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ABSTRACT

Climate modelers have recognized the possibility of abrupt climate changes caused by a reorganization of the North Atlantic's current pattern (technically known as a thermohaline circulation collapse). This circulation system now warms north-western Europe and transports carbon dioxide to the deep oceans. The posited collapse of this system could produce severe cooling in north-western Europe, even when general global warming is in progress. In this paper we use a simple integrated assessment model to investigate the optimal policy response to this risk. Adding the constraint of avoiding a thermohaline circulation collapse would significantly reduce the allowable greenhouse gas emissions in the long run along an optimal path. Our analysis implies that relatively small damages associated with a collapse (less than 1 % of gross world product) would justify a considerable reduction of future carbon dioxide emissions.

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Introduction

The UN framework convention on climate change [*UNFCCC*, 1992] requires a stabilization of greenhouse gases at a level that will "prevent dangerous anthropogenic interference with the climate system". Which stabilization level for greenhouse gases would avoid dangerous interference and whether this risk justifies costly reductions in greenhouse gas emissions is controversial. The policies derived from optimal growth analyses of climate change typically suggest relatively small reductions in carbon emissions [*Nordhaus*, 1992, *Nordhaus*, 1997, *Tol*, 1997]. Such policies may result in a global mean atmospheric warming in excess of 6 ^{o}C within 500 years [*Nordhaus*, 1997], a temperature increase comparable to the warming since the last Ice Age [*Lorius et al.*, 1990].

In contrast to these conclusions, several authors have suggested that the dangerous level of interference may start when anthropogenic climate change exceeds substantially the range of relatively recent (e.g., over the last millennium) natural variations [*WBGU*, 1995, *Azar and Rodhe*, 1997]. This more precautionary view — partially motivated by the possibility of catastrophic and/or irreversible climate events caused by anthropogenic greenhouse gas emissions — implies that the greenhouse gas emissions should be limited to considerably lower levels than suggested by many optimal growth analyses. One might ask whether the precautionary view adopts a value framework different from that of the optimal growth analysis or rather differently evaluates the possibility of negative climate effects.

It is important to note that "optimal" refers here to a policy that maximizes a function of per capita consumption within an economic growth model, which depends on a variety of simplifying assumptions and value judgments. It is possible that the omission of high damage and/or irreversible events in previous optimal growth studies may explain most of the discrepancies between the optimal growth studies and the more precautionary view. Here we investigate whether a potential change in the ocean circulation system may constitute such an event and what an optimal growth framework prescribes as the policy response to this risk.

Coupled ocean-atmosphere models indicate that a long lasting change in the ocean circulation (technically known as a thermohaline circulation collapse) is a plausible response to increasing greenhouse gas concentrations [*Manabe and Stouffer*, 1993, *Wood et al.*, 1999, *Schmittner and Stocker*, 1999, *Rahmstorf and Ganopolski*, 1999]. An important link between atmospheric greenhouse gas concentrations and the ocean circulation is the density of the surface waters in regions like the North Atlantic where ocean deep waters are formed. Warm and salty oceanic surface waters flowing towards the North Atlantic cool by heat loss to the overlying atmosphere. This cooling acts to increase the densities of the surface waters. This effect of the cooling is, however, counteracted by the net freshwater input into the North Atlantic [*Baumgartner and Reichel*, 1975], which acts to decrease the salinities (and in turn the densities) of the surface waters. Surface waters reaching a density sufficiently higher than the underlying waters sink and form deep-waters. Because this density-driven ocean circulation is governed by changes in temperature and salt content, it is referred to as the “thermohaline circulation”.

Both concentration and rate of increase of atmospheric greenhouse gases influence the intensity of the thermohaline circulation [*Stocker and Schmittner*, 1997]. The concentration of greenhouse gases is important because higher greenhouse gas concentrations cause higher atmospheric temperatures. A warmer atmosphere acts (i) to increase the temperature of ocean surface waters, and (ii) to increase the freshwater input into the North-Atlantic (via an increase in the atmospheric water vapor transport) [*Schmittner and Stocker*, 1999]. Both processes act to decrease the surface water densities and the deep-water formation rates. One reason why the rate of increase of greenhouse gas concentrations affects the thermohaline circulation is the limited oceanic heat transport to the deep-waters [*Schmittner and Stocker*, 1999, *Stocker*, 1999]. Higher rates of increase of greenhouse gas concentrations result in larger heat fluxes into the surface waters and the oceanic heat transport to the deep-waters becomes relatively less important. As a result, the surface waters heat up more and the deep-water formation rates are lower compared to situations with lower rates of increase of greenhouse gas concentrations. These mechanisms are detailed, for example, in *Schmittner and Stocker* [1999], and *Stouffer and Manabe* [1999]. Note, that the projected thermohaline circulation response to the greenhouse gas forcing is uncertain due to model uncertainties.

The consequences of such a thermohaline circulation collapse might include decreased oceanic carbon uptake, decreased heat and water vapor transport to Europe with concomitant climate modifications, decreased fishery and agricultural yields, increased warming in the Southern Hemisphere, as well as damages to natural ecosystems [*Rahmstorf*, 1997, *Broecker*, 1997, *Rahmstorf and Ganopolski*, 1999, *Schmittner and Stocker*, 1999]. Previous studies have considered economically optimal pathways for carbon dioxide (CO_2) stabilization (e.g., *Richels and Edmonds* [1995], *Wigley et al.* [1996]), rate-dependent damages of global warming (e.g., *Peck and Teisberg* [1994], *Toth et al.* [1997]), or the possibility of abrupt climate changes (e.g., *Lempert et al.* [1994]). However, the specific damage and the dependency of the thermohaline circulation collapse on the rate of greenhouse gas increase have not been analyzed in an optimal growth framework so far.

We use a simple integrated assessment model that incorporates published simulation results of an ocean circulation model. We derive, for a range of climate sensitivities, the optimal investment and emissions paths in our model with the added constraint to preserve the thermohaline circulation. We compare the additional costs of maintaining the thermohaline circulation with estimates of the specific damages caused by a thermohaline circulation collapse and evaluate the trade-offs the equivalent carbon dioxide concentration ($\mathrm{P}_{CO_{2,e}}$) at various levels. Finally, we argue that preserving the thermohaline circulation may be justified in a benefit-cost sense for lower bound estimates of the specific damages and conventional values of the pure rate of social time preference.

Choice of integrated assessment model

The United Nations Framework Convention on Climate Change calls for a cost-effective policy to stabilize CO_2 concentrations at levels that would ”prevent dangerous anthropogenic interference with the climate system.” Causing a breakdown of the ocean circulation system might well deserve the label ”dangerous anthropogenic interference with the climate system”. A policy that maximizes a weighted sum of the welfare of the different generations (subject to the constraint to avoid such a breakdown) might well be described as cost-effective in avoiding this specific anthropogenic interference. This method is similar to the climate targeting approaches discussed, for example, by *Nordhaus* [1997], or *Ha-Duong et al.* [1997]. We refine a basic integrated assessment model to include specific consideration of the thermohaline circulation. In particular, we add the preservation of the thermohaline circulation as a constraint to an optimal growth model. This results in an optimal emissions path which conserves the thermohaline circulation and specifies a necessary stabilization level for greenhouse gases. One benefit of this method is that the choice of greenhouse gas stabilization level is motivated by a threshold response in the natural system. This choice is likely more efficient in the sense of an optimal growth model than an arbitrary choice of greenhouse gas stabilization level. This approach allows us additionally to consider the economic trade-offs associated with accepting the natural threshold.

We defer to the DICE model [*Nordhaus*, 1994] as the basis for our study. DICE has several advantages: (i) the model results are generally consistent with more complex integrated assessment models [*Dowlatabadi*, 1995, *Weyant et al.*, 1996]; (ii) it is relatively simple and transparent such that the effects of the model refinements are easily identified; (iii) the DICE model has been used in a large number of sensitivity studies (for example, with respect to the representation of the carbon cycle [*Kaufmann*, 1997, *Schulz and Kasting*, 1997]), so our results can be compared relatively easily to those of other studies; and (iv) the model identifies the optimal policy, given a set of explicit value judgments.

The model-derived policy recommendations should, however, be interpreted with caution. The DICE model is nothing more than a tool to draw consistent conclusions from a set of assumptions. The assumptions include more or less radically simplified descriptions of the natural system (e.g., the carbon cycle) and the economic system (e.g., there is just one consumption good and only one kind of representative consumer at each point in time), and the objective of the policy is to maximize a weighted sum of utilities. The model can of course not predict misfortunes not yet identified that would render its application inappropriate. The function of such models, rather, is to allow us to work out the implications of stylized interactions between natural and economic systems and simple but explicit specification of value judgments.

THE DICE MODEL OF ECONOMICALLY OPTIMAL CLIMATE CHANGE POLICY

The DICE model is a dynamic model of optimal economical growth that incorporates a simple feedback mechanism between economic activities and climate change. Central to the model is a criterion for ranking distributions of social well-being over time, which means in effect across generations. Well-being is represented in the model by a flow of aggregate utility U, defined as the product of the logarithm of per capita consumption per year c, and the exogenously given population L:

$$U(t) = L(t)\ \ln\ c(t). \tag{1}$$

The choice among alternative paths of utility thus defined is determined by the maximization of a discounted sum (U^*):

$$U^* \ = \ \sum_{t=t_o}^{t^*} U(t)\,(1+\rho)^{-t}, \tag{2}$$

which is calculated by applying a "pure rate of social time preference" ρ to the flow of utility at time t from some starting point t_o to an appropriate time horizon t^*. It is important to note that discounting in this objective function applies to utility, not money values, and serves the function of specifying a value judgment about the distribution of utility across generations. A positive pure rate of social time preference implies that future utility is discounted relative to present utility. Because reducing CO_2 emissions causes present costs but avoids mostly future climate damages, the optimal CO_2 emissions derived from a discounted utilitarian approach (equation 2) are sensitive to the pure rate of social time preference (e.g., *Manne* [1995]). We will return later to a discussion of this important, and controversial, point. Note also, that this single-actor model neglects intragenerational distribution effects like an asymmetric distribution of benefits and costs between the northern and southern hemisphere (e.g., *Dowlatabadi and Lave* [1993]). Last but not least, it is important to stress that the underlying benefit-cost reasoning likely misrepresents non-market values, thus potentially resulting in too lenient abatement measures (for a further discussion see, for example, *Nordhaus* [1994], or *Bradford* [1999]).

Feasible consumption paths depend on the economy's output. The gross world product Q is assumed to be determined by a Cobb-Douglas production function of capital K and population with the parameters: level of technology A, output scaling factor Ω, and elasticity of output γ with respect to capital:

$$Q(t) = \Omega(t)\ A(t)\ K(t)^{\gamma}\ L(t)^{1-\gamma}. \tag{3}$$

Gross world product is gross with respect to depreciation of capital but net with respect to abatement costs and climate related damages. The effect of abatement costs and climate related damages on output is incorporated into the model via the output scaling factor (discussed below). Total consumption C is the difference between gross world product and gross investment I:

$$C(t) = Q(t) - I(t). \tag{4}$$

To simulate the feedback between economic activities and climate change, the DICE model assumes that carbon emissions, E, during one year into the atmosphere are proportional to the gross world product, with the proportionality determined by the time-varying exogenous carbon intensity of production σ and the policy choice of the level of carbon emissions abatement μ:

$$E(t) = [1 - \mu(t)]\ \sigma(t)\ Q(t). \tag{5}$$

A constant fraction β of carbon emissions is added to the atmospheric carbon stock M (the rest is assumed to be absorbed by carbon sinks). A portion δ_M of the atmospheric carbon in excess of the preindustrial stock of 590 Gt is exported during each time step to the deep ocean so that the atmospheric stock evolves according to

$$\begin{aligned} M(t) &= 590 + \beta\, E(t-1) \\ &+ (1-\delta_M)[M(t-1) - 590]. \end{aligned} \tag{6}$$

Atmospheric carbon dioxide acts as a greenhouse gas, causing a change F in the radiative forcing from the preindustrial level according to:

$$F(t) = 4.1 \frac{\ln(M(t)/590)}{\ln(2)} + O(t), \tag{7}$$

where O represents the (exogenously determined) change in forcing due to other greenhouse gases like methane or CFCs. An increase in radiative forcing causes an increase in global mean atmospheric temperature T from its preindustrial level, which is modeled using a simple atmosphere-ocean climate model according to:

$$\begin{aligned} T(t) &= T(t-1) + (1/R_1)[F(t) - \lambda T(t-1) \\ &\quad - (R_2/\tau_{12})(T(t-1) - T^*(t-1))]. \end{aligned} \tag{8}$$

In this equation R_1 and R_2 denote the thermal capacity of the oceanic mixed layer and the deep ocean, respectively, λ is the climate feedback parameter, τ_{12} is the transfer rate from the oceanic mixed layer to the deep ocean, and T^* is the deviation of the deep-ocean temperature from the preindustrial level approximated by:

$$\begin{aligned} T^*(t) &= T^*(t-1) + (1/R_2)[(R_2/\tau_{12}) \\ &\quad (T(t-1) - T^*(t-1))]. \end{aligned} \tag{9}$$

A key property of the climate system is the ”climate sensitivity,” which is the hypothetical increase in equilibrium temperature for a doubling of atmospheric CO_2, placed by the IPCC between 1.5

and 4.5 ^{o}C. In the DICE model, the climate sensitivity is inversely related to the parameter λ. Specifically, the modeled climate sensitivity is given by the ratio of the increase in radiative forcing for a doubling of atmospheric CO_2 (equal to 4.1, equation 7) to λ.

The damages relative to gross world product (D) are assumed to be a function of the deviation of the global average temperature from it's preindustrial value:

$$D(t) = \theta_1 \, T(t)^{\theta_2}, \tag{10}$$

where θ_1 and θ_2 are model parameters. The cost of CO_2 emissions abatement TC, measured as a fraction of gross world product, is given by:

$$TC(t) = b_1 \, \mu(t)^{b_2}, \tag{11}$$

where b_1 and b_2 are model parameters. Given the calculated abatement costs and climate damages, global output is rescaled with the scaling factor Ω:

$$\Omega(t) = [1 - TC(t)]/(1 + D(t)). \tag{12}$$

This scaling factor approximates the effects of small damages reasonably well, compared to the explicit accounting, which would imply $\Omega(t) = 1 - TC(t) - D(t)$.

In the business-as-usual (BAU) scenario of this model, carbon emissions are unabated. Discounted utility is maximized, but only through the choice of an optimal investment path over time. The BAU scenario is then compared with the results of optimally setting both investment and emission abatement rates over time.

Model parameter values are used from the original DICE model, with one exception. We adopt a climate sensitivity of 3.5 ^{o}C instead of the previously used 2.9 ^{o}C as our standard value. Based on the analysis of climate data and the expert opinion of the IPCC, *Tol and de Vos* [1998] estimate the values of the median and the standard deviation of the climate sensitivity as 3.6 and 1.1 ^{o}C.

REPRESENTATION OF THE NORTH ATLANTIC THERMOHALINE CIRCULATION COLLAPSE

To represent the sensitivity of the thermohaline circulation to changes in radiative forcing (which depends on the atmospheric CO_2 concentration as well as the forcing by other greenhouse gases (eq. 7)), we express the radiative forcing term in the DICE model as an equivalent carbon dioxide level ($P_{CO_{2,e}}$), according to:

$$P_{CO_{2,e}} = 280 \ \exp\left(\frac{F(t)\ \ln\ 2}{4.1}\right). \tag{13}$$

The calculated $P_{CO_{2,e}}$ levels are compared with the critical $P_{CO_{2,e}}$ level beyond which the thermohaline circulation is supposed to collapse. This critical level is calculated by a polynomial fit to the model results of *Stocker and Schmittner* [1997] (Figure 1). At a rate of $P_{CO_{2,e}}$ increase of 0.68 % a^{-1} (approximately the present rate in the DICE model) and a climate sensitivity of 3.5 ^{o}C the critical $P_{CO_{2,e}}$ is 776 ppmV (denoted by the star in Figure 1). A climate sensitivity of 4 ^{o}C results in a lower critical $P_{CO_{2,e}}$ of 665 ppmV. The $P_{CO_{2,e}}$ stabilization level necessary to maintain the thermohaline circulation is very sensitive to the climate sensitivity parameter, which is, however, only imperfectly known. The uncertainty in the climate sensitivity, which has been characterized by *Tol and de Vos* [1998] as having a standard deviation of 1.1 ^{o}C, implies considerable variations in the critical $P_{CO_{2,e}}$ levels.

SOLUTION METHOD

To calculate the optimal emissions path that preserves the thermohaline circulation, we constrain the DICE model to keep the $P_{CO_{2,e}}$ levels below the critical $P_{CO_{2,e}}$ level. We approximate the rate of increase in $P_{CO_{2,e}}$ by the average rate of increase for all time periods before the stabilization occurred. Different values for the climate sensitivity are used in the sensitivity analysis to estimate the economically optimal policy with and without the thermohaline circulation constraint.

The constrained optimization problem is solved for the time period between 1965 and 2295,

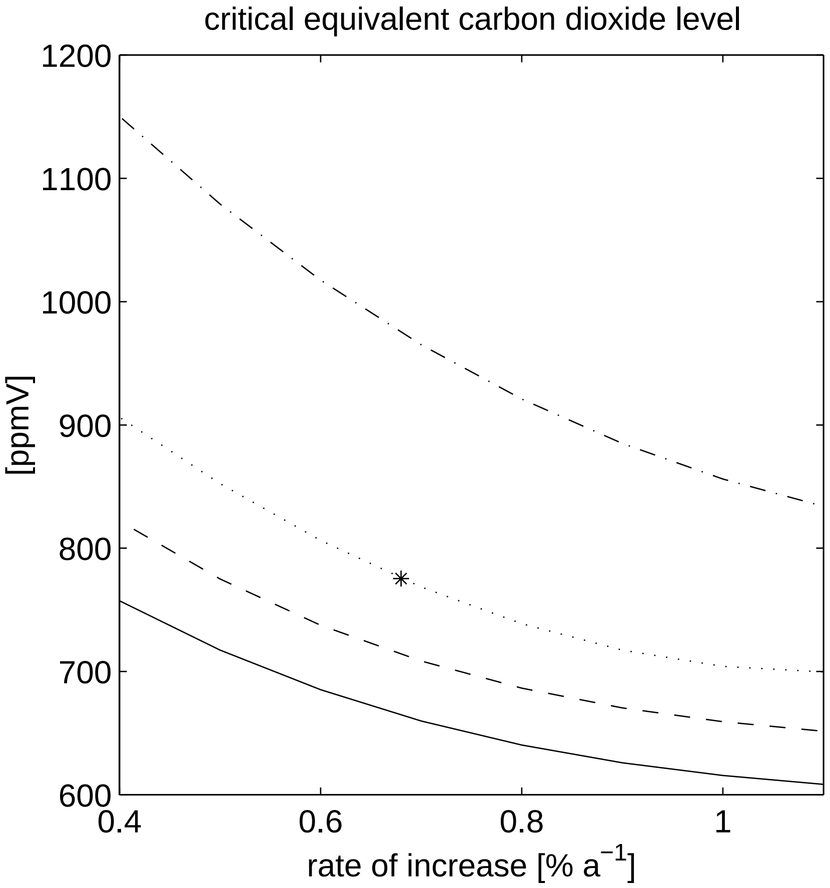

FIGURE 1: Critical atmospheric $P_{CO_{2,e}}$ concentrations as a function of the rate of $P_{CO_{2,e}}$ increase plotted for different values of climate sensitivity. Shown are polynomial fits to the model results reported by *Stocker and Schmittner* [1997]. The lines represent climate sensitivities of 4 ^{o}C (full line), 3.75 ^{o}C (dashed line), 3.5 ^{o}C (dotted line), and 3 ^{o}C (dash-dotted line). The star represents the critical atmospheric $P_{CO_{2,e}}$ level for the approximate present rate of $P_{CO_{2,e}}$ increase in the DICE model and the adopted climate sensitivity of 3.5 ^{o}C.

using the AMPL programming language [*Fourer et al.*, 1993] and the nonlinear solver LOQO3.11 [*Vanderbei*, 1997] (kindly provided by R. Vanderbei). We used simulation results until the year 2765 to set the transversality conditions on the optimized run. Varying the terminal conditions has negligible effects on the reported results. Note that a significant social rate of time preference is needed for this approximation to work (for a discussion of this technical point see, for example, *Schultz* [1996]). Our implementation of the DICE model — with the original model structure and parameters — tracks closely the previously reported results of the original DICE model [*Nordhaus*, 1994] (for example, the optimal carbon abatement in 2005 is 9.6 % in both model implementations). In the following discussion we refer to the “DICE model” as the above defined model structure at various climate sensitivities (with or without the thermohaline circulation constraint).

Results and Discussion

OPTIMAL CARBON DIOXIDE TRAJECTORIES

At a climate sensitivity of 3.5 ^{o}C, the optimal P$_{CO_{2,e}}$ levels in the unconstrained DICE model (Figure 2, crosses) are considerably higher than the optimal P$_{CO_{2,e}}$ levels that maintain the thermohaline circulation (Figure 2, dotted line), which stabilize around 840 ppmV. Note that the slight

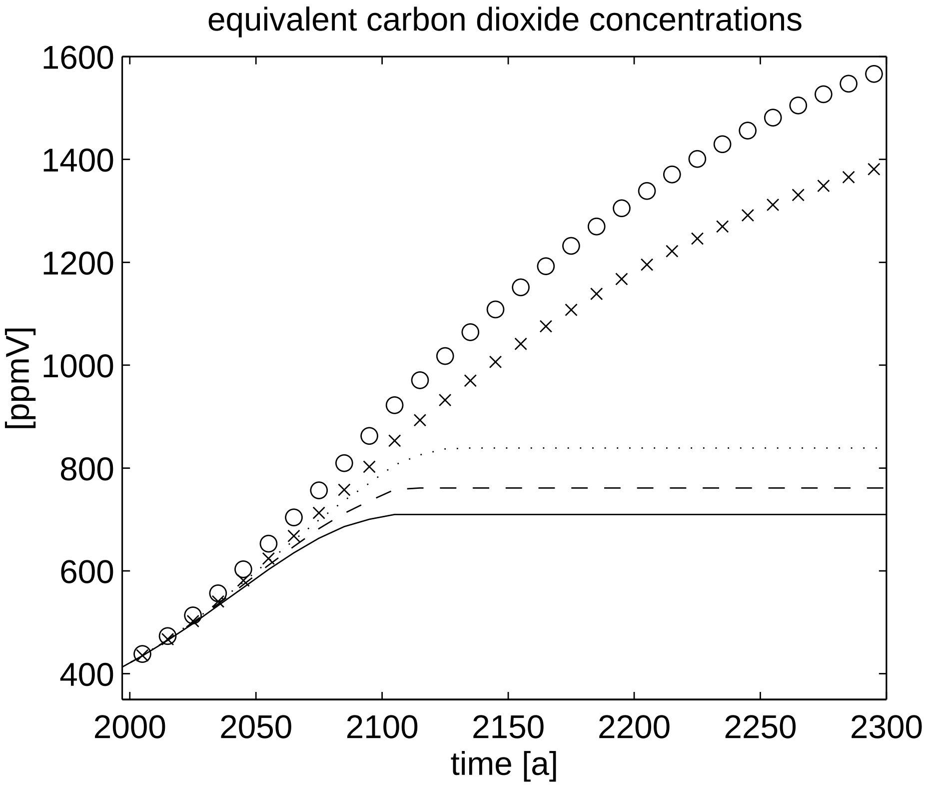

FIGURE 2: Model derived P$_{CO_{2,e}}$ trajectories for different policies and climate sensitivities. Shown are the optimal trajectory according to our implementation of the DICE model that results in a thermohaline circulation collapse (i.e., unconstrained, crosses), and the optimal trajectory that maintains the thermohaline circulation (i.e., constrained, dotted line) for a climate sensitivity of 3.5 ^{o}C. Given for comparison are also the optimal P$_{CO_{2,e}}$ trajectories to maintain the thermohaline circulation at climate sensitivities of 4 ^{o}C (full line) and 3.75 ^{o}C (dashed line). The business-as-usual scenario for a climate sensitivity of 3.5 ^{o}C is represented by the circles.

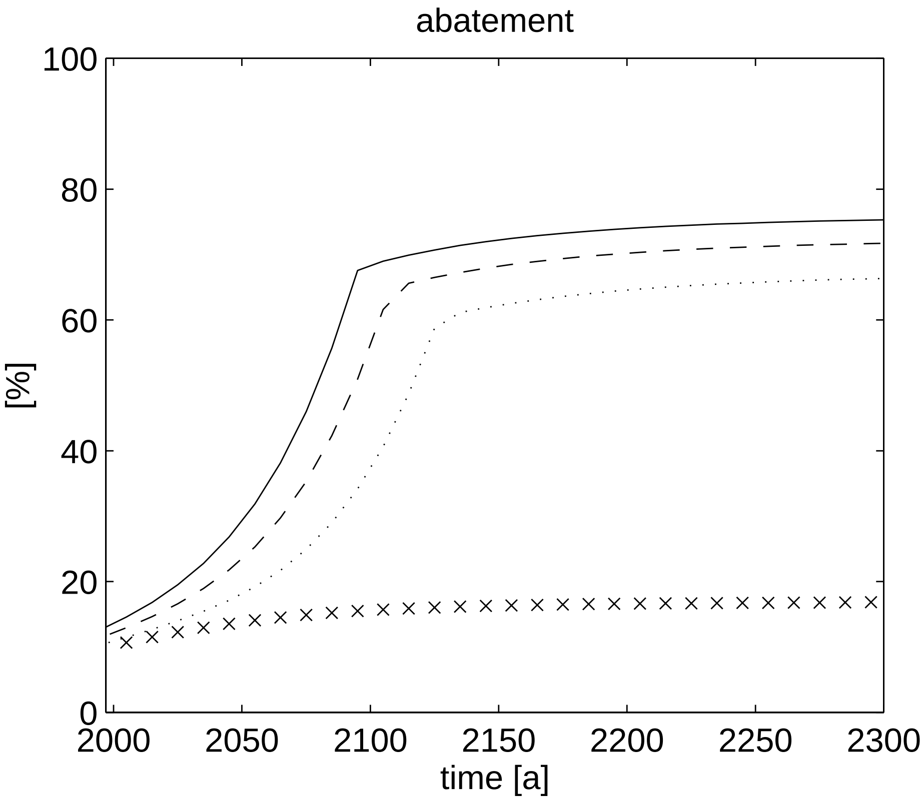

FIGURE 3: Necessary reductions in carbon emissions relative to the business as usual scenario to stabilize $P_{CO_{2,e}}$ at the levels shown in Figure 2. Symbols are the same as in Figure 2.

increase in the stabilization $P_{CO_{2,e}}$ relative to the estimate obtained at the present conditions (star in Figure 1) is caused by the slight decrease in the average $P_{CO_{2,e}}$ growth rate between the present and the time of $P_{CO_{2,e}}$ stabilization. Using a higher climate sensitivity requires stabilizing $P_{CO_{2,e}}$ at earlier times and at lower levels (Figure 2, dashed and solid line, for climate sensitivities of 3.75 and 4 ^{o}C, respectively). Perhaps surprisingly, the optimal $P_{CO_{2,e}}$ trajectories in Figure 2 do not appear to diverge much from the unconstrained DICE result until the year 2050.

NECESSARY EMISSION ABATEMENTS

The optimal policy neglecting the potential thermohaline circulation collapse suggests only small emission abatements (between 10 and 20 %) for the next 300 years (Figure 3, crosses). To maintain the thermohaline circulation, anthropogenic carbon emissions have to be reduced consid-

TABLE 1: Effects of variations in climate sensitivity and consideration of the thermohaline circulation constraint on abatement in 2005 and 2035.

thermohaline circulation constraint considered?	climate sensitivity [^oC]	abatement in 2005 [%]	abatement in 2035 [%]
no	2.9	9.6	11.7
no	3.5	10.7	13.0
yes	3.0	9.8	12.0
yes	3.5	11.5	15.5
yes	3.75	13.0	18.9
yes	4.0	14.6	22.8

erably. At a climate sensitivity of 3.5 ^oC the optimal policy (Figure 3, dotted line) to preserve the thermohaline circulation requires reducing carbon emissions by 59 % in 2125, over 42 percentage points more than the policy that neglects the thermohaline constraint. Interestingly, the additional constraint of avoiding a thermohaline circulation collapse affects abatement levels in the next 40 years only marginally in this case (e.g., 15.5 % in 2035 relative to 13.0 % in the unconstrained case, Table 1). However, assuming a climate sensitivity of 4 ^oC (Figure 3, solid line) changes the picture substantially. To maintain a thermohaline circulation in this example, emissions have to be reduced by roughly 23 % in 2035 (compared to 14 % in the unconstrained case), and the emission reduction increases to roughly 70 % in 2115 (compared to 17 % in the unconstrained case). These higher emission reductions are needed because a higher climate sensitivity results in a lower $P_{CO_{2,e}}$ stabilization level that is reached earlier. To maintain the thermohaline circulation at a climate sensitivity of 4 ^oC requires a large change compared to the optimal policy suggested by the unconstrained DICE model. Note that the increase in abatement relative to the results reported by *Nordhaus* [1994] (with abatements ranging between 10 and 20 %) are predominantly caused by the consideration of the thermohaline circulation constraint and not by our change in the base-case climate sensitivity. For example, the effect of changing the climate sensitivity from the 2.9 ^{o}C estimate of *Nordhaus* [1994] to our base-case of 3.5 ^{o}C without the thermohaline circulation constraint increases the abatement by less than 2 percentage points in 2115.

Analyzing the optimal abatement measures shown in Figure 3, one could conclude that only a slight change in the near term policy (e.g., changes in abatement in 2005 of less than 4 percentage points, Table 1) is called for to reduce the risk of a thermohaline circulation collapse. It should be noted, however, that the results in Figure 3 refer to implemented abatement. The DICE model incorporates no explicit treatment of socioeconomic inertia. Several studies (e.g., *Ha-Duong et al.* [1997], *Hasselmann et al.* [1997]) have argued that a realistic representation of socioeconomic inertia would imply that abatement has to be initiated earlier. Further, estimates of the time required to put in place technology optimized for deep cuts in CO_2 emissions range around 50 years [*Ishitani and Johansson*, 1996]. So, a plan to follow the abatement path proposed by this model would almost certainly include current planning actions and increased investments into low CO_2 emitting technologies.

Note that the optimal policy in all cases suggests roughly a 10 % reduction of carbon emissions starting in 1995. The emission abatement implemented so far is close to zero and below the optimal policy suggested by the model. This situation might continue in the near future, since the Kyoto agreement imposes limits only on the Annex 1 (developed) nations.

EFFECT OF RATE DEPENDENCY ON POLICY

Because smaller rates of increase in $P_{CO_{2,e}}$ allow for higher $P_{CO_{2,e}}$ stabilization levels (Figure 1), reducing carbon emissions now constitutes an investment that pays off in an increased stabilization level for future generations. Alternatively, reducing carbon emissions could be delayed to the future, resulting, however, in a lower $P_{CO_{2,e}}$ stabilization level.

We evaluate the influence of the rate dependency on the estimated optimal near term policy by replacing the rate dependent stabilization level shown in Figure 2 (dotted line) by the same value (roughly equal to 840 ppmV) without a rate dependency. If the rate dependency of the constraint influences the estimated optimal policy for the near future, the calculated near term abatement should change. However, replacing the rate dependent constraint with a fixed P$_{CO_{2,e}}$ target results in an optimal abatement path virtually indistinguishable from the rate dependent results shown in Figure 3.

This small effect of the rate dependency on the estimated optimal policy in the near future is similar to the findings of *Peck and Teisberg* [1994], and is mainly caused in our model by the relatively low sensitivity of the critical P$_{CO_{2,e}}$ level to the average rate of P$_{CO_{2,e}}$ increase (Figure 1), and the relatively large pure rate of social time preference of 3 %. For example, perturbing the optimized P$_{CO_{2,e}}$ trajectory shown in Figure 2 (dotted line) by stabilizing P$_{CO_{2,e}}$ for one year in 1999 would reduce the average rate of P$_{CO_{2,e}}$ increase calculated over the next 130 years only marginally. This change in policy would increase the critical P$_{CO_{2,e}}$ level by roughly 2 ppmV (assuming an otherwise constant policy as shown in Figure 3 (dotted line) for a climate sensitivity of 3.5 ^{o}C). The expensive reduction today would hence influence the threshold level in 130 years only little. The resulting small increase in utility in 130 years, caused by the slightly higher allowable emissions, is furthermore reduced in significance by the application of a pure rate of social time preference of 3 % over the 130 year time period.

DOES PRESERVING THE THERMOHALINE CIRCULATION PASS A BENEFIT-COST TEST?

Our model determines the optimal policy in the same way as the original DICE model but with the additional constraint to preserve the thermohaline circulation. One may ask whether this constraint — imposed by a precautionary policy choice — might pass a benefit-cost test.

One possible approach to address this question is to amend the damage function in the unconstrained model and estimate the necessary incremental damage due to a thermohaline circulation collapse that would preserve the thermohaline circulation as an optimization result. However, this approach introduces local maxima and non-smooth gradients in the objective function which complicate the solution method considerably. To report solely the optimization results would also hide the trade-offs between costs and benefits for the different policy choices. We hence choose an alternative and more transparent method by analyzing the changes in costs and damages due to the additional constraint and weigh them by the discount rate on goods.

We calculate the time dependent discount rate on goods along the optimal path from the original DICE model. Using the original DICE model results in a high estimate of the discount rate since it neglects the thermohaline circulation constraint and uses a relatively low climate sensitivity. The discount rate can be calculated either from the marginal productivity of capital or from the path of per capita consumption. Although these two methods should — in theory — yield identical results, the numerical implementation gives slightly different numbers. We choose to calculate the discount rate from the marginal productivity of capital which yields higher estimates of the discount rates on goods than the alternative method (and as a result higher thermohaline specific damages to justify the $P_{CO_{2,e}}$ stabilization in a benefit-cost sense). Note that this approach differs from that usually applied in benefit-cost analyses, which applies a constant discount rate on goods (e.g., *Maddison* [1995]). By using the discount rate on goods representative for the optimal growth trajectory, we additionally consider effects like the decreasing rate of technological progress that cause the future discount rate on goods to decline. For example, our calculated discount rate on goods declines from 5.9 % in 1995 to 3.5 % in 2295.

To test whether a policy to preserve the thermohaline circulation passes a benefit-cost test we first calculate the present value of the additional abatement costs introduced by this constraint. We then determine the hypothetical thermohaline circulation specific damage that would result in a present value of avoided damages that balances the present value of the additional abatement costs. Finally, this hypothetical damage is compared with our independent estimate of the likely economic effects of a thermohaline circulation collapse.

Costs of maintaining an active thermohaline circulation

At a climate sensitivity of 3.5 ^{o}C, the projected total abatement costs along the optimal path subject to the thermohaline circulation constraint rise roughly from 2 billion U.S.$ per year in 1995 to 2.3 trillion U.S.$ per year in 2155 (expressed in 1989 prices) (Figure 4 A, dotted line). Compared to the policy suggested by the unconstrained DICE model (Figure 4 A, crosses), the extra costs of preserving the thermohaline circulation are negligible in the near future but very significant starting in roughly 50 to 100 years. Higher climate sensitivities result in higher abatement costs. Maintaining an active thermohaline circulation implies an extra sacrifice, which may range — depending, for example, on the climate sensitivity and the future levels of technology — between 2 and 3 % of gross world product in the long run (Figure 4 B).

Thermohaline circulation specific damages that would justify the constraint in a benefit-cost sense

The minimum level of thermohaline circulation collapse specific damages that would justify a P$_{CO_{2,e}}$ stabilization would just equate present values of the costs and benefits caused by this policy at the appropriate discount rate on goods. We assume that the thermohaline circulation specific damages are proportional to the gross world product and occur in a step function whenever P$_{CO_{2,e}}$ in the unconstrained model exceeds the calculated P$_{CO_{2,e}}$ stabilization level in the next time step. This very simplified representation of the specific damages is supposed to mimic the hysteresis response of the thermohaline circulation to the forcing [*Rahmstorf*, 1996]. Once the deep water formation rate is below a certain level, removing the forcing will not restore the full thermohaline circulation for a considerable time. By iteration we then determine the minimum level of thermohaline circulation collapse specific damages that would justify a P$_{CO_{2,e}}$ stabilization as defined above. This specific damage is estimated in our model as roughly 0.86 % of gross world product (for a climate sensitivity of 3.5 ^{o}C and based on a discounting implied by optimizing with a pure rate of social time preference of 3 %). The elements of this calculation can be illustrated by referring to Figure 5.

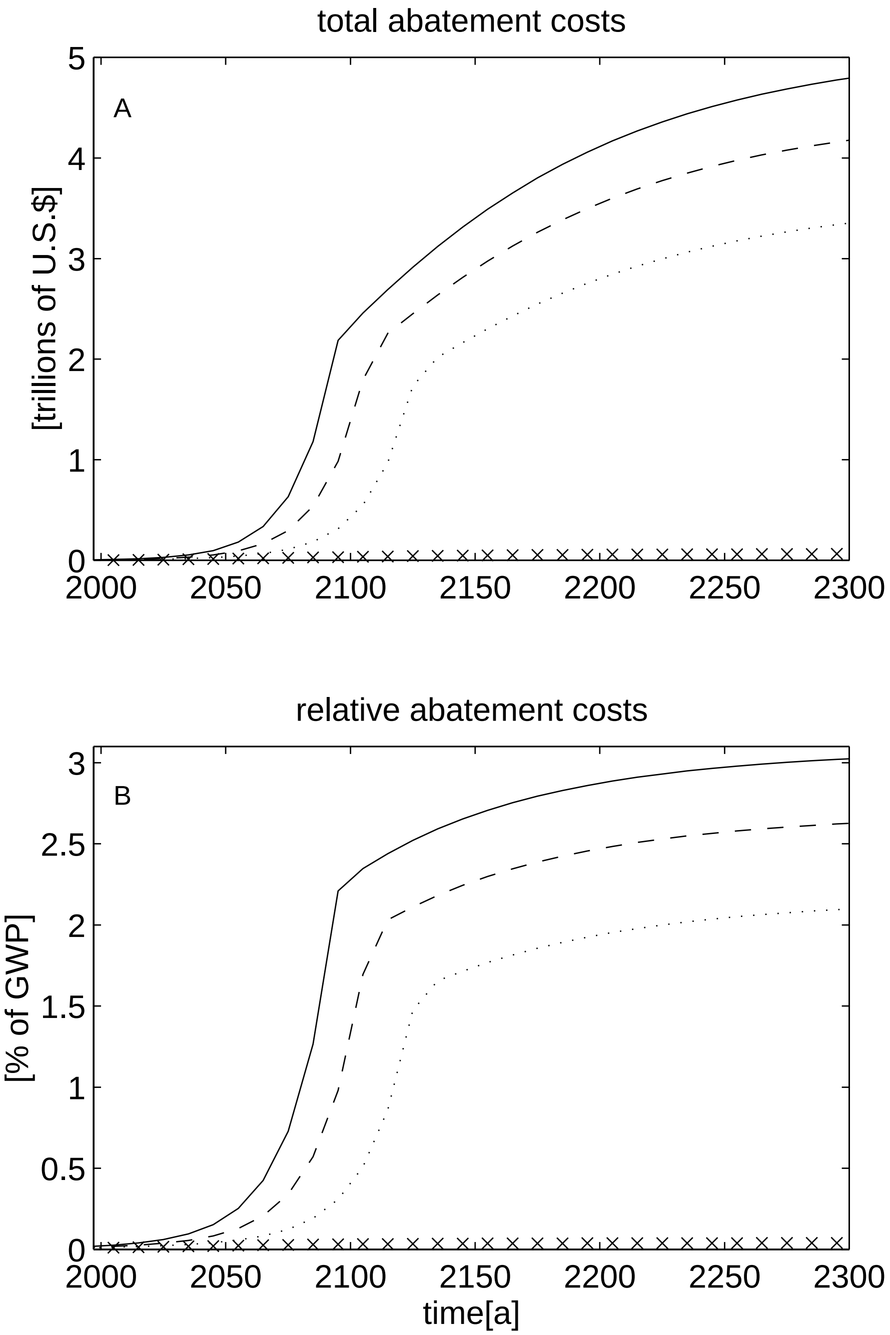

FIGURE 4: Costs of climate change abatement expressed in constant 1989 $ (upper panel, A) and as % of gross world product (lower panel, B). Symbols are the same as in Figure 2.

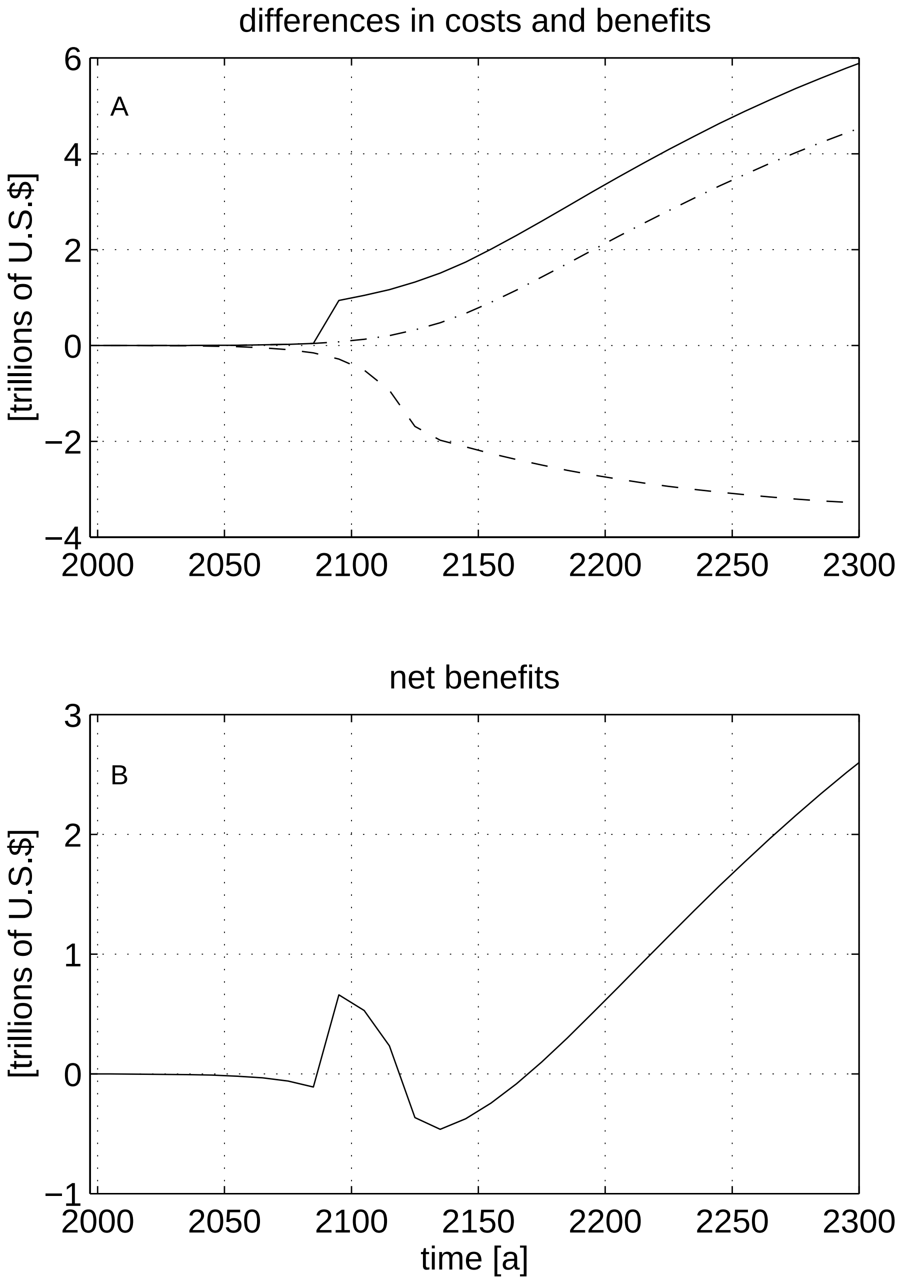

FIGURE 5: Comparison of the differences in total costs and benefits between the constrained and unconstrained policy. Shown are results (in 1989 U.S.$ per year) for a climate sensitivity of 3.5 ^{o}C, and a specific damage caused by a thermohaline circulation collapse of 0.86 % of gross world product. The total benefits of avoiding a thermohaline circulation collapse (full line, upper panel, A) are the sum of the avoided damages by a temperature increase (dash-dotted line, upper panel, A) and the constant relative damage specific to a thermohaline circulation collapse (shown as the difference between the solid and the dash-dotted line in the upper panel, A). The total costs of implementing the necessary abatement of carbon emissions are shown in the upper panel as dashed line. The net benefits of maintaining the thermohaline circulation for this example are shown in the lower panel (B).

To preserve the thermohaline circulation, the P$_{CO_{2,e}}$ levels have to be reduced relative to the unconstrained case. The lower P$_{CO_{2,e}}$ levels result in less global warming and hence avoid some temperature dependent damages. The avoided temperature dependent damages (shown in Figure 5 A, dash-dotted line) are one important benefit of preserving the thermohaline circulation.

A second benefit of preserving the thermohaline circulation is the avoided damages caused by a thermohaline circulation collapse, [shown in Figure 5 A as the difference between the total benefits (solid line) and the temperature dependent benefits (dash-dotted line)].

The benefits of preserving the thermohaline circulation are then compared to the additional costs of more stringent abatement measures (Figure 5 A, dashed line). The net benefits of the stabilization policy are shown in Figure 5 B. For this example, the present value of benefits slightly exceeds the present value of the costs. Given our assumptions, stabilizing P$_{CO_{2,e}}$ around 840 ppmV is worth accepting in a benefit-cost sense and would be a profitable policy. Note that the above analysis is only an approximation to the optimal growth model since it neglects, for example, changes in investment.

It may seem surprising that an apparently relatively small damaging effect in relation to GWP — under 1% — can justify a shift from a policy that would imply no limit on P$_{CO_{2,e}}$ (ca. 930 ppmV in the year 2125 and 1200 ppmV in the year 2205 in the unconstrained model) to one that would cap the concentration at about 840 ppmV by 2135 (Figure 2). To describe a climate catastrophe that would justify a temperature stabilization policy, Nordhaus uses a damage function with an extreme nonlinearity in the form of a very high exponent (12, to be precise) on temperature, implying damages of 60 % of global GWP for a temperature increase of 3.5 degrees (Nordhaus [1994, p. 115]). *Chao* [1995] uses a similar value to describe a catastrophic climate event. Our analysis implies that much lower climate damages can justify a P$_{CO_{2,e}}$ stabilization in a benefit-cost sense.

The high sensitivity of abatement to additional damages can be explained as follows. First, abatement over the relatively near term is already rather sensitive to small additional damages in the original DICE model of *Nordhaus* [1994]. For example, doubling the intercept of the damage function in the model formulation of *Nordhaus* [1994] results in additional damages of about 1.2

percent of GWP in 2095. These additional climate damages increase abatement in 2045 from 12.5 to 18 % [*Nordhaus*, 1994]. 18 % is very similar to the 17 % abatement in 2045, justified in our analysis by avoiding a thermohaline circulation collapse (which would otherwise cause additional damages of 0.86 % of GWP from 2095 on). (Note, though, that in the unconstrained DICE model with the doubled damage function intercept, $P_{CO_{2,e}}$ rises without limit.)

Second, stabilizing $P_{CO_{2,e}}$ to preserve the thermohaline circulation results in the additional benefits of lower climate damages due to lower atmospheric temperatures. These additional benefits amplify the benefits of preserving the thermohaline circulation. As can be seen in Figure 5 A, the additional benefits of less global warming are rather large and even exceed the benefits of avoided thermohaline circulation damages within the next century. As a result, preserving the thermohaline circulation yields benefits that grow faster than the costs of emission abatement (Figure 5A), mainly because technological efficiency increases.

Third, we use a climate sensitivity slightly higher than Nordhaus (1994), which amplifies the benefits of $P_{CO_{2,e}}$ stabilization relative to his model formulation. Fourth, note that stabilizing $P_{CO_{2,e}}$ is a less costly objective than stabilizing atmospheric temperatures — the scenario analyzed by Nordhaus (1994). The latter would require more stringent abatement levels (and in turn higher climate damages as a justification). Finally, our benefit-cost analysis neglects changes in investment on utility. It is conceivable that somewhat higher thermohaline circulation specific damages are necessary to result in the same $P_{CO_{2,e}}$ stabilization policy in an utility maximizing optimal growth model.

Estimate of the specific damages of a thermohaline circulation collapse

Current methods used to assign monetary values to the damages caused by global climate change are still under development and yield a wide range of results [*Fankhauser*, 1994, *Pearce et al.*, 1996]. We are aware that attempts to quantify the potential economic impacts of largely unknown changes in climate on future societies involve a significant amount of guesswork and typically result in order-of-magnitude estimates. We nonetheless attempt to describe and when possible quantify the likely range of economic impacts for a subset of damages caused by (i) the decrease in oceanic carbon uptake, (ii) the decrease in fishery yields, and (iii) the changes in temperature distributions. Since we consider only a subset of the potential impacts (for example, by omitting the non-market damages caused by species loss), a more complete attempt of quantifying the potential damages would arguably result in higher damage estimates.

First, the decrease in future oceanic uptake associated with a thermohaline circulation collapse causes economic damage because a carbon sink is valuable. Cold, carbon-dioxide-rich waters are subducted in the North Atlantic and transfer carbon dioxide from the atmosphere to the deep-ocean. This "temperature pump" is an important sink for atmospheric CO_2 to the deep ocean. A weakening in the thermohaline circulation may cause a reduction in oceanic carbon uptake. *Sarmiento and Le Quéré* [1996] estimate the reduction in oceanic carbon uptake due to a weakening of the thermohaline circulation at around 3 billion tons of carbon per year. If atmospheric carbon dioxide levels are constrained, any decrease in the natural sinks must be compensated by an increase in abatement measures that causes additional costs. The marginal cost of reducing carbon emissions in 2100 is estimated at roughly 20 U.S.$ per ton of carbon (1989 prices) [*Nordhaus*, 1994]. We hence estimate the resulting damage due to the decreased oceanic CO_2 uptake to be around 60 billion U.S.$ annually. This is on the order of 0.1 % of projected gross world product in 2100.

Second, the thermohaline circulation collapse might also decrease fishery yields, analogous to the effects observed during past changes in ocean currents [*Barber and Chávez*, 1986, *Grove*, 1988]. The thermohaline circulation collapse may result in a decrease in sea-surface temperatures in the North Atlantic of up to 8 ^{o}C and an increased warming of Southern Hemisphere surface waters [*Manabe and Stouffer*, 1993, *Schmittner and Stocker*, 1999], influencing the distribution of temperature-sensitive fish species and potentially resulting in significant losses of oceanic food production. *Constanza et al.* [1997] estimate the annual value of food production by the oceans in the vicinity of 0.8 trillion U.S.$, roughly 4 % of gross world product. While the relative impairment of oceanic food production is uncertain, one might attempt to bracket it (rather arbitrarily) by 0.5

and 10 %, resulting in estimates of potential damages on the order of 0.02 to 0.4 % of gross world product.

Third, the decrease in heat transport due to a thermohaline circulation collapse may result in largely unknown but potentially significant effects on climate patterns, particularly in north-western Europe. Presently, the North Atlantic thermohaline circulation transports large amounts of heat from low to high latitudes, partially causing the relatively warm climates in north-western Europe. Attempts to quantify the temperature changes caused by the thermohaline circulation collapse alone range between -20 ^{o}C in high latitudes to +5 ^{o}C in low latitudes [*Schiller et al.*, 1997]. These changes in average temperatures are superimposed on the general global warming and the net effect could be a cooling in high latitudes and a stronger warming in low latitudes, depending on the timing of the thermohaline circulation collapse. *Tol* [1998] reports an illustrative estimate of the economic damages in Western Europe caused by a thermohaline circulation collapse. According to *Tol's* [1998] estimate, a thermohaline circulation collapse may temporarily increase the climate damage by up to 3 % of gross domestic product in Western Europe (a damage exceeding roughly 0.5 % of gross world product at present conditions). To extrapolate *Tol's* [1998] study to a global scale and different times is extremely problematic, since the damages depend, for example, on the future degrees of industrialization and the temperature changes for all regions.

One might reasonably conclude, however, that the first two effects alone could explain damages ranging between 0.1 to 0.5 % of gross world product. Considering additionally the largely unknown effects of changes in climate patterns and other neglected effects, one might conclude that the potential economic impacts of a thermohaline circulation collapse are likely to exceed 0.1 % and potentially exceed 1 % of gross world product. In the light of these considerations, the necessary 0.86 % damages that would justify a $P_{CO_{2,e}}$ stabilization in a benefit-cost sense seem plausible.

EFFECTS OF MODEL SIMPLIFICATIONS AND UNCERTAINTIES

Our model shares with the original DICE model its simplifications and shortcomings. In particular, certain currently neglected effects would tend to favor earlier and more stringent abatements. Here we focus on three prominent examples: (i) the likely saturation of some carbon sinks, (ii) the potential upwards bias in cost estimates of carbon emission abatement, and (iii) the uncertainty in model parameters.

First, the oceanic and terrestrial carbon sinks are likely to saturate in the future. Oceanic carbon uptake is prone to saturate as the chemical buffering capacity of the oceans is reduced at increasing atmospheric carbon dioxide levels [*Broecker and Peng*, 1982]. Terrestrial carbon uptake may saturate as well, caused, for example, by a decline of forest regrowth [*Fan et al.*, 1998], or a saturation of the CO_2-fertilization effect at higher CO_2 concentrations [*Cao and Woodward*, 1998]. The exact partitioning of the anthropogenic CO_2 emissions between the oceanic and terrestrial carbon sinks (with different saturation effects) is uncertain at this time [*Joos*, 1994, *Kaiser*, 1998]. The neglected saturation effects may reduce the intensity of the future carbon sinks. Taking the saturation effects into account would increase optimal abatement measures [*Kaufmann*, 1997, *Schulz and Kasting*, 1997].

Second, the estimated costs of reducing CO_2 emissions used in this study may be too high. Numerous studies suggest that a sizeable fraction of CO_2 emissions could be achieved at no extra costs (for example, by alleviating existing market imperfections) and that low CO_2 emissions energy backstop technologies are increasingly likely at reasonable costs [*Hourcade et al.*, 1996, *Parson and Keith*, 1998]. Both possibilities imply cheaper abatement measures than the ones considered in the model and would imply higher optimal abatement measures.

Finally, the model parameters are uncertain. Parameters are better represented by probability distributions than by single numbers. Some have concluded these uncertainties raise the optimal abatement measures (relative to policy based on expected parameter values) (e.g., *Nordhaus and Popp* [1997], *Roughgarden and Schneider* [1999]).

Drawing the appropriate implications for policy of uncertainty about the model and its key parameters is one of the more difficult analytical challenges. To illustrate the effects of parameter uncertainty, we consider the example of climate sensitivity. Uncertainty about the climate sensitivity translates rather directly into uncertainty about the stabilization target (Figure 1); higher climate sensitivities result in lower values. *Tol and de Vos* [1998] have developed estimates of the mean and variance of the climate sensitivity. If we treat the distribution as normal, we can describe the cumulative probability distribution by the approximately straight line shown in Figure 6A. This tells us that with roughly 52 % probability our base-case climate sensitivity will be revised upward in the future, as the true value emerges with increasing precision. With roughly 48 % probability, the climate sensitivity will be revised downward.

There is a perhaps natural tendency toward conservatism in such a situation, suggesting one plan for the worst, or at least the relatively bad. This might imply setting policy on the basis of a climate sensitivity of 4 ^{o}C, instead of 3.5 ^{o}C. To prevent a thermohaline circulation collapse would then require a stabilization level of about 710 ppmV (Figure 6B). (We neglect the possibility, suggested by Figure 6C, that this policy might not be justified in a benefit-cost sense due to the large abatement costs.) Based on present knowledge, with probability of 64 %, emerging knowledge would allow easing the restraint on emissions, relative to the originally planned path.

But revisions, whether toward more or less stringency, are costly to some degree and conservatism in this sense is not necessarily the best policy. That must be based not just on the degree of uncertainty about the parameters but on a model of the process by which that uncertainty will be resolved. If, for example, the knowledge will emerge in a smooth way, the optimizing policy is likely to be less sensitive to error than in the case the knowledge will itself emerge with a jump (so that we all of a sudden discover we are about to go over the waterfall). Suppose, for example, it were known that the true critical value of P$_{CO_{2,e}}$ that would cause a thermohaline circulation collapse will be revealed in 2090, with no improvement in information between now and then. At that point, it would be too late to make more than minor adjustments in the P$_{CO_{2,e}}$ to be reached in the succeeding couple of decades. So, a more stringent control policy would be advised in this

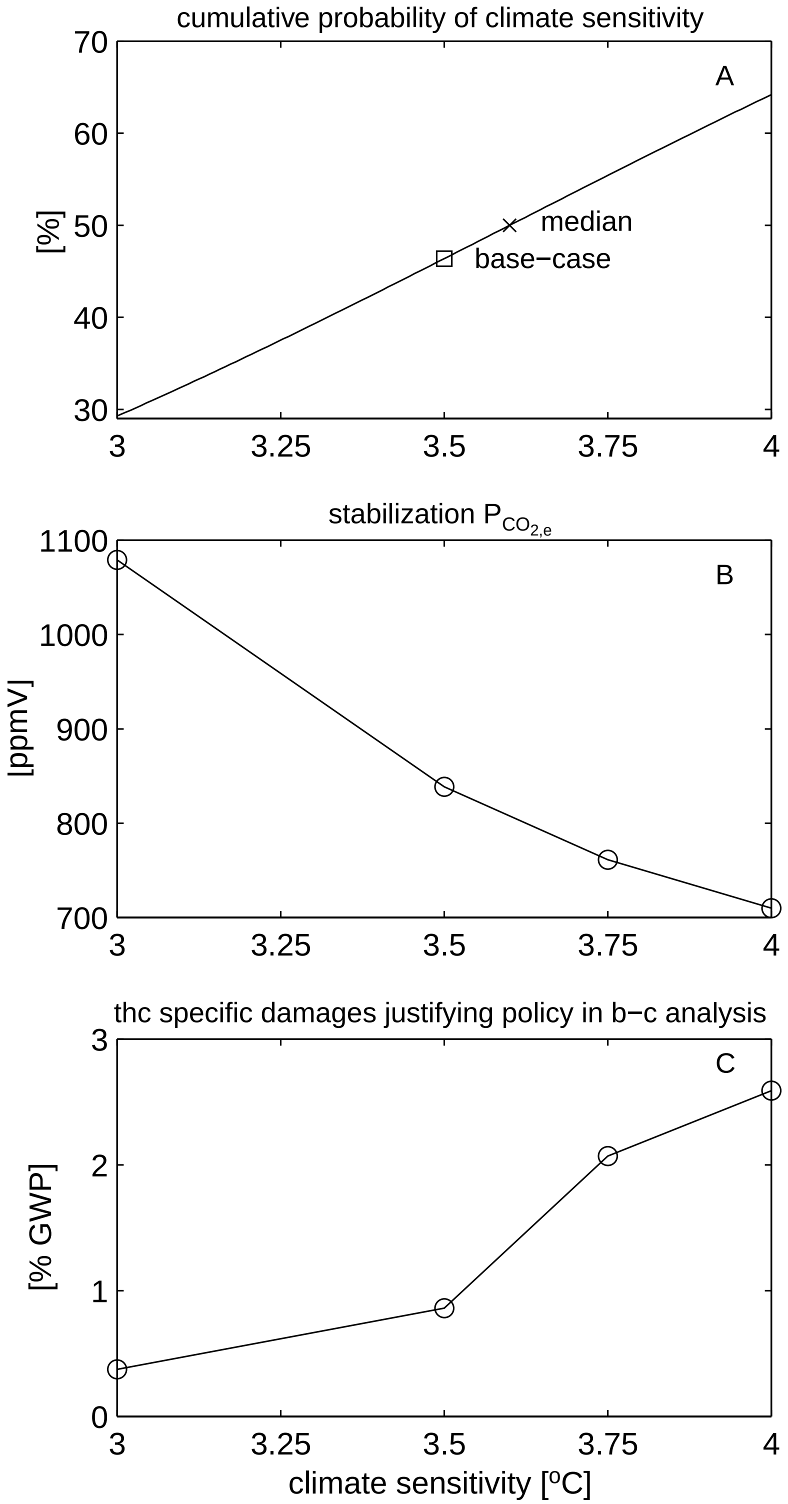

FIGURE 6: Model sensitivity analysis with respect to uncertainty in the climate sensitivity parameter. The upper panel (A) shows the cumulative probability density function of the climate sensitivity. The square denotes our base-case of 3.5 ^{o}C. We assume a normal distribution and adopt a median of 3.6 ^{o}C (cross) and a standard deviation of 1.1 ^{o}C [*Tol and de Vos*, 1998]. The necessary P$_{CO_{2,e}}$ stabilization levels derived from the model for a given climate sensitivity are shown in panel B. The damages of a thermohaline circulation collapse that would justify the various P$_{CO_{2,e}}$ stabilization levels (panel B) in a benefit-cost sense are shown in panel C.

case compared to the case in which improved knowledge would emerge in adequate time to take corrective action — even with the same present uncertainty about the true parameters.

Note that in this paper we have laid out the consequences of uncertainty only about the climate sensitivity. We neglect uncertainty in the other parameters, as well as the uncertainty about the model structure other than the possibility of a thermohaline circulation collapse. Furthermore, we consider only alternative scenarios based on perfect information (i.e., each scenario neglects parameter uncertainty). As the sketch of the problem indicates, a more appropriate procedure would be to model the probabilistic structure of knowledge, including its development over time, and use expected utility maximization as the policy criterion (along the lines discussed by *Nordhaus and Popp* [1997]).

VALUE JUDGMENTS IN THE MODEL

One of the most controversial value judgments in the model is associated with the question of how to distribute welfare between generations. The DICE model represents society's preference on intergenerational welfare distribution by a pure rate of social time preference. The pure rate of social time preference affects the investment behavior in the model which in turn influences the discount rate on goods. Higher pure social rates of time preference imply higher discount rates on goods along an optimal path in the model.

Different pure rates of social time preference represent different value judgments about intergenerational welfare distribution and result in different optimal policies, each optimal in the sense of the value judgments incorporated in the model. In general, valuing the welfare of future generations more (and hence choosing a lower pure rate of social time preference) results in higher abatement measures [*Nordhaus*, 1994, *Schulz and Kasting*, 1997]. While the chosen pure rate of social time preference of 3 % may be an appropriate description of present market conditions, the application of this value to long term projects may lead to questionable results since it significantly devalues future utility [*Heal*, 1997].

Consider, for example, the temporal distribution of costs and benefits caused by the thermohaline circulation constraint (Figure 5 B). For the chosen example, a small cost in the beginning results in a substantial benefit in the long run. The decision whether preserving the thermohaline circulation is profitable is in this case sensitive to the underlying pure social rate of time preference and the investment opportunities in the optimal growth model since they affect the applied discount rate on goods.

To further illustrate the intergenerational distribution effects of the discounted utilitarian approach, we analyze the effect of the thermohaline circulation constraint on per capita consumption. We compare the per capita consumption for the constrained and unconstrained policy neglecting for simplicity any economic damage of a thermohaline circulation collapse. Regardless whether $P_{CO_{2,e}}$ is stabilized or not, per capita consumption in this stylized example increases significantly with time (Figure 7 A), driven mainly by technological progress.

The per capita consumption for the stabilization policy (Figure 7 A, dotted line) is only marginally lower compared to the unconstrained policy (Figure 7 A, crosses). The decrease in per capita consumption caused by the higher abatement costs for a $P_{CO_{2,e}}$ stabilization shows an interesting intergenerational distribution (Figure 7 B). In the near future, per capita consumption is virtually unaffected. Significant increases in abatement costs occur only after a considerable time (Figure 5, dashed line) causing first a concomitant decrease in per capita consumption. The roughly constant abatement costs are in the long run more and more compensated by the increasing benefits of avoided global warming (Figure 5 A, dash-dotted line). In the long run, benefits grow faster than abatement cost so that consumption losses are regained and per capita consumption in the constrained case is commensurate with per capita consumption in the unconstrained case — and in fact exceeds it in the end.

The allocation of per capita consumption over time shown in Figure 7 is mainly due to two factors: (i) Per capita consumption is higher in the future and the decrease in the utility of consumption for a given cost is lower than in the present. (ii) The model values future utilities less. Whether this distribution of burden represents the preference of society is open to debate. Alter-

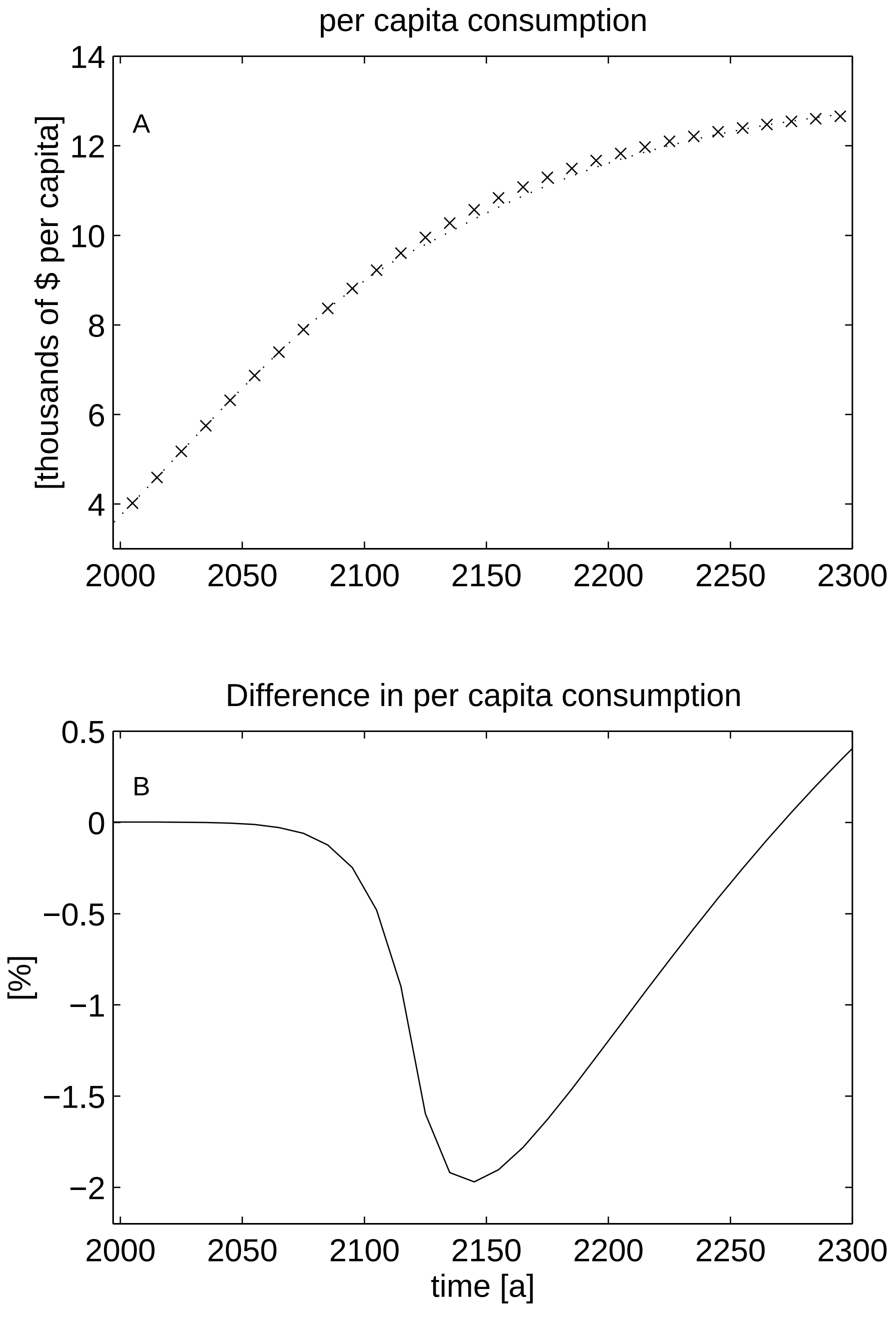

FIGURE 7: Effect of constraining the $P_{CO_{2,e}}$ levels on per capita consumption. Shown in the upper panel (A) are results considering (dotted line) and neglecting (crosses) the thermohaline circulation constraint. The lower panel (B) depicts the relative decrease in per capita consumption by choosing to stabilize $P_{CO_{2,e}}$ at approximately 840 ppmV. Note that the calculations shown neglect any economic damages associated with a thermohaline circulation collapse.

native patterns of distributing the burdens (like equalizing the decrease in utility, or maximizing the long term maintainable flow of utility [*Heal*, 1997]) are possible and could be used in this framework.

It should be noted that a lower pure rate of social time preference does not only increase optimal CO_2 abatement levels but also acts to increase the unabated CO_2 emissions. This is because valuing the welfare of future generations more results in the model in decreasing present consumption and endowing future generations with higher capital stocks. Higher capital stocks result in higher production levels that act to increase unabated carbon emissions. This effect of increasing unabated CO_2 emissions counteract the effects of higher CO_2 abatements. These two effects of changing the pure social rate of time preference are of comparable magnitude in the DICE model. As a result, the atmospheric CO_2 levels are rather insensitive to changes in the pure social rate of time preference. For example, cutting the pure social rate of time preference by two thirds in the unconstrained model reduces the accumulation of atmospheric CO_2 until 2165 by less than 9 %. This rather low sensitivity of atmospheric CO_2 to changes in the pure social rate of time preference in the optimal growth model suggests that the results of our benefit-cost analysis are not very sensitive to the choice of the pure social rate of time preference.

COMPARISON WITH PREVIOUS STUDIES

The first step of our analysis is to identify optimal policies to maintain an exogenously defined environmental standard. This step is perhaps closest to the approach proposed by the German advisory council on global change [*WBGU*, 1995], which allows changes in climate only within a specific "tolerable window" (see also *Toth et al.* [1997], or *Toth et al.* [1998]).

One tolerable window proposed by the WBGU is defined by a maximal anthropogenic temperature increase of 2 ^oC, and a maximal rate of temperature change of 0.2 ^oC/decade [*WBGU*, 1995]. This specific choice of climate constraints is partially motivated by the uncertainties in the climate models and impact estimates. Compared to making predictions about an uncertain future, the climate history may be a better indicator for bearable climates. Less stringent tolerable windows are derived by allowing higher and faster temperature increases, or by using estimates for the sensitivity of the thermohaline circulation to global warming (e.g., *Toth et al.* [1998]).

Implementing the WBGU window in our model as a constraint shows that all our discussed $\mathrm{P}_{CO_{2,e}}$ stabilization scenarios would violate the WBGU-constraints (for example by causing a global mean atmospheric warming exceeding 2 ^{o}C). More stringent (and costly) reductions in carbon emission than discussed in our study would be needed to reduce the risks of climate change to the level favored by the WBGU. Whether the lower risks associated with the WBGU constraints justify the higher abatement costs is an open and controversial question. Although the tolerable windows approach does not address this trade-off between costs and benefits explicitly (e.g., *Toth et al.* [1998]) this question can be analyzed using our framework.

The discrepancy between the WBGU constraints and the thermohaline circulation constraint discussed in this study illustrate again that the presented $\mathrm{P}_{CO_{2,e}}$ stabilization scenarios cannot exclude a thermohaline circulation shutdown or other surprises not considered in our simple model. However, the profitable $\mathrm{P}_{CO_{2,e}}$ stabilization levels derived in our study are significantly lower than suggested by previous optimal growth analyses (e.g., *Nordhaus* [1992], or *Tol* [1997]), even for a significant pure rate of social time preference.

Conclusions

We estimate optimal policies to reduce the risk of a North Atlantic thermohaline circulation collapse for a range of climate sensitivities. Our results indicate (mediated by numerous caveats) that in order to reduce the risk of a thermohaline circulation collapse considerably, the equivalent carbon dioxide concentrations have to be stabilized far below the concentrations suggested by previous optimal growth studies. The high sensitivity of the optimal policy to previously neglected and still largely unquantifiable effects is an indication of the caution with which optimal growth studies should be interpreted. However, our study decreases the discrepancy between the strong precautionary view that significantly restrict carbon emissions and the policy recommendations suggested by many previous optimal growth studies that are less restrictive. Clearly, our knowledge about the likelihood as well as the potential socioeconomic impacts of a thermohaline circulation collapse are sketchy at best. Causing a thermohaline circulation collapse would, however, arguably result in a "dangerous level of interference with the climate system" and would violate the UN framework convention on climate change. Our analysis suggests that maintaining the thermohaline circulation, with the implied increased rates of emission abatement, is probably worth the costs.

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