimal carbon tax forecasts for the E-DICE/SCD model with the optimal forecasts from the original DICE results containing no enhanced damages (see Appendix A for information on methods). Discount rates, carbon cycle formulation, and other parameters are all left as in DICE to isolate the enhanced damage effects we single out. This graph indicates that incorporating THC damages always increases the optimal carbon taxes in the E-DICE model compared to the original DICE model. It also shows that while the lower enhanced damage estimates (1–10% gross world product (GWP) were there to be a full collapse of the THC) lead to noticeable changes in the optimal carbon tax forecast, a very

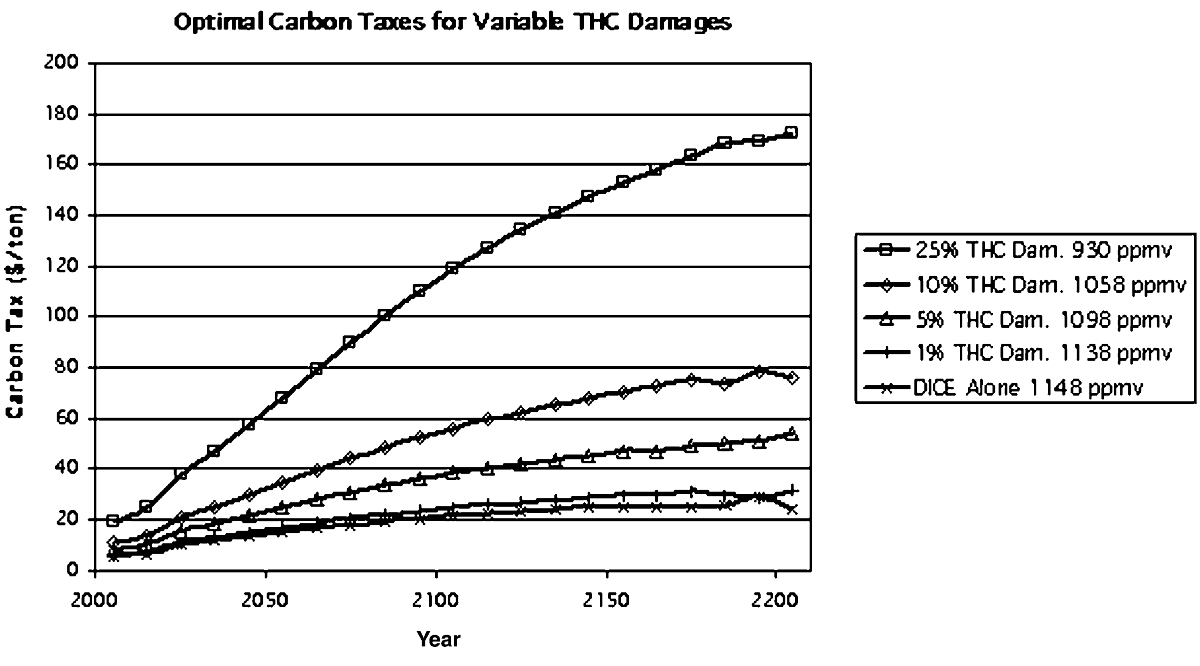

Fig. 2. E-DICE optimal carbon taxes for selected maximum THC enhanced damages compared to original DICE. Optimal carbon taxes increase as THC enhanced damage estimates increase. Relatively sizable enhanced damages are required before a significant increase in carbon tax occurs. Final atmospheric CO_2 concentrations (in model year 2350) are shown for each run in parts per million by volume (ppmv).

large damage estimate for THC collapse (25% GWP) is required before a sizable change in near-term control rates appears[3].

Final (model year 2355) CO_2 concentrations shown on the graph similarly reflect sizable changes only with large enhanced damages. Only then are significant controls on emissions implemented — which are needed if atmospheric concentrations are to be significantly reduced relative to the case without enhanced damages. All the simulations produce more than a tripling of CO_2 in the distant future because they are based on conventional economy, technology and population assumptions. These are certainly only one set of social scenarios that are possible, but in this study we concentrate on the abrupt climate change issue, and do not argue the plausibility or desirability of such conventional scenarios (see IPCC, 2000 for alternative scenarios or Schneider, 2001 for discussion of the likelihood of future climate changes that might be inferred from such scenarios).

5. The discount rate

A prime reason for the more than tripling of CO_2 concentrations in most DICE runs is the discount rate of the DICE model. Discounting in DICE is governed by two terms, growth in income in combination with declining marginal utility of income, and a pure rate of time preference (PRTP). Nordhaus sets the PRTP equal to 3% per year so as to obtain an effective discount rate equal to 6% per year (Toth, 1995; see Appendix A). Because of geophysical processes, changes in THC overturning lag by many decades behind the CO_2 emissions that cause them. Thus, damages from THC changes are pushed far into the future, making the present value of the enhanced damages in our model particularly sensitive to discounting. Different but equally plausible PRTP can be chosen for the model (Arrow, 1996). Howarth suggests setting the discount rate equal to the return on risk-free assets: 0.4% per year (Howarth, 2001). To explore the sensitivity to alternative discounting assumptions, we employ a range of PRTPs: 1.5, 3% (original DICE default), and 4%. An elimination of time preference (PRTP $= 0$) that treats all time periods equally is also considered (Azar and Sterner, 1996; Rabl, 1996).

Another alternative to changing the classic discount rate is “hyperbolic discounting”. A growing literature in the psychological and economic communities hypothesizes that the discount rate placed on future projects declines as a project moves further into the future (Ainslie, 1992; Heal, 1997). In other words, a person’s preferences vary greatly when asked whether a project should be initiated next year or the year afterward, but vary to a far lesser extent for a project initiated 50 years from now or fifty one. According to interpretations of this data, in the near future (e.g. 5 years) the preferred discount rate is very high. However, as the time horizon extends, the preferred discount rate declines significantly. Laboratory and field studies support such findings (Ainslie, 1992).

Tables 1–3 present optimal carbon taxes for the coupled E-DICE/SCD model runs, compared to the uncoupled DICE model, for this range of discount rates and approaches. The original DICE model uses a

[3] Keller et al. (2000b) describe scenarios in which a low control rate can be “optimal” even with a THC collapse because, given their chosen damage functions and discount rate, it is cheaper to allow a collapse than to reduce emissions to preserve THC. In some of our model runs, THC collapses because its preservation is not “optimally” efficient, for example, when climate sensitivity is high, initial circulation strength is low, and the maximum damage estimate is low. Keller et al. use an enhanced damage estimate of 1.5%, comparable to our low enhanced damages estimates, and thus have not broadly explored the range of possible values for such significant parameters.

Table 1
Optimal carbon taxes (US$/t C), 2005

Model: PRTP [a]:	Uncoupled DICE	E-DICE/SCD 1% maximum damage enhancement	E-DICE/SCD 5% maximum damage enhancement
0%	101.01	118.06	210.20
1.5%	17.06	19.14	27.61
3%	5.43	5.99	8.17
4%	2.90	3.19	4.29
Hyperbolic	67.39	78.54	137.80

[a] PRTP = pure rate of time preference.

Table 2
Optimal carbon taxes (US$/t C), 2055

Model: PRTP [a]:	Uncoupled DICE	E-DICE/SCD 1% maximum damage enhancement	E-DICE/SCD 5% maximum damage enhancement
0%	178.37	211.81	395.14
1.5%	38.79	44.36	67.90
3%	15.04	16.97	24.83
4%	9.14	10.28	14.83
Hyperbolic	153.24	180.98	331.87

[a] PRTP = pure rate of time preference.

PRTP of 3%, and the tables include the results of uncoupled DICE runs using other PRTPs or hyperbolic discounting.

The numerical results in the tables confirm that our results are particularly sensitive to the choice of PRTP, which affects both the magnitude of the carbon taxes and also the magnitude of the change in carbon tax due to THC-enhanced damages. As is well-known, the lower the PRTP, the higher the present value of distant future climatic damages, and thus, the larger the increase an incorporation of THC damages causes in the optimal carbon tax. It is interesting that the E-DICE results appear more sensitive to the PRTP

Table 3
Optimal carbon taxes (US$/t C), 2105

Model: PRTP [a]:	Uncoupled DICE	E-DICE/SCD 1% maximum damage enhancement	E-DICE/SCD 5% maximum damage enhancement
0%	231.92	278.59	540.85
1.5%	54.47	63.30	101.78
3%	21.73	24.89	38.36
4%	13.35	15.76	22.89
Hyperbolic	214.77	256.81	483.71

[a] PRTP = pure rate of time preference.

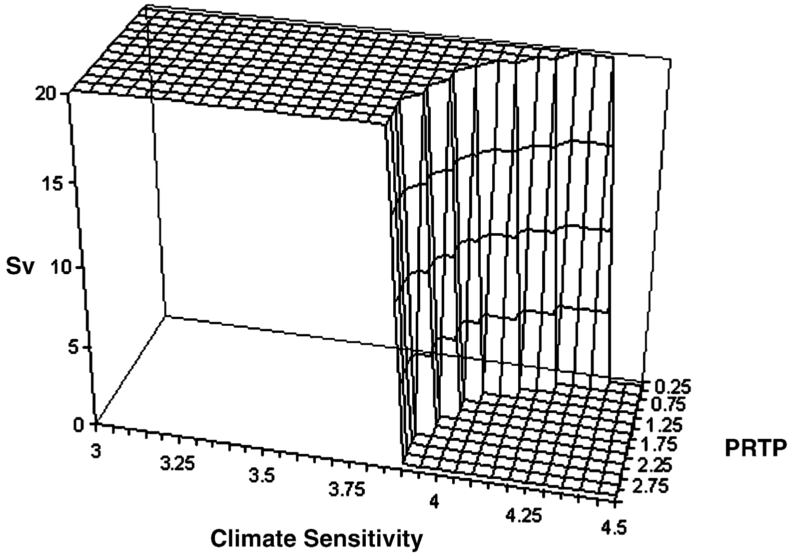

Fig. 3. “Cliff diagram” of equilibrium THC overturning varying PRTP and climate sensitivity. As PRTP increases, the climate sensitivity threshold at which collapse of the THC occurs decreases (with a central value of initial overturning rate of 20 Sv). This is because higher discount factors lead to lower emissions control rates, and thus allow a greater risk of climate change sufficient to trigger abrupt non-linear climatic responses (the “threshold” value of climate sensitivity above which a collapse occurs should not be taken as quantatively fixed, a possible impression from this figure. This diagram holds many other parameters relevant to that threshold in the middle of their ranges, and thus collapse thresholds for each PRTP could be either higher or lower than those in this figure if other relevant parameters were simultaneously co-varied).

than to varied physical parameters such as climate sensitivity (IPCC, 2001a). Fig. 3 is a “cliff diagram” showing the equilibrium THC overturning for different combinations of climate sensitivity and PRTP values. As the PRTP decreases, circulation is preserved for disproportionately higher climate sensitivities since the lower PRTP allows larger emissions reductions and thus it takes a higher climate sensitivity to reach the “cliff”. Conversely, the higher the discounting factor, the lower the climate sensitivity needed to experience the overturning collapse.

Employing hyperbolic discounting yields optimal carbon taxes almost as high as the 0% PRTP case, despite the fact that for the first few decades of the simulation the hyperbolic formulation actually has a higher discounting effect than conventional exponential discounting. However, more than a century hence, when the THC-enhanced damages are largest, the hyperbolic discount factor is smallest. Under hyperbolic discounting, these large future damages affect near-term optimal carbon taxes significantly and outweigh the reduction due to the high discounting of the first half of the 21st century. If hyperbolic discounting is a better empirical expression of the PRTP than conventional exponential discounting, the present value of long term highly damaging events will lead to much stronger “optimal” near-term emissions reductions. Of course, as discussed earlier, the “correct” choice of discount rate (or discounting formulation) is as much a value laden preference as it is a technical issue about economic growth rates over time, opportunity costs or other factors that are part of the debate (Arrow, 1996). Our IAM, which incorporates rapid climatic changes in the distant future created by choices made and implemented over the 21st century, highlights the policy consequences of such value choices.

6. Emergent properties of coupling physical and social sub-models

One of the main purposes of the use of integrated assessment models is to characterize a range of possible events and test the sensitivity of outcomes like THC weakening to a variety of plausible assumed parameter values or baseline assumptions. Such analysis is also important because it can reveal emergent properties of the studied system — in this case the coupled social–natural system of climate, ocean, and economy. In this spirit, we summarize our results by constructing a broad (but not full) range of scenarios with our E-DICE model, based on picking moderately high and low estimates for several parameters simultaneously, so that we cascade our uncertainties on the "high" and "low" sides for illustrative purposes (Fig. 4). We do not claim these to be defined range limits, as we have not conducted a formal procedure to estimate the subjective probabilities of these high and low cases, let alone to investigate possible outlier events beyond the range limits we explore here (e.g. see discussions in Moss and Schneider (2000); Schneider (2001)). The THC profiles corresponding to DICE runs are the results of uncoupled SCD model runs using the optimal CO_2 concentrations from DICE.

For our "lower bound" case we allow the cascade of low climate sensitivity (1.5°C for $2 \times CO_2$) with high initial THC overturning rate (25 Sv), low enhanced damages (1% additional GWP loss from a total collapse), and baseline DICE PRTP (3%). The high initial overturning rate and low climate sensitivity decrease the likelihood of a THC collapse (Schneider and Thompson, 2000). Fig. 4 shows (filled square curve) that the reduction in THC over the 200-year period of the simulation is not trivial (from 25 to about 15 Sv), but at 2200 the THC is still far away from an abrupt collapse. Carbon taxes for this case are shown in the lower panel of the figure, also with filled square (optimal taxes for this DICE run start at about US$ 4/t C and end at about US$ 24/t C). The unfilled square curves show the results of E-DICE for these same parameter choices. Note that the enhanced E-DICE damages are sufficient to slightly increase the optimal carbon tax relative to the DICE run without THC damages. The increased carbon tax lowers emissions slightly but in this "lower bound" case the small decline produces only a trivial reduction to the THC weakening.

The triangle curves represent an intermediate case, with 20 Sv initial overturning rate, 5% enhanced maximum damages, 3°C climate sensitivity for CO_2 doubling and a 2% PRTP. Note that the higher climate sensitivity produces a much greater reduction in THC strength, and thus much larger damages in E-DICE relative to DICE. Thus, the optimal carbon taxes for E-DICE are substantially larger than those for DICE — and likewise the mitigation of THC weakening is more noticeable, but still not very sizable.

Our "upper bound" case (filled circles for DICE and open circles for E-DICE) use a 15 Sv initial THC overturning rate, a 4.5°C climate sensitivity for CO_2 doubling, 10% maximum enhanced damages and a 1.5% PRTP. The high impact case is the most interesting because it shows why abrupt non-linear changes can make such a large difference to integrated assessment conclusions. Note that the original DICE run shows a rapid decline in THC almost immediately after 2000, and there is an "abrupt" collapse of the THC — "abrupt" meaning over a decade or so — around 2100. The rapidly decreasing profile of THC — filled circle curve on the upper panel of Fig. 4 — shows that enhanced damages will be much larger than for our lower and intermediate cases since the percent change in THC is very large and because the changes occur earlier, and thus, will have a much higher present value, even with exponential discounting.

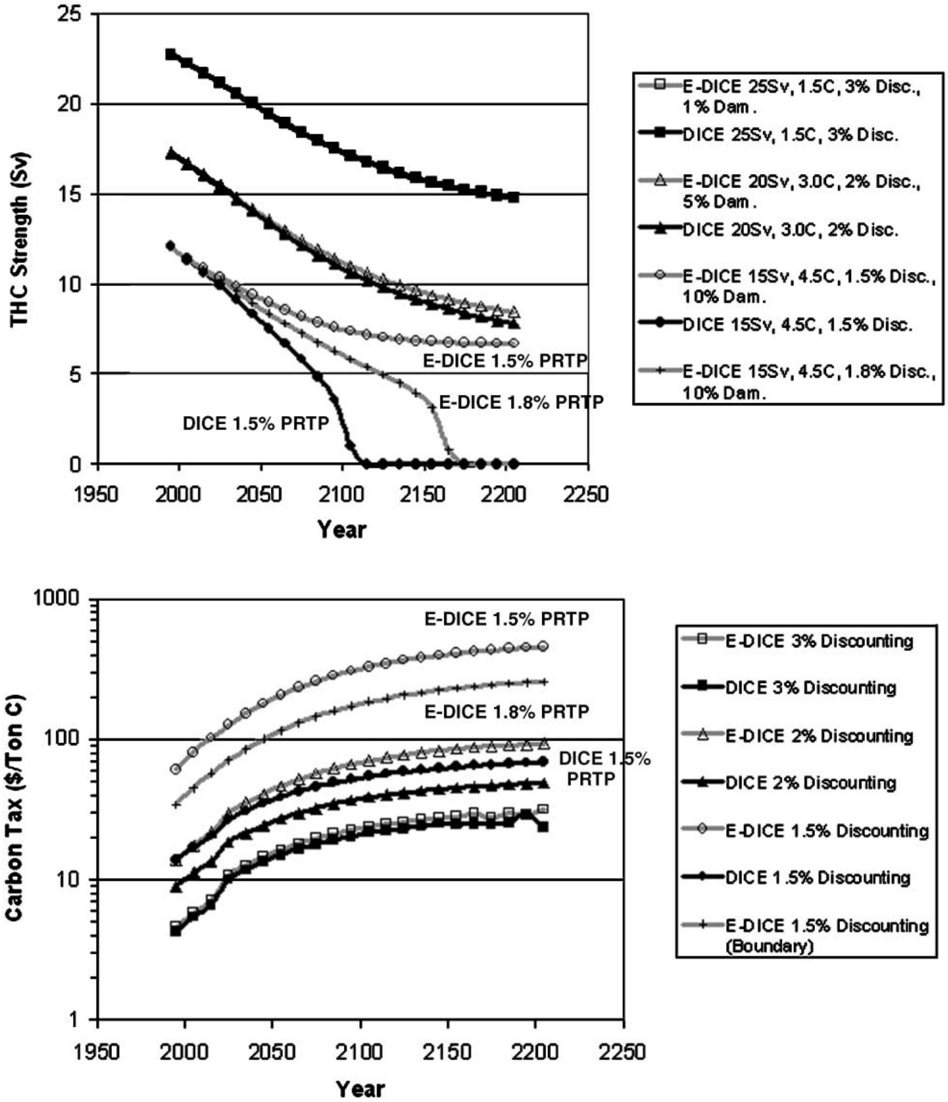

Fig. 4. Optimal carbon taxes for E-DICE and DICE with a range of parameter values, and the THC overturning profiles associated with those scenarios. The curves delineate a range of solutions, and illustrate the sensitivity of the E-DICE model to the PRTP. As the PRTP decreases, the increase in carbon tax grows when THC enhanced damages are included. The circle curves illustrate an emergent property of this coupled socio–natural system. Under the optimal DICE run (filled circle curve), THC collapses abruptly. When the potential THC damages are incorporated, the increase in optimal carbon tax reduces emissions sufficiently to prevent the collapse (open circle curve). However, when PRTP is increased from 1.5 to 1.8% or greater, the discounted present value of the enhanced damages is insufficient to lower emissions below the threshold that causes abrupt THC collapse.

As a result, the carbon taxes for the E-DICE case (open circle curve in lower panel of Fig. 4) are much larger than for the DICE case in which the abrupt THC shutoff occurs. Note that this shutoff in THC occurred in conventional DICE despite the carbon tax seen in the lower panel with filled circles — starting about \$14/t C and rising to about US\$ 68/t C in 2200. That tax — based on a damage function that was keyed only to mean global temperature rise and having no enhancement to represent the rapid non-linear change to the THC — was insufficient to slow down the emissions of CO_2 enough to prevent the abrupt non-linear change some 100 years hence. But when the enhanced damage function is used in the E-DICE run, the optimal carbon tax is increased substantially (starting at US$ 61/t C in 2000 and rising to US$ 453/t C in 2200). Interestingly, this induces enough emissions reductions to produce a THC profile that is qualitatively different from the canonical DICE version — the open circle curve on the top panel of Fig. 4, which *does not* undergo a full THC collapse, only a smooth decline. Because of the non-linear behavior of the SCD model, its coupling to DICE to create the E-DICE model leads to an emergent property of the coupled climate–economy system that is qualitatively different from DICE with its lack of internal abrupt non-linear dynamics. The enhanced carbon tax actually "works" in the sense that it is sufficient to prevent the full collapse of the THC (for these system parameters).

Finally, we repeat the "upper bound" case with PRTP increased to 1.8% (crossed lines). This is the rate that qualitatively alters the coupled E-DICE behavior, since this higher discount rate sufficiently devalues future enhanced damages so that carbon taxes are just low enough that emissions are just high enough that the abrupt non-linearity — the THC collapse — occurs, despite the fact that increases in taxes are not negligible. Again, we repeat that the insights here are much more likely to be robust than the particular numbers, given the simplicity of the models and the arbitrariness of various key assumptions.

7. Conclusions

The coupled E-DICE/SCD model makes it possible to investigate quantitatively the effects of explicitly coupling a physical model that can produce an abrupt non-linear climatic change into an integrated assessment model of "optimal" climate policy. Sensitivity experiments with the E-DICE/SCD model indicate that the incorporation of large non-linear damages — the 10–25% THC damage cases — even if those damages are delayed by a century or more, significantly increases (by a factor of several) present optimal carbon taxes, using conventional discounting with PRTPs of 1.5–3%. Furthermore, if the model uses a low PRTP — or a hyperbolic discounting function — present "optimal" carbon taxes with the E-DICE/SCD model are increased by an order of magnitude relative to conventional IAMs. We show, even with our simple formalism, that emergent properties of coupled social–natural systems can be obtained that would not be easily revealed by stand-alone models of nature or of society. It is very doubtful that such solutions (e.g. as in Figs. 3 and 4) could easily be found by running uncoupled economic or climate models, or even IAMs that couple climate and economic systems but do not contain either abrupt non-linear dynamics or enhanced damage functions accounting for the foreseen future THC collapse. Therefore, we anticipate that the framework explored here may be usefully generalized, even if the specific numerical results are only intended to be illustrative of basic principles. We believe that a hierarchy of models of increasing comprehensiveness will eventually need to be used to refine the basic insights, we provide here.

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), signed by 162 Nations by 1993, expressed the opinion of the Parties that steps be taken to "prevent dangerous anthropogenic interference with the climate system". (UNFCCC, 1992). Although the Convention did not specify what constitutes the value judgment of being "dangerous", Working Group II of the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC, 2001b) has noted that exposure and sensitivity to climate changes influence "vulnerability", and clearly a highly vulnerable sector or region is more in "danger" than one that is less vulnerable to some change. Since sensitivity is reduced if a society or an environmental system has high adaptive capacity (Chapter 18 of IPCC, 2001b), then the ability to adapt is itself a measure of whether any particular climate stimulus is "dangerous". The capacity to adapt is enhanced by foresight of upcoming changes and reduced when changes are abrupt, large and/or relatively unforeseen. Thus, abrupt changes are likely to be more dangerous than changes that are more slowly evolving and better foreseen.

Comparing our results to those reported in the IPCC TAR by the EMF models introduced previously (IPCC, 2001c) accentuates the importance of considering abrupt non-linearities. Building on our results, a THC collapse can occur even when substantial mitigation measures are instituted, if these measures are insufficient to prevent crossing a threshold in the physical model in which abrupt non-linear behaviors are triggered. Moreover, only when the potential damages of an abrupt change are endogenized into the IAM is it likely that mitigation measures will increase sufficiently to prevent a collapse. Therefore, following a path with little near-term abatement until after uncertainty about the occurrence of large damages is resolved, as suggested by the EMF models, could make it impossible to prevent those damages from occurring once they are identified. Moreover, the admirable search for "robust strategies" based on acting and learning over time rather than optimization with perfect foresight (e.g. Lempert and Schlesinger, 2000) also may not be able to prevent abrupt events if the formulations in the robust strategies models do not explicitly account for threshold-crossing possibilities.

Research suggests a THC collapse could be effectively irreversible on civilization time scales (Rahmstorf, 1999). Subsequently, any THC collapse would persist long after natural sinks (or deliberate sequestration activities as well) remove anthropogenic greenhouse gases from the atmosphere (Rahmstorf and Ganopolski, 1999), leaving Europe considerably cooler (by as much as 10°C) than under present conditions. Under such conditions the sustainability of European sector economic activities and natural amenities could be radically different than during the enhanced greenhouse gas era anticipated for the next several centuries in most IPCC scenarios — for example, the six illustrative SRES scenarios of (IPCC, 2000). Society 400–500 years in the future would likely have to live with the consequences of decisions made now if the decisions cause a THC collapse. The ethical legitimacy of discounting to present value at some historical rate of growth of the economy to calculate an "optimal" path over a millennium in the face of such dramatic and distant possibilities for irreversible legacies should create a wider debate, but one beyond the scope of this investigation. Our purpose is simply to reiterate that these issues should not be left out of the debate.

Therefore, to be fully responsive to the UNFCCC framework goal to prevent "dangerous" anthropogenic climate change, we believe that the analytic tools that inform the climate policy debate must be continuously refined by incorporating a wide range of plausible climatic effects, impacts and mitigation assumptions (including potential abrupt, non-linear phenomena in both climate effects and impacts). This would encourage policy makers to use these results not as "optimal" recommendations, but rather in a risk management framework, where the models present the logical consequences of a wide range of explicit assumptions and the intellectual debate proceeds over the likelihood of the assumptions, what values to put on various risks and to whom the costs and benefits might accrue (e.g. see the discussion of this framework in Chapter 1 of IPCC (2001b)). In the meantime, while the scientific community develops and tests such complex integrated assessment modeling tools (see Appendix B), it would seem wise for the policy community to conceive of most important outcomes via wide ranges of possibilities, or, when feasible, as subjective probability distributions that capture the many uncertainties in nearly all phases of IAM analysis.

Acknowledgements

The authors would like to thank William Nordhaus, Michael Grubb, Billy Pizer, Christian Azar, Klaus Keller, and Paul Baer for their suggestions. M.D. Mastrandrea gratefully acknowledges support from the Global Change Education Program of the US Department of Energy, the Institute for International Studies Program in Science, Technology, and Policy at Stanford University and the Winslow Foundation. S.H. Schneider acknowledges partial support from the Winslow Foundation.

Appendix A

Appendix A presents further technical details of the models and discounting used for this paper.

A.1. DICE and E-DICE

The DICE climate damage function, $D(t)$, measured in percentage loss of GWP, is of the form

$$D(t) = a\Delta T(t)^b$$

Here $\Delta T(t)$ is the rise in globally and seasonally-averaged surface temperature in each time period, and a and b the constants that define the magnitude of damages. Nordhaus first estimated the damage from a CO_2 doubling (in his calculations equivalent to a 3°C warming) to be 1.33% GWP (Nordhaus, 1992). Additionally, he argued that damage will increase sharply as temperature increases, — thus, he uses a quadratic function in which $b = 2$ and a is chosen to have $D = 1.33\%$ loss of GWP for a 3°C warming. Incorporating THC damages requires modification of the damage function to reflect the additional and abruptly increasing potential damages due to THC changes. Currently, there are no studies we are aware of that perform a mechanistic "bottom-up" analysis of how a given decrease in THC might affect fisheries, forests, agriculture, wildlife or other sectors in various parts of the world. Thus, while the scientific community waits for such research to be performed, arbitrary, but we believe plausible, assumptions allow the damage function to be modified to deal with abrupt non-linear changes. E-DICE augments the exponent

$$D(t) = a\Delta T(t)^{2+\varepsilon} \tag{A.1}$$

The added term ϵ increases the exponent and creates a more non-linear damage function.

A.2. Simple climate demonstrator (SCD)

As found in more complex models, SCD exhibits two stable states for THC overturning. One state has the baseline overturning circulation of about 20 Sverdrups. The second state has no overturning. Lowering the density of the water in the northern upper ocean box sufficiently due to climate change can trigger a jump from the overturning to the no-overturning state (Schneider and Thompson, 2000) [4]. SCD, like other

[4] Density lowers by increasing either the temperature or the amount of freshwater injected, likely responses to increasing CO_2, and movement from the no-overturning collapsed state back to baseline circulation requires a large decrease in global temperature or a large increase in salinity — a hysteresis loop (Rahmstorf, 1999).

climate models, produces a temporary THC decline and recovery over centuries or a permanent collapse. The rate of increase of CO_2, not just the absolute amount, can influence thermohaline collapse (Stocker and Schmittner, 1997). Rate matters since the northern ocean can rid itself of lower density surface water by mixing, thus, effectively diluting the perturbation; but such mixing takes time. Thus, a sudden disturbance will have more impact than a more slowly building disturbance, even if both disturbances eventually represent the same cumulative amount of fresh water injection. Such path dependence helps to create abrupt non-linear behavior.

A.3. E-DICE/SCD

An E-DICE/SCD run consists of the following steps. First, a run of the standard DICE model ($\varepsilon = 0$) generates an initial optimal carbon tax projection [5]. From this, a forecast of atmospheric CO_2 concentrations is obtained and fed into the SCD model. The initial SCD model run, thus calculates a new climate response — this time including the THC — to the input of exogenous atmospheric CO_2 concentrations from the initial DICE run. Resulting changes in THC are then used to create an enhanced damage function with a positive ε. An E-DICE (DICE with enhanced damage function (1)) run then determines a new optimal projection with lowered CO_2, and the updated concentration profile is again fed into SCD, changing the THC overturning response. This interchange of projected variables between the two models is reiterated until the change in ε between iterations is less than 0.0001. We observe excellent convergence for a wide range of parameter values, and we believe our solutions found by iteration are, qualitatively at least, a reasonable representation of what would be obtained if SCD were fully endogenized into E-DICE [6].

To account for the uncertainties in both the direct impacts of climate change and the ways in which diverse market and non-market impacts are evaluated and aggregated, we choose a wide range of possible values for the *equivalent* loss of gross world product associated with THC collapse: 1, 5, 10, and 25% loss of GWP [7]. These enhanced damages are added to the damages otherwise calculated by DICE, and ε is adjusted to produce damages at the end of the run equal to the original DICE damages plus the enhanced incremental damages from THC decline times the fraction of THC decline relative to a full collapse (i.e. a full collapse means full enhanced incremental damages, 50% THC reduction implies half enhanced damages, etc.). A 25% GWP loss is equivalent to a world depression like the Great Depression (Nordhaus, 1994), which might have a nontrivial likelihood of occurring if a catastrophic event such as a full THC collapse were to take place and impacts in Europe were to have broader geopolitical implications. Furthermore, in the DICE formulation economic agents have perfect foresight of the evolution of damages. If such abrupt changes were true surprises, then enhanced damages could be quite significant. There is

[5] Optimal carbon taxes in the DICE model are the ratio of the shadow price of consumption (equivalent to the change in the DICE objective function from an additional unit of consumption) and the shadow price of carbon emissions (equivalent to the increase in utility from an additional unit of emissions).

[6] The theoretical possibility remains that other solutions exist that are not identified by this technique (e.g. a consumption profile possessing both local and global utility maxima). Further research, such as full endogenization of SCD into E-DICE, should explore whether such alternate optima exist and whether they affect conclusions.

[7] The conventional measure of value in IAMs is a monetary “numeraire” (i.e. US\$/t C emitted). Other numeraires are also possible, such as human lives lost per tonne of C. Schneider et al. (2000), for example, have listed five numeraires or metrics with which the costs of climate change might be captured. Their list includes monetary losses, loss of life, changes in the quality of life (including a need to migrate, conflict over resources, cultural diversity, loss of cultural heritage sites, etc.), species or biodiversity loss, and distributional equity alterations.

also evidence that even a weakening of THC could have significant deleterious climatic effects. In past climate history, a substantial slowdown, not a shutdown of THC may have caused the Younger Dryas abrupt cooling (Manabe and Stouffer, 1999). Therefore, the range of THC damages are parameterized in terms of damages from both weakening and total shutdown. Other functions could be easily tested in future applications of this IAM. We do not claim to know which particular damage enhancement is more probable, but strongly suspect the highest and lowest estimates are least probable.

A.4. Discounting

The DICE model uses a pure rate of time preference (PRTP) equal to 3% per year so as to obtain an effective discount rate equal to 6% per year (Toth, 1995). As explained by Toth, the real discount rate r^* is derived from three factors — the pure rate of social time preference (a), the elasticity of the marginal utility of consumption (j), and the growth in consumption (f) — by the expression $r^* = a + jf$. In the DICE model, the pure rate of social time preference is 3%, the growth of consumption is 3%, and the elasticity is 1, which follows from the logarithmic utility function used in the DICE model. Therefore, r^* is 6% [8].

The E-DICE model employs a range of PRTPs: 0, 1.5, 3% (original DICE default), and 4%. Proponents of strongly valuing intergenerational equity often argue on normative grounds that the pure rate of time preference should be zero, because the welfare of future generations should not count less simply because they exist in the future. (Azar and Sterner, 1996), for example, show that the marginal cost of climate change increases from US$ 5/t C (Nordhaus' estimate) to US$ 260/t C when the pure rate of time preference is lowered from 3% per year to zero. The E-DICE model also considers hyperbolic discounting. Heal suggests the following function. The discount factor $q(t)$ is

$$q(t) = t^K$$

K is a negative constant. In our model, K is -0.9873, from Heal's proposal of a discount rate of 10% for the near term that dips to 5% in 50 years in the future and 2% by 100 years. It should be noted that such a formulation makes the optimal policy sensitive to when the optimization is performed — optimal policy today is not the same as optimal policy in 100 years, assuming t is measured relative to the current period. This is referred to as time inconsistency (Cropper et al., 1994). It should also be noted that Heal suggested this formulation as a discount factor on income, while in the DICE framework it becomes a discount factor on the utility of income. We primarily include hyperbolic discounting to illustrate the sensitivity of our results to alternative discounting formulations that are proposed in the literature.

Appendix B. Model improvements needed

We stress two relevant areas where this research can be enhanced. The first is an extensive analysis of the thermohaline overturning and the possible downstream effects of changes in that overturning. These changes must be quantified to allow more accurate estimation of potential economic damages due to THC effects. There are many possible sectors of the economy that could be affected by THC changes. Changes in ocean circulation patterns would directly affect fisheries, and abrupt climate changes may be detrimental

[8] For a robust discussion of discounting, see IPCC (1996).

to agriculture — but what is “abrupt” is itself debatable since a change of THC magnitude over 100 years is very abrupt from the perspective of some ecosystem migration rates but may be relatively slow from the point of view of adaptation of agricultural infrastructure. Natural ecosystems will be affected by changing climate, altering and possibly eliminating some ecosystem services and threatening biodiversity (Root and Schneider, 1995; DeCanio et al., 2000). Ocean circulation changes may also decrease the capability of the ocean to uptake carbon, a positive feedback to the increase in atmospheric CO_2 that caused the circulation changes. Further understanding of the possible changes to climate and ocean circulation due to THC changes will help to reduce the very large uncertainties now inherent in damage estimates.

Second, our coupled model utilizes simple sub-models comparable in complexity to many other IAM efforts. This analysis does not debate the legitimacy of the use of simple models, nor the validity of the cost–benefit framework as applied to climate change policy. For example, our damage estimations are again similar in complexity to the simple models used, representing aggregations over all numeraires (Schneider et al., 2000). Application and extension of the cost–benefit paradigm certainly focuses attention on cost measures that are denominated in currency, but practitioners have been criticized on the grounds that these measures inadequately recognize non-market costs (or even the monetized costs of loss of ecosystem services). Furthermore, the model does not incorporate endogenous effects such as the incentive that a carbon tax offers to producers of non-carbon based energy systems which might induce technological changes at a faster rate than if there were no carbon policies. Such “induced technological change” (Grubb et al., 1995; Goulder and Schneider, 1999) could act to decrease mitigation costs in the future.

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