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Reducing the risk of a collapse of the Atlantic thermohaline circulation

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Abstract

The ability of mitigation to reduce the likelihood of a collapse of the Atlantic thermohaline circulation (THC) is explored given profound uncertainty in our understanding of climate sensitivity and THC processes. At the current time, uniform distributions across the ranges of this uncertainty puts the likelihood of a collapse sometime over the next 200 years at roughly 2 chances in 3 without mitigation from a single baseline emissions trajectory produced by the Nordhaus and Boyer DICE-99 economic model. The subjective likelihood declines with mitigation, and can be influenced by alternative prior distributions, but even the immediate imposition of extremely stringent climate policy would leave a 1 in 4 chance of a THC collapse in the uniform distribution case. Other representations of profound uncertainty are also explored. In all cases, waiting 30 years to act increases the odds of a collapse significantly.

Keywords: climate policy, thermohaline circulation collapse, profound uncertainty

1 Introduction

The collapse of the Atlantic thermohaline circulation (THC) is a primary example of possible non-linear impacts of climate change that were highlighted

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by the Intergovernmental Panel on Climate Change as a significant "source of concern" for global decision-makers who take seriously their obligation under the United Nations Framework Convention on Climate Change to avoid "dangerous anthropogenic interference with the climate" (IPCC, 2001). Subsequent work offered by the U.S. National Research Council (in their report on abrupt climate change, NRC, 2002), Alley et al. (2003) and Keller et al. (2005) has reaffirmed that this concern continues to be supported by more recent assessments of the state of scientific knowledge. While the physical, natural, and economic effects of a collapse of the THC have not been fully evaluated, it is now widely accepted that the planet's climate has, in the past, sustained conditions that did not support the THC. Here we take the view that returning to this unfamiliar state is *not* an experiment that should be performed on our planet. We examine the efficacy of various levels of mitigation in reducing the likelihood of a THC collapse sometime in the next two hundred years, given profound uncertainty in our estimates of the climate's sensitivity to changes in atmospheric concentrations of greenhouse gases and in our characterization of THC processes.

Section 2 presents a brief description of our modeling approach before four major sources of uncertainty are identified explicitly in Section 3. Simulation results across all four sources are presented in Section 4, the relative strengths of these sources are explored in the Subsection 5.1, and the robustness of the qualitative results to alternative portraits of the distributions of our fundamental sources of uncertainty is discussed in Subsection 5.2. Concluding remarks offered in a final section place the results into the context of the current state of knowledge about the THC process. While our simulations do not allow us to conclude that there is a 50% chance that the THC would collapse if global-mean temperatures were to climb 2 degrees above 1900 levels, they do suggest that we may not yet know enough about the THC to assert that the likelihood of a collapse would be less than the likelihood that "heads" would emerge from a single toss of a single coin.

2 The Modeling Approach

Figure 1 offers a schematic portrait of our modeling approach. The DICE-99 model from Nordhaus and Boyer (2001) produced a baseline trajectory over time for economic activity and corresponding emissions of greenhouse gases (GHGs). DICE-99 also calibrated a representation of the IPCC-Bern model that relates GHG emissions with atmospheric GHG concentrations and produces temperature trajectories for various climate sensitivities. Mitigation was modeled in the DICE-99 framework as a tax on carbon emissions that would be imposed globally either in 2005 or, in a case of delayed action, 2035. The mitigation intervention in both cases mimicked (approximately) the minimum discounted cost trajectories for achieving specific concentration targets of the sort reported by Wigley, et al. (1996) by setting a carbon tax equal to an initial scarcity rent at the beginning of the policy period and then allowing that tax to increase at an

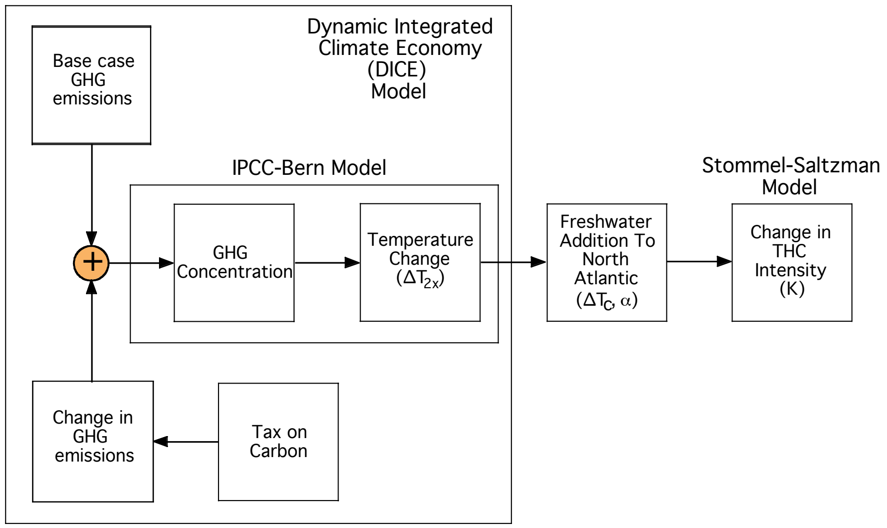

Figure 1: **A schematic of the modeling structure:** The DICE-99 integrated climate-economic model feeds the Stommel-Saltzman model of the THC through temperature change and freshwater addition

endogenously determined rate of interest. Put another way, the approach does not choose optimal climate policy by maximizing global welfare net of climate damages. Instead, the approach models climate policy simply to approximate least-cost trajectories associated with whatever concentration limit would be endogenously determined by various specifications of policy intervention.

The resulting temperature trajectories produced corresponding series of freshwater addition to the North Atlantic that drove the Stommel-Saltzman (S-S) model of the THC. In Stommel's (1961) original model of the THC, heat and salt are transported from an equatorial box to a polar box with each box taken to have its own temperature and salinity. The direction of this transport is the same regardless of whether the circulation is clockwise (as viewed from Europe), as in the present-day THC, or counter-clockwise as in a reversed THC. Later Saltzman (2002) simplified the model by taking the temperature difference between the boxes as a constant, but he also extended its applicability by including the salt transport by the non-THC motions in the ocean—the wind-driven gyre circulation and eddies akin to weather disturbances in the atmosphere.

3 Sources of Uncertainty

Four sources of uncertainty were recognized explicitly. Notwithstanding an assumed baseline of economic activity, uncertainty about climate sensitivity (the equilibrium increase in global-mean surface-air temperature associated with a doubling of pre-industrial concentrations of greenhouse gases) supported a wide

Table 1: Maximum temperature increases between 2105 and 2205 for a policy of immediate taxation (in U.S. (1990) dollars per ton of carbon).

Climate Sensitivity	$0.00	$10.00	$25.00	$50.00	$75.00	$100.00	$150.00	$200.00
1.5	2.61	1.76	1.46	1.16	1.00	0.97	0.97	0.97
2	3.24	2.23	1.81	1.45	1.26	1.21	1.21	1.21
3	4.14	2.88	2.26	1.82	1.61	1.56	1.56	1.56
4	4.67	3.30	2.58	2.09	1.86	1.81	1.80	1.80
5	5.00	3.62	2.82	2.30	2.06	2.00	2.00	2.00
6	5.23	3.85	3.02	2.47	2.22	2.15	2.15	2.15
7	5.40	4.02	3.18	2.61	2.34	2.28	2.27	2.27
8	5.53	4.15	3.30	2.71	2.43	2.37	2.37	2.37
9	5.63	4.25	3.39	2.79	2.51	2.44	2.44	2.44
Mean:	3.91	2.77	2.21	1.79	1.58	1.53	1.53	1.53

Table 2: Maximum temperature increases between 2105 and 2205 for a policy of taxation beginning in 2035 (in U.S. (1990) dollars per ton of carbon).

Climate Sensitivity	$0.00	$10.00	$25.00	$50.00	$75.00	$100.00	$150.00	$200.00
1.5	2.61	2.16	1.86	1.64	1.52	1.43	1.30	1.30
2	3.24	2.74	2.35	2.06	1.89	1.77	1.62	1.62
3	4.14	3.63	3.07	2.63	2.37	2.21	2.03	2.03
4	4.67	4.16	3.53	2.99	2.70	2.51	2.32	2.31
5	5.00	4.51	3.87	3.28	2.96	2.75	2.54	2.54
6	5.23	4.74	4.11	3.50	3.17	2.95	2.73	2.72
7	5.40	4.91	4.28	3.67	3.33	3.10	2.88	2.87
8	5.53	5.04	4.42	3.80	3.45	3.22	2.99	2.99
9	5.63	5.14	4.52	3.90	3.55	3.31	3.08	3.08
Mean	3.91	3.42	2.94	2.54	2.31	2.16	1.99	1.99

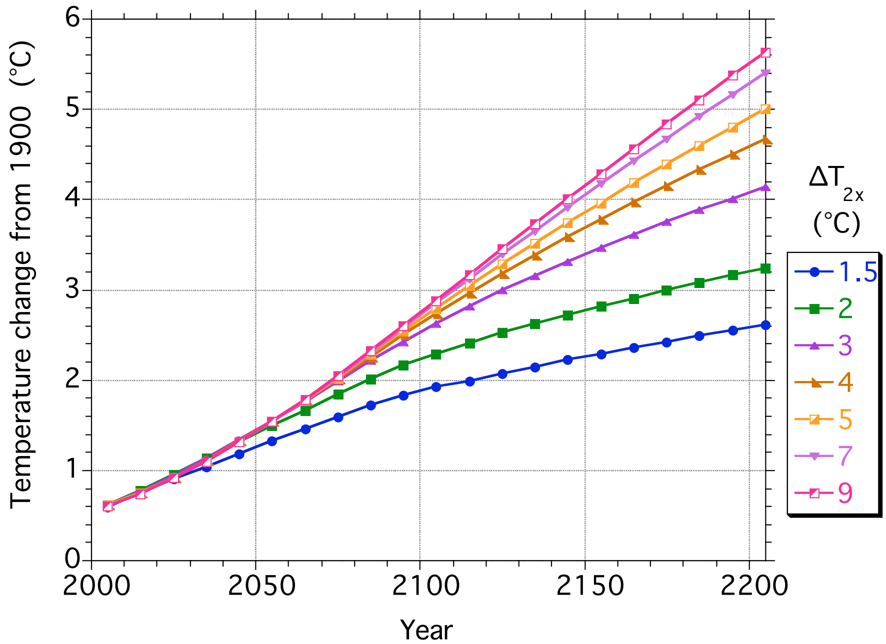

Figure 2: **Temperature increases along unregulated emissions paths:** Temperature increases relative to 1900 along unregulated emissions paths for alternative climate sensitivities.

range of temperature trajectories. Andronova & Schlesinger (2001) produced a cumulative probability distribution of climate sensitivity from the historical record of surface-air temperature; its underlying probability density function is displayed in Panel D of Figure 6. The discrete version of this density function employed by Yohe et al. (2004) was imported here to span a range from 1.5°C to 9°C. The relative likelihoods for each sensitivity and the associated lag parameter for deep ocean heat infusion show a median of 2 degrees, but they also show a 25% likelihood that the climate sensitivity which best describes the historical record is 5 degrees or higher. For reference, Figure 2 displays transient temperature trajectories that emerge from unregulated DICE baseline emissions across the range of climate sensitivities. Table 1 and Table 2 meanwhile highlight the maximum temperatures allowed by various initial taxes whose levels increase at an endogenously determined rate of interest. Table 1 shows these maxima for interventions begun in 2005; Table 2, maximum temperatures for interventions begun after a 30-year delay to 2035.

Following the procedure described more fully in Schlesinger et al. (2006), uncertainty in the specification of the freshwater addition module was reflected in two places of the THC modelling framework. As reported there, the governing equation of the Stommel-Saltzman (S-S) 2-box ocean model for nondimensional variables is

$$\frac{\mathrm{ds}}{\mathrm{dt}^*} = \Pi - |1-s| \cdot s - Ks \tag{1}$$

where s is the difference in salinity between the equatorial and polar boxes, $t^*$is time, Π is the freshwater addition, and K is the ratio of the transport coefficient for the gyre circulation and eddies (denoted κ_Φ) to that for the THC (denoted κ_Ψ). The K term was absent from the original Stommel model and was taken to be as large as unity by Saltzman. The maximum streamfunction of the THC is

$$\Psi = \kappa_\Psi \, \mu_T \, \delta T^* (1-s) \tag{2}$$

where μ_T is the thermal volume expansion coefficient, and δT^* is the temperature difference between the equatorial and polar boxes, taken to be constant.

The S-S model was calibrated so that it was about as sensitive to a freshwater addition as the University of Illinois at Urbana-Champaign (UIUC) coupled atmosphere-ocean general circulation model (AOGCM)—a model which requires a freshwater addition of 0.6 Sv ($10^6 \mathrm{m}^3$/sec) between 50°N to 70°N in the Atlantic to shut down the THC (Yin, 2004; Yin et al., 2006). From Equation 2, then, a THC shutdown (i.e., $\Psi = 0$) requires $s = 1$. From the steady-state version of Equation 1, this condition subsequently requires a dimensionless freshwater addition of $\Pi = K$. The corresponding dimensional freshwater addition is $F = \beta\Pi = \beta K$, where β is a conversion coefficient. The largest value of K we consider is $K = 2.5$, which is the value required by the S-S model to reproduce the reversible THC shutdown simulated by the UIUC AOGCM (Yin, 2004; Yin et al., 2006). Taking $F = 0.6$ Sv for $K = 2.5$ yields $\beta = 0.24$ Sv. Schlesinger et al. (2000) report results from simulations by the UIUC atmospheric GCM coupled to a 60 m deep mixed-layer ocean model for several different radiative forcings that suggest a linear relationship between freshwater addition, Π, and global mean temperature change, ΔT,

$$\Pi(t) = \alpha \cdot [\Delta T(t) - \Delta T_c] \cdot H(\Delta T(t) - \Delta T_c) \tag{3}$$

where

$$H(x) = \begin{cases} 0 \text{ if } x < 0 \\ 1 \text{ if } x \geq 0 \end{cases} \tag{4}$$

is the Heavyside step function and α is the 'hydraulic sensitivity'. The Heavyside step function is introduced to prevent any freshwater addition until a critical temperature change, ΔT_c, is reached. Substituting Equation 3 into $F = \beta\Pi$ and solving for α yields

$$\alpha = \frac{F}{\beta \cdot [\Delta T(t) - \Delta T_c] \cdot H(\Delta T(t) - \Delta T_c)} \tag{5}$$

If we assume that $\Delta T(t) - \Delta T_c = 2.5$°C for $F = 0.6$ Sv, then $\alpha = 1.0(°\mathrm{C})^{-1}$ for $\beta = 0.24$ Sv. The values of α and ΔT_c are highly uncertain, though. Accordingly, and still following Schlesinger et al. (2006), we initially took these quantities to have uniform probability distributions between 0.2 and 1.0 (°C)$^{-1}$ (in increments of 0.2) for α and between 0.0°C and 0.6°C (in 0.1 degree increments) for ΔT_c.

Finally, the S-S model translates freshwater addition to flow in the THC. Yin (2004) and Yin et al. (2006) show that this depends critically on the ratio of salinity transport by the gyre/eddies and the THC, represented by K. We therefore began with a uniform prior on K ranging from 0.0 through 2.5 (in five increments of 0.5); the range was based on the studies by Yin (2004) and Yin et al. (2006); they showed that the S-S model with $K = 0$ (the original Stommel model) reproduced the irreversible THC shutdown simulated by an uncoupled UIUC ocean general circulation model, while the S-S model with $K = 2.5$ reproduced the reversible THC shutdown simulated by the coupled UIUC atmosphere-ocean general circulation model.

Given these discrete representations of the uniform priors on ΔT_c, α, and K, it was possible to run a complete set of permutations and combinations of the four random variables. The likelihood of any combination equaled $(\pi^i_{\Delta T_{2x}}/210)$, where $\pi^i_{\Delta T_{2x}}$ represents the likelihood of the any one of the nine possible climate sensitivities. The sum of the likelihoods of combinations for which the intensity of the THC fell to zero or below at any point in time was interpreted to be the time-dependent subjective likelihood that a collapse will have occurred; and the maximum likelihood of a collapse was then taken to be the largest of these subjective likelihoods from 2005 through some end-date (either 2105 of 2205 to provide two points of reference).

4 Some Simulation Results

Figure 3 displays summary results in terms of the maximum probability of a THC collapse recorded sometime between now and 2205 (i.e., that the intensity of the THC had fallen from its current level of approximately 18 Sv to 0 Sv). Panel A shows maximum likelihoods through 2105 while Panel B extends the time period through 2205. The lower curve in each panel associates the likelihood of a THC collapse (based on current understanding) for policies initiated in 2005; the higher curve associates the same likelihood for equivalent intervention (in terms of tax per ton of carbon) delayed by 30 years of inaction. Characterizing the available best scientific information in 2005 with the uniform distributions described above puts the likelihood of a collapse of the THC over the next 200 years at more than 2 chances in 3 if we do nothing (and more than 2 chances in 5 through 2105). Both trajectories show that the maximum probability declines with mitigation but that the most rigorous immediate climate policy still leaves a likelihood of a THC collapse in excess of 1 chance in 5 through 2105 and 1 in 4 through 2205. Waiting 30 years to act increases the likelihood associated with the most stringent policy to more than 1 chance in 3 across both time horizons.

Figure 4 presents the results in terms of an association between the expected value of the minimum THC intensity between now and 2205 and the maximum

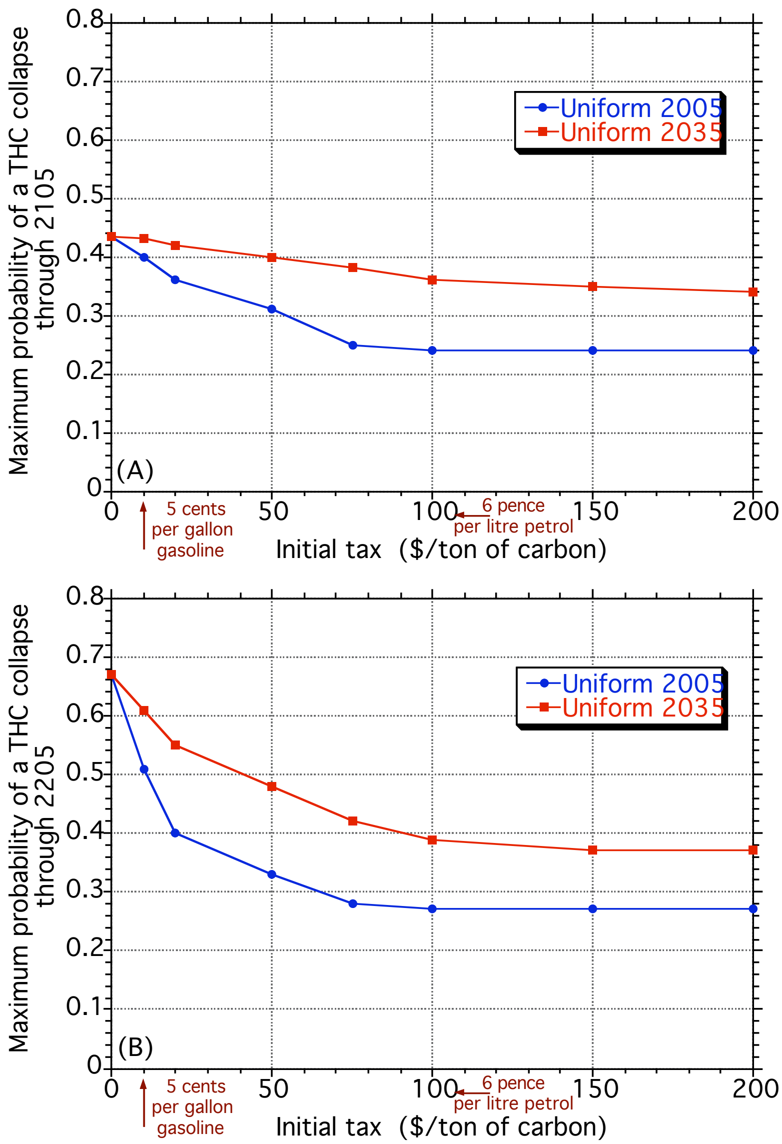

Figure 3: **Maximum probabilities of a THC collapse through 2105 and 2205 for uniform priors on ΔT_c, α, and K:** Maximum probabilities of a collapse of the THC between 2005 and 2205 are plotted against various carbon taxes initiated in either 2005 or 2035. Once they are imposed, the taxes increase over time at the endogenously determined rate of interest derived by DICE-99. The probabilities were computed across a complete sample of scenarios defined by spanning all sources of uncertainty. Panel A reports maxima through 2105; Panel B replicates Figure 5.9 in Schlesinger et al. (2006) in reporting maxima through 2205.

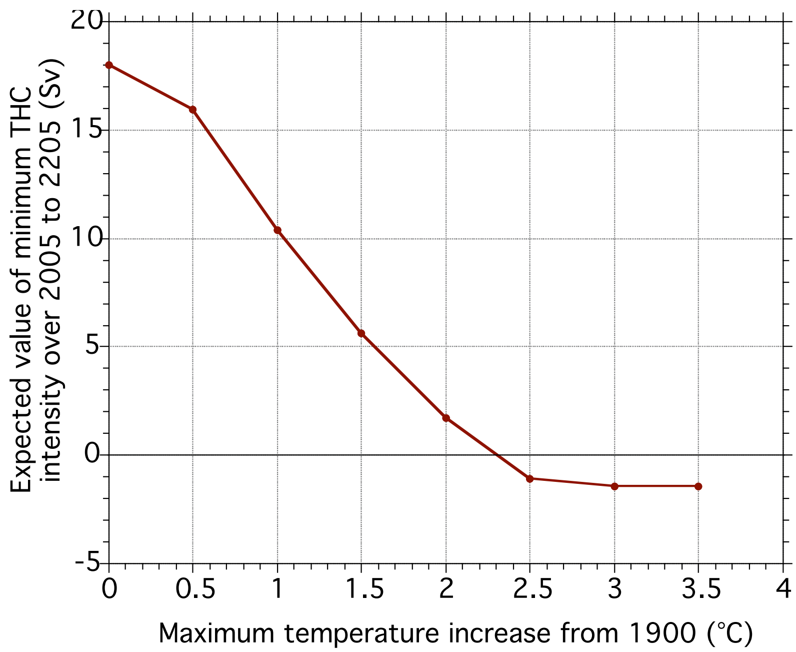

Figure 4: **The expected value of minimum THC intensity:** Minimum THC intensity between 2005 and 2205 as a function of an increase in the global-mean temperature from 1900 levels between now and 2205. This figure appears in Schlesinger et al. (2006) as Figure 5.10.

temperature increase (from 1900 levels) over that time span. Notice that this minimum intensity reaches a state of complete collapse sometime in the next 200 years, in expected value at least, when the increase in global-mean temperature, measured from 1900 levels, climbs by slightly more than 2°C.

The various panels of Figure 5 show that these results are not the product of mitigation that is simply too weak to create any significant reduction in emissions and temperature change for a climate sensitivity of 3°C (which is above the median estimate for climate sensitivity). Panel A shows that emissions eventually fall to zero in every case in response to the powerful restraint imposed by a tax that is compounded at a rate of interest over 200 years. As a result, carbon dioxide concentrations always reach a peak and then decline, though these peaks happen earlier for more robust interventions. Perhaps more importantly, temperature change also peaks along each intervention trajectory so that the likelihood of a THC collapse can eventually decline (again, at an earlier date for more strenuous near-term policy). The qualitative insights to be drawn from Figures 3 and 4 are therefore robust for climate sensitivities above

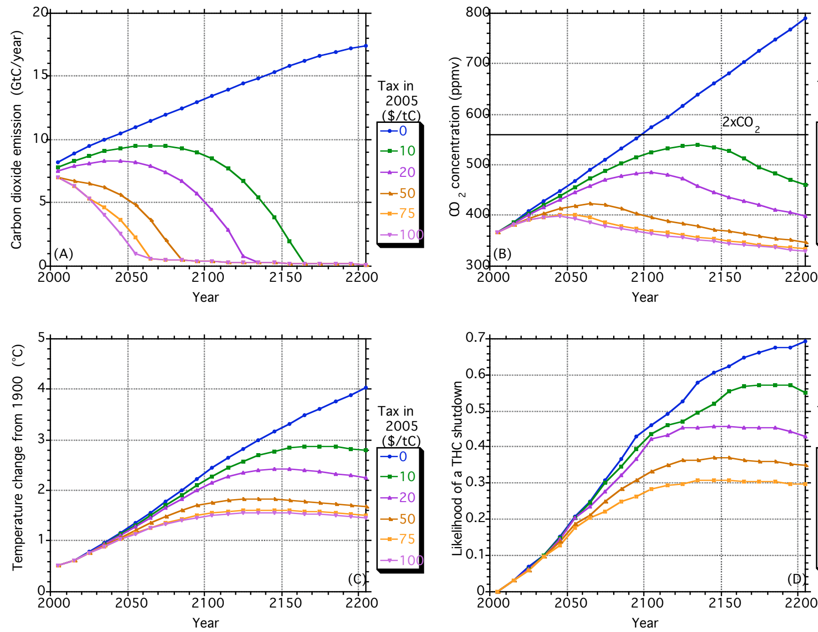

Figure 5: **Transient trajectories for the 3-degree climate sensitivity case:** Intertemporal trajectories of carbon emissions (Panel A), atmospheric concentrations of carbon dioxide (Panel B), temperature change relative to 1900 (Panel C), and the likelihood of a collapse of the THC (Panel D) are displayed for various taxes initiated in 2005 and a climate sensitivity of 3 degrees. The probabilities were computed across a complete sample of scenarios defined by spanning the three remaining sources of uncertainty. This figure appears in Schlesinger et al. (2006) as Figure 5.7.

and below 3°C: even if maximally robust policies designed to bring emissions to zero were forthcoming, the uniform representation of current scientific understanding about the THC process suggests that they could not preclude the potential of a THC collapse.

5 Analysis of sensitivity to uncertainty in ΔT_{2x}, ΔT_c, α, and K

5.1 Specific values

Table 3 and Table 4 report the results of some contingent simulations that were conducted to identify the most important sources of uncertainty. Maximum

Table 3: The sensitivity of maximum likelihoods of collapse through 2105 to the ranges of K, α, ΔT_c and ΔT_{2x}. Taxes are denoted in U.S. dollars (1990) per ton of carbon and initiated in 2005.

	No Tax	\$25.00	\$50.00	\$100.00	\$200.00
Kappa (K)	1%–97%	0%–92%	0%–88%	0%–79%	0%–79%
Alpha (α)	14%–70%	12%–61%	8%–51%	4%–41%	4%–41%
Climate Sensitivity (ΔT_{2x})	38%–50%	27%–47%	21%–41%	15%–34%	15%–34%
Critical Temperature (ΔT_c)	39%–49%	30%–44%	21%–38%	17%–33%	17%–32%

Table 4: The sensitivity of maximum likelihoods of collapse through 2205 to the ranges of K, α, ΔT_c and ΔT_{2x}. Taxes are denoted in U.S. dollars (1990) per ton of carbon and initiated in 2005.

	No Tax	\$25.00	\$50.00	\$100.00	\$200.00
Kappa (K)	30%–100%	5%–93%	1%–90%	0%–82%	0%–82%
Alpha (α)	25%–88%	15%–69%	9%–55%	6%–46%	6%–46%
Climate Sensitivity (ΔT_{2x})	44%–78%	27%–68%	21%–56%	15%–48%	15%–48%
Critical Temperature (ΔT_c)	45%–65%	35%–49%	26%–40%	20%–35%	20%–35%

probabilities of a collapse of the THC between 2005 and 2205, contingent on specific values for specific sources of uncertainty with complete sampling across the other three random variables were calculated; the resulting ranges are reported for each of the four sources of uncertainty The conditional probabilities associated with each uncertain variable were computed by assuming that the distributions described above continued to describe the state of knowledge for the other three variables.

Uncertainty about the value to be assigned to parameter K dominates the four possibilities, while ΔT_c turned out to be the least significant source. Perhaps more instructively, the contingency runs show that a \$75 per ton globally imposed carbon tax could reduce the maximum probability of a THC collapse below 25% if the climate sensitivity turned out to be less than 2°C, if the value for K were greater than 2, if the value for α were lower than 0.4 $(°\mathrm{C})^{-1}$, or if the critical THC temperature threshold were higher than 0.6 degrees. On the other side of the coin, however, a value for K of less than 0.5 would put the likelihood of a THC collapse at no less than 50%.

5.2 Subjective probability distributions

Uniform prior distributions for ΔT_c, α, and K are not, of course, the only way to represent the profound subjective uncertainty with which we view the THC processes in the reduced-form model described in Section 2 and Section 3. Indeed, other priors that (1) place more weight to the center of the ranges and/or (2) reflect asymmetry in the likelihood that any variable might assume a value outside of its quoted range could have been employed. To explore the possibility that our results could be highly sensitive to the shape of the chosen prior, we repeated the analysis with two alternatives. The first is a Beta distribution suggested for a decision-theoretic context in Clement (1996) and Morgan & Henrion (1990). It has been applied to climate issues by Webster et al. (2002) and in other contexts by, for example, Gill & Walker (2005) and Fente et al. (2000). Its shape addresses the first concern by locating most of the probabilistic weight into the center of the distribution even though it does display wider "tails" than a more conventional normal distribution. The second, a Weibull distribution employed, for example, by McInereney & Keller (2006) not only shifts weight to the center of the range, but also allows us to reflect our recognition that we are certain that ΔT_c, α, and K will be bounded from below by 0 but uncertain that they will be bounded from above by 0.6°C, $1.0(°\mathrm{C})^{-1}$, and 2.5, respectively.

Figure 6 displays the specific Beta and Weibull density functions for the three variables (ΔT_c, α, and K) that were employed here. Note that a fourth panel displays the density function for climate sensitivity (denoted by ΔT_{2x}) as estimated by Andronova & Schlesinger (2001). Denoting the relatively likelihoods derived from these density functions that $\{\Delta T_c; \alpha; K; \Delta T_{2x}\}$ will assume values $\{j; l; k; i\}$ as $\pi^j_{\Delta T_c}$, π^l_α, π^k_K and $\pi^i_{\Delta T_{2x}}$, respectively, then the likelihood assigned to a specific scenario defined by that combination of variables is $\pi^j_{\Delta T_c} \cdot \pi^l_\alpha \cdot \pi^k_K \cdot \pi^i_{\Delta T_{2x}}$.

The two panels of Figure 7 compare the results for the Beta distribution with the previously recorded results for the uniform prior. Panel A reflects the maximum likelihood of a THC collapse through 2105, and Panel B does the same through 2205. In both cases, the results for switching to the Beta distribution for only one variable are bounded from above for policies initiated in 2105 by the uniform prior results and from below by the case in which the priors for ΔT_c, α, and K were described by the Beta distribution. In every case, the likelihoods are lower than they are for the uniform prior, but not reassuringly so; notice that the smallest likelihood for a THC collapse before 2105 along an unregulated emissions trajectory exceeds 30%. Perhaps the most encouraging comparative result is that initiating mitigation in 2005 can become more effective (by more than 50% for the most stringent policies). The two panels of Figure 8 repeat the process for the Weibull prior and show qualitatively similar results with one exception—moving the center of mass for the distribution of K further from the lower portion of its range dramatically increases the ability of climate-policy intervention to reduce significantly the likelihood of a collapse. Given the sensitivities noted in Table 3 and Table 4, this is not a surprise. Nonetheless,

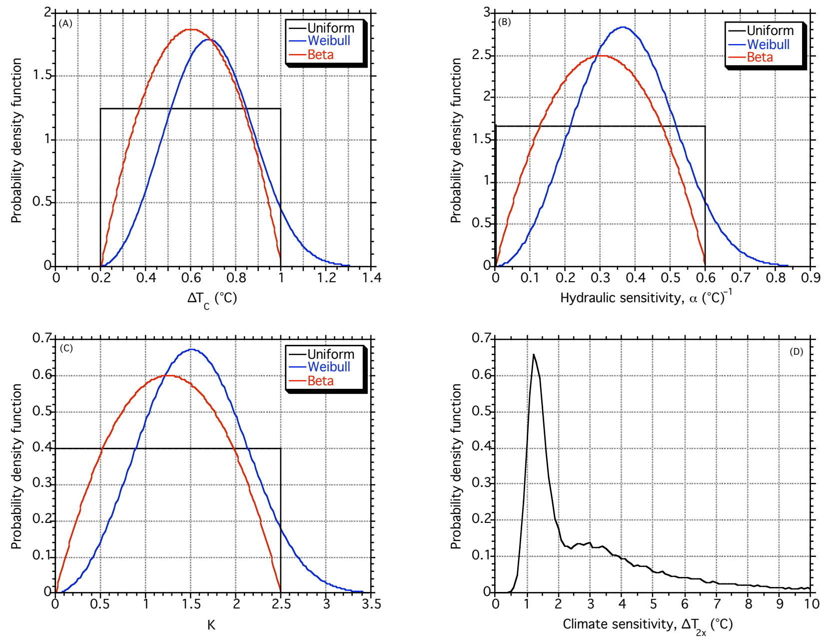

Figure 6: **Probability density functions for alternative priors:** Density functions for the Beta (2,2) and Weibull (x,3,100) priors employed for ΔT_c, α, and K are displayed in Panels A through C. Panel D displays the density function for climate sensitivity from Andronova & Schlesinger (2001).

the likelihood remains above 1 chance in 5 and 1 chance in 2 (through 2105 and 2205, respectively) in the absence of any policy intervention.

6 Concluding Remarks

A one-in-four chance of a THC collapse can attract considerable attention for those who calculate risk as the product of the probability of a specific event and some measure of the associated consequences (even if those consequences are not particularly well defined). For those who take this calculus seriously, the current state of knowledge as reflected here suggests that we need to do more than just tax carbon to obtain more acceptable odds—say one in ten or, better, one in 20. Doing more would entail drawing down the CO_2 concentrations by other means (perhaps by growing a large amount of biofuel and bioenergy together with carbon capture and storage). As an insurance hedge against a very uncomfortable future, looking into these means while pursuing a modest mitigative intervention (using the revenue to promote alternatives) would certainly seem to be prudent. As emphasized in Yohe et al. (2004) uncertainty cannot be

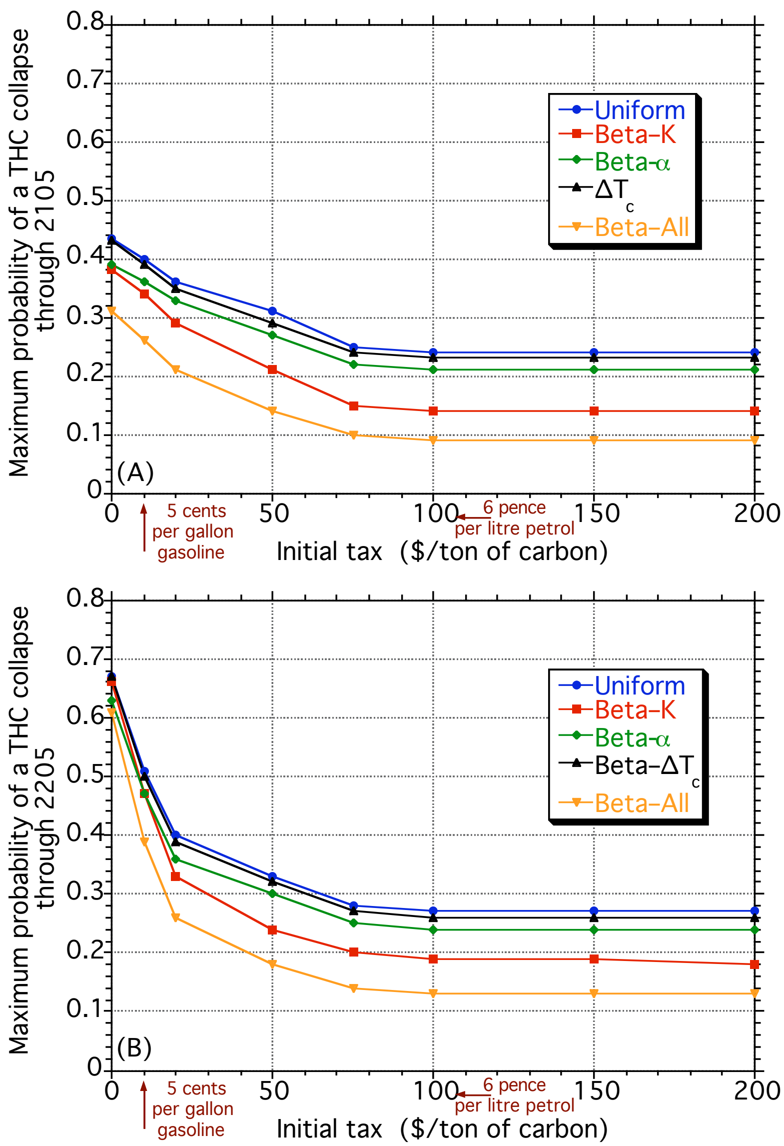

Figure 7: **Maximum probabilities of a THC collapse through 2105 and 2205 for Beta priors on ΔT_c, α, and K:** Maximum probabilities of a collapse of the THC between 2005 and 2105 (Panel A) and 2205 (Panel B) are plotted against various carbon taxes initiated in 2005. Once they are imposed, the taxes increase over time at the endogenously determined rate of interest derived by DICE-99. The probabilities were computed across a complete sample of scenarios defined by spanning all sources of uncertainty.

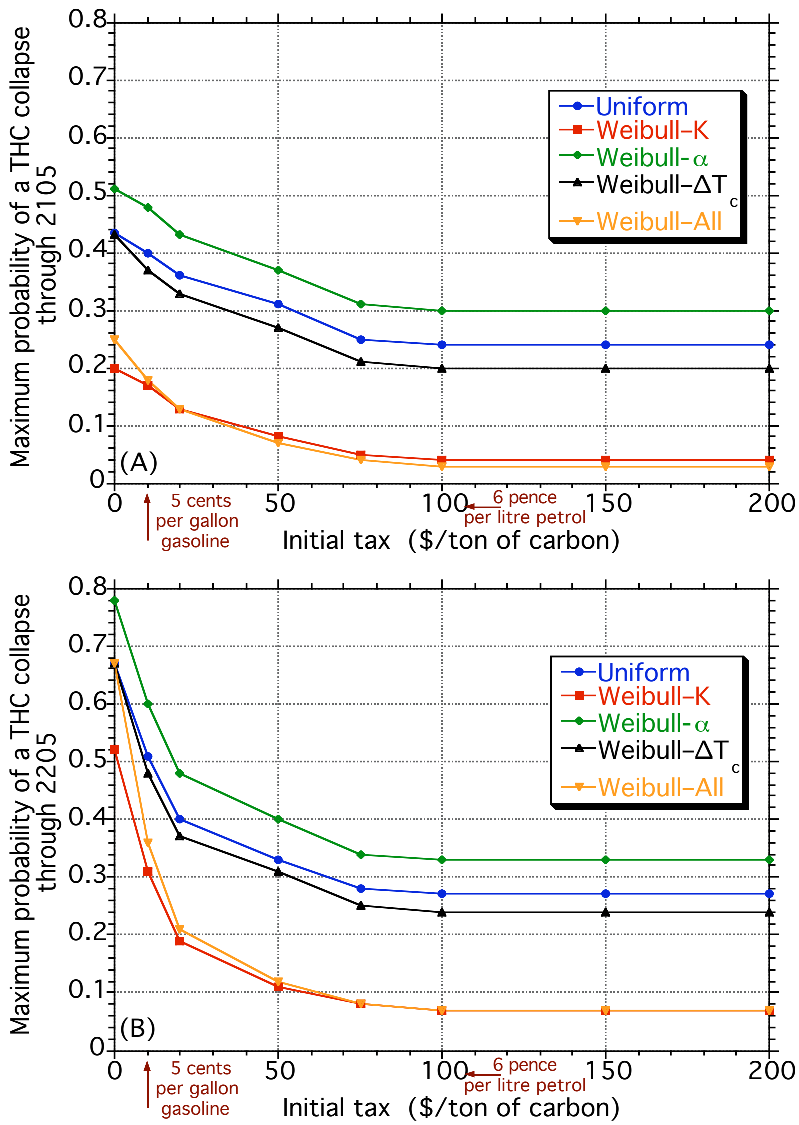

Figure 8: **Maximum probabilities of a THC collapse through 2105 and 2205 for Weibull priors on ΔT_c, α, and K:** Maximum probabilities of a collapse of the THC between 2005 and 2105 (Panel A) and 2205 (Panel B) are plotted against various carbon taxes initiated in 2005. Once they are imposed, the taxes increase over time at the endogenously determined rate of interest derived by DICE-99. The probabilities were computed across a complete sample of scenarios defined by spanning all sources of uncertainty.

a reason not to act.

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