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Reducing the risk of a collapse of the Atlantic thermohaline circulation

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Abstract

Using state of the art models, we examine the ability of mitigation to reduce the likelihood of a collapse of the Atlantic thermohaline circulation (THC) given profound uncertainty in our understanding of climate sensitivity and THC processes. Our estimates show that a collapse becomes more likely than not, given current information, with a 2 degree warming from 1900 levels. Put another way, the likelihood of a collapse sometime over the next 200 years is estimated to be more than 2 chances in 3 if we do nothing. The likelihood declines with mitigation, but even the most rigorous immediate climate policy would leave an estimated chance of a THC collapse at 1 in 4; and waiting 30 years to act increases the estimated odds to more than 1 chance in 3.

The collapse of the Atlantic thermohaline circulation (THC) is the primary example of possible non-linear impacts of climate change that were highlighted 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".[1] The authors of the U.S. National Research Council report on abrupt climate change reaffirmed this concern in their more recent assessment of the current state of scientific knowledge [2, 3]. While the physical, natural, and economic effects of a collapse of the THC have not been fully evaluated, it is now widely accepted that a slowing of the THC would bring a colder climate to western Europe. Morever, it is agreed that the planet's climate has, in the past, persisted in an equilibrium that did not support the THC.[4] Here we take the view that returning to this unfamiliar equilibrium 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.

Methods

Figure 1 offers a schematic portrait of our approach. The DICE-99 model from Nordhaus and Boyer produced a baseline trajectory over time for economic activity and corresponding emissions of greenhouse gases.[5] DICE-99 also calibrated a representation of the IPCC-Bern model that relates emissions with atmospheric concentrations and produces temperature trajectories for various climate sensitivities. Mitigation was modeled as a tax on carbon emissions that would be imposed globally in 2005 or, in a case of delayed action, in 2035. In both cases the carbon tax increased at an endogenously determined rate of interest so that the resulting reductions in the likelihood of a THC collapse would be achieved along (approximately) minimum (discounted) cost trajectories of the sort reported in Wigley, et al.[6]

The various 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 model of the THC[7], 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. Saltzman later simplified the model by taking the temperature difference between the boxes as a constant, but he also extended it 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.[8]

The governing equation of the Stommel-Saltzman (S-S) 2-box ocean model for nondimensional variables is

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

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 to that for the THC (denoted below by k_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

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

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.

We calibrated the S-S model so that it is about as sensitive to a freshwater addition as the University of Illinois at Urbana-Champaign (UIUC) coupled atmosphere-ocean general circulation model (AOGCM), which requires a freshwater addition of 0.6 Sv (10^6 m^3/sec) between 50°N to 70°N in the Atlantic to shut down the THC [9, 10]. From Eq. (2), a THC shutdown (i.e., $\Psi = 0$) requires $s = 1$. From the steady-state version of Eq. (1), the latter condition 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 [9, 10]. Taking $F = 0.6$ Sv for $K = 2.5$ yields $\beta = 0.24$ Sv.

Results from simulations by the UIUC atmospheric GCM coupled to a 60 m deep mixed-layer ocean model for several different radiative forcings [11, 12] suggest a linear relationship between freshwater addition, Π, and global mean temperature change, $\Delta\overline{T}$,

$$\Pi(t) = \alpha\left[\Delta\overline{T}(t) - \Delta\overline{T}_c\right] H\left[\Delta\overline{T}(t) - \Delta\overline{T}_c\right] \quad , \tag{3}$$

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, $\Delta\overline{T}_c$, is reached.

Substituting Eq. (3) into $F = \beta\Pi$ and solving for α yields

$$\alpha = \frac{F}{\beta\left[\Delta\overline{T} - \Delta\overline{T}_c\right] H\left[\Delta\overline{T} - \Delta\overline{T}_c\right]} \quad . \tag{5}$$

If we assume that $\Delta\overline{T} - \Delta\overline{T}_c = 2.5°\text{C}$ for $F = 0.6$ Sv, then α = 1.0 $(^{o}\text{C})^{-1}$ for $\beta = 0.24$ Sv. The values of α and $\Delta\overline{T}_c$ are highly uncertain, though. Accordingly, we took these quantities to have uniform probability distributions, between 0.2 and 1.0 $(^{o}\text{C})^{-1}$ for α, and between 0.0°C and 0.6°C for $\Delta\overline{T}_c$.

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 range of temperature trajectories. Andronova and Schlesinger [13] produced a cumulative probability distribution of climate sensitivity from the historical record of surface air temperature; the discrete version employed by Yohe, et al.[14] was imported here to span a range from 1.5 degrees to 9 degrees. 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 that there is a 25% likelihood that the climate sensitivity which best describes the historical record is higher than 5 degrees.

Uncertainty in the specification of the freshwater addition module was reflected in two places. First, seven different values for a critical temperature threshold at which the THC begins to slow down (denoted above by $\Delta\overline{T}_c$) ranging from 0 to 0.6 degrees centigrade above the 1900 level (in 0.1 degree increments) were assumed to be equally likely. In addition, a parameter required in the specification of the freshwater addition to the North Atlantic as a function of the global mean temperature change (denoted above by α) was assumed to range from 0.2 through 1.0 $(^{o}C)^{-1}$; five values (in increments of 0.2) were taken to be equally likely [see Methods section]. Finally, the S-S model translates freshwater addition to flow in the THC. This depends critically on the ratio of salinity transports by the gyre/eddies and the THC (denoted above by K) [9, 10]. A uniform prior ranging from 0.0 through 2.5 (in six increments of 0.5) was assumed. The likelihood of any specific combination of climate sensitivity, ΔT_c, α, and K thus equaled (π_i / 210), where π_i represents the likelihood of the various climate sensitivities.

A uniform prior on K was chosen based on the study by Yin[10] and Yin et al.[10] which showed that the S-S model with K = 0 (the original Stommel model) reproduced the irreversible THC shutdown simulated by an uncoupled ocean general circulation model, while the S-S model with K = 2.5 reproduced the reversible THC shutdown simulated by a coupled atmosphere-ocean general circulation model.

Results

Our first results focus attention on estimates of the strength of the THC under the assumption that temperature change proceeds to a specified maximum along a trajectory driven by baseline economic activity and a range of climate sensitivities. More specifically, we tracked time series of temperature increases driven by the baseline economic drivers in DICE-99 for 9 different climate sensitivities until they reached a range of thresholds that span the space between 1.5°C to 3.5°C (measured from 1900 levels). In each case, and contingent on the date at which the temperature would reach each threshold, we then computed the corresponding minimum long-run equilibrium THC intensity between 2005 and for all of the possible combinations of $\Delta \overline{T}_c$, α, and K. The results of these experiments were summarized as cumulative distributions for each temperature threshold based on our prior assessments of the relative likelihood of each combination of uncertain parameters. Figure 2 displays the 5th, 25th, 50th, 75th and 95th percentiles of these distributions for a range of temperature limits the critical values highlighted in the Third Assessment Report. Notice that our estimate for the median value of this streamfunction falls to zero with a 2 degree warming measured from 1900 levels – a 1.5 degree warming from present levels.

Figure 3 presents summary results in terms of an alternative measure: the maximum probability of a THC collapse recorded sometime between now and 2205. The lower curve 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. The best scientific information available in 2005 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. 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 4. Waiting 30 years to act increases the likelihood associated with the most stringent policy to more than 1 chance in 3.

The various panels of Figure 4 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 degrees (above the median estimate for climate sensitivity). Panel A shows that carbon dioxide 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 the peak happens earlier for more robust interventions. Perhaps more importantly, temperature change always peaks 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 Figure 3 are robust for climate sensitivities above and below 3 degrees: even if maximally robust policies designed to bring emissions to zero were forthcoming, current scientific understanding suggests that they could not preclude the potential of a THC collapse.

Figure 5 continues the diagnostics. The most important source of uncertainty is K; the least important source is ΔT_c. The panels 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 degrees, if the value for K were greater than 2, if the value for α were lower than 0.4, or if the critical THC temperature threshold were higher than 0.6 degrees. The panels also show, however, that a value for K less than 0.5 would put the likelihood of a THC collapse at no less than 50%.

Discussion

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). A 50-50 coin toss for a THC collapse with another 1.5 degrees of warming is a pretty good definition of how the adjective “dangerous” might be attached to climate change.

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, uncertainty cannot be a reason not to act [14].

Acknowledgements

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Figure Legends

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

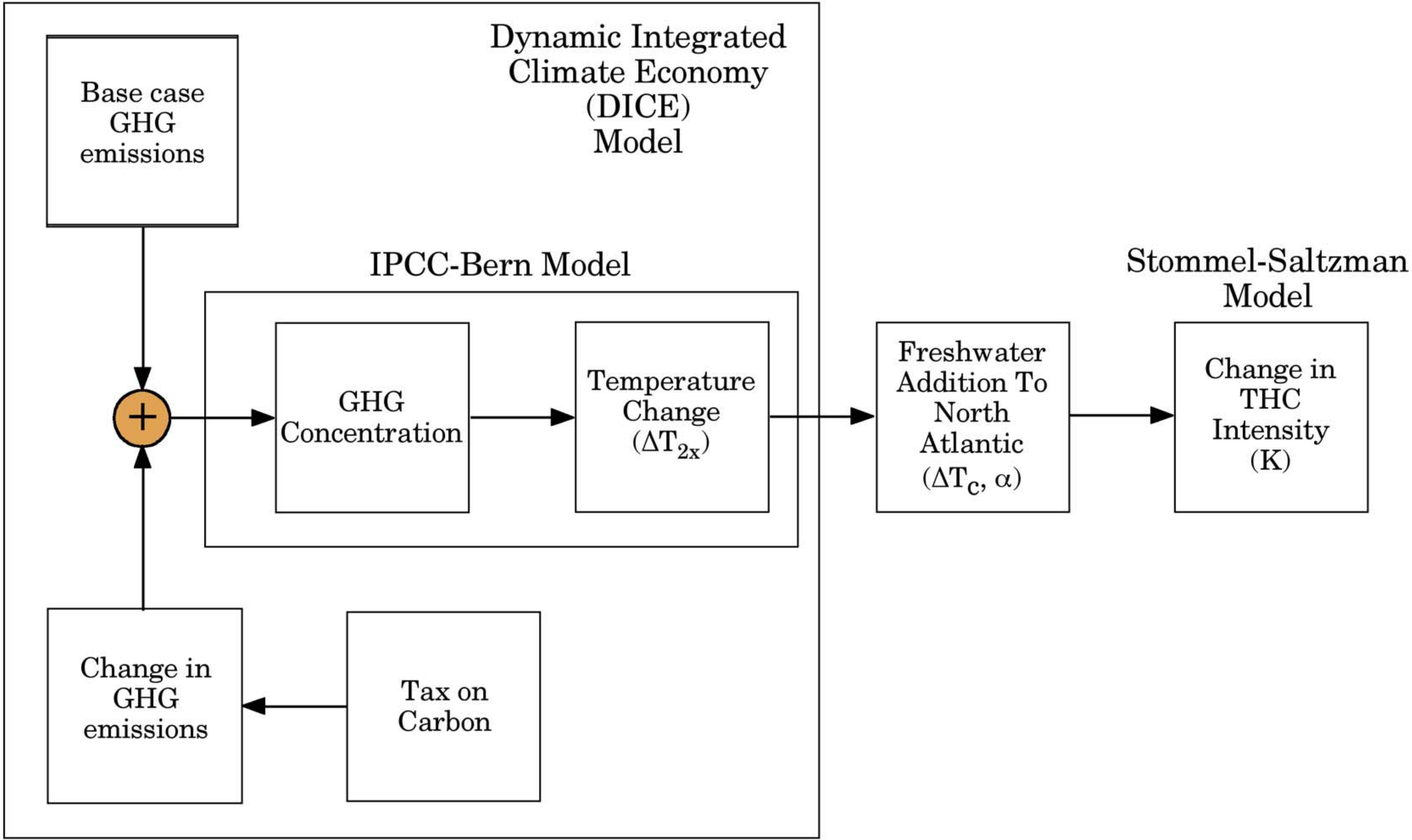
Figure 2 – Strength of the THC as a function of economically driven temperature maxima: Percentile estimates of the minimum equilibrium intensity of the THC between 2005 and 2205 as a function of temperature limits that are achieved along economically driven temperature trajectories.

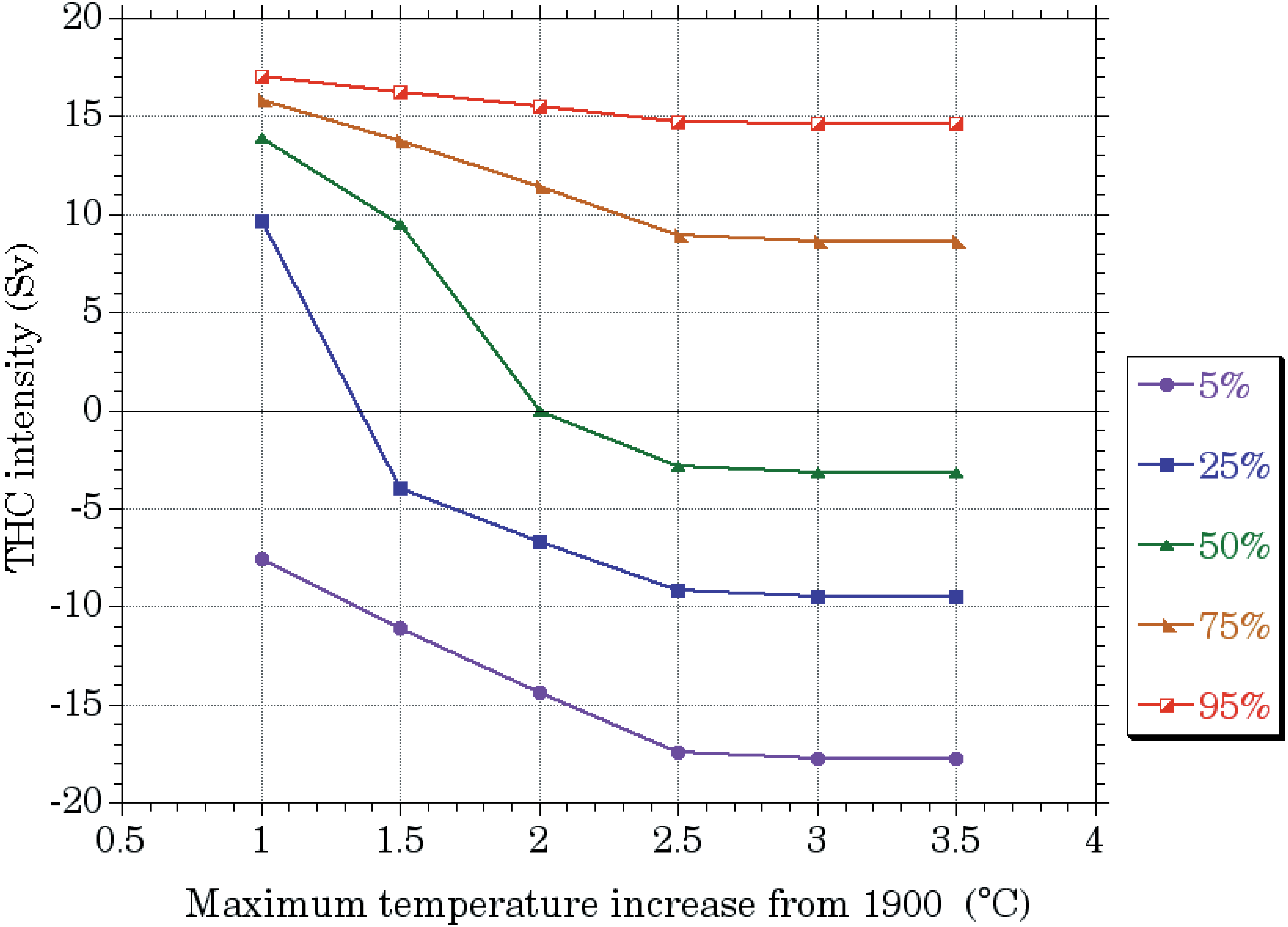
Figure 3 – Maximum probabilities of a THC collapse through 2205: Maximum probabilities of a collapse of the THC between 2005 and 2205 are plotted against various carbon taxes initiated in either 2005 or 2035. Once they are imposed, the taxes increase over time at the endogenously determined rate of interest derived by DICE-99. The probabilities were computed across a complete sample of scenarios defined by spanning all for sources of uncertainty.

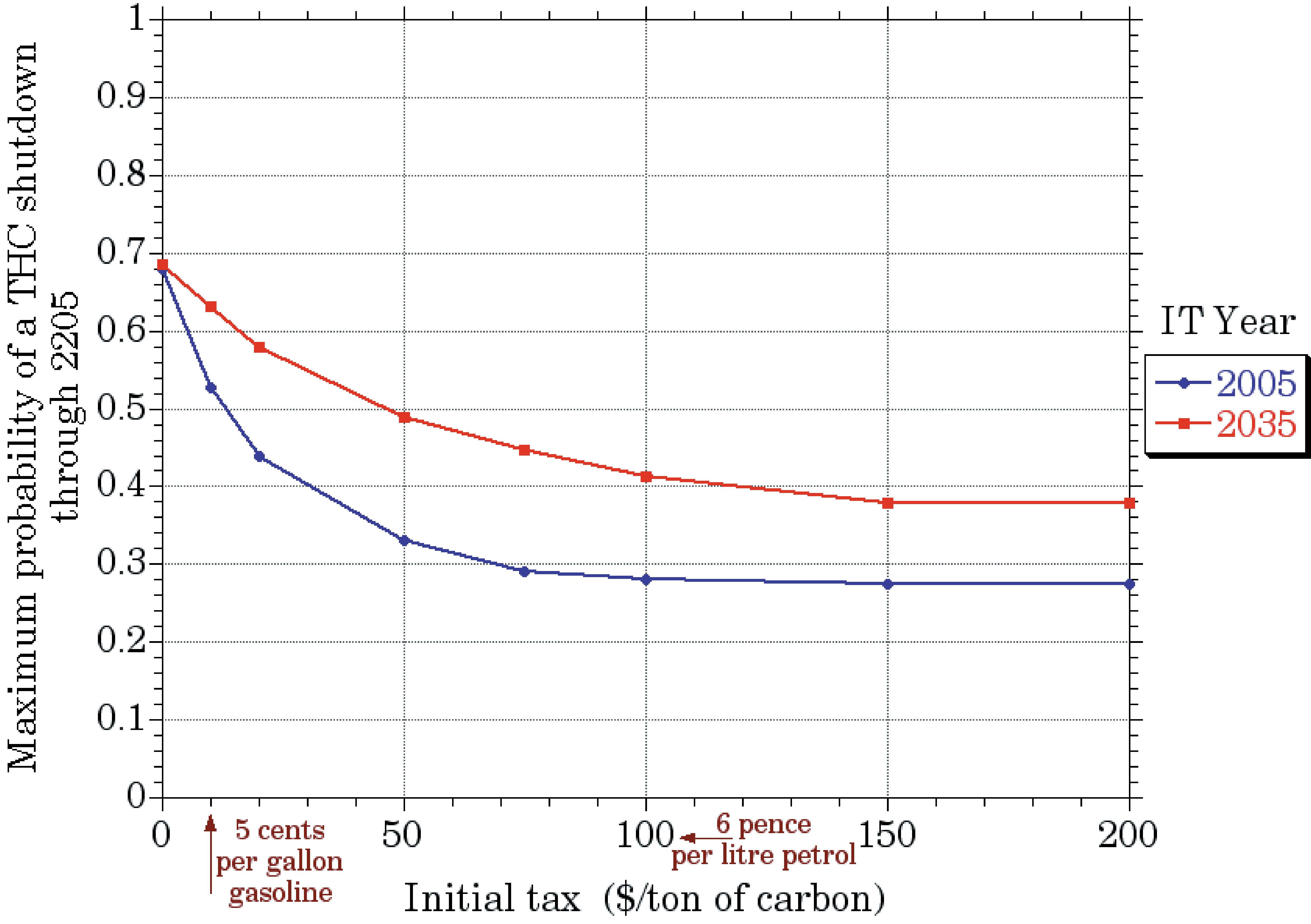
Figure 4 – Transient trajectories for the 3-degree climate sensitivity case: Intertemporal trajectories of carbon emissions (Panel A), atmospheric concentrations of carbon dioxide (Panel B), temperature change relative to 1900 (Panel C), and the likelihood of a collapse of the THC (Panel D) are displayed 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.

Figure 5 – Maximum probabilities of a THC collapse through 2205 contingent on uncertain parameters: Maximum probabilities of a collapse of the THC between 2005

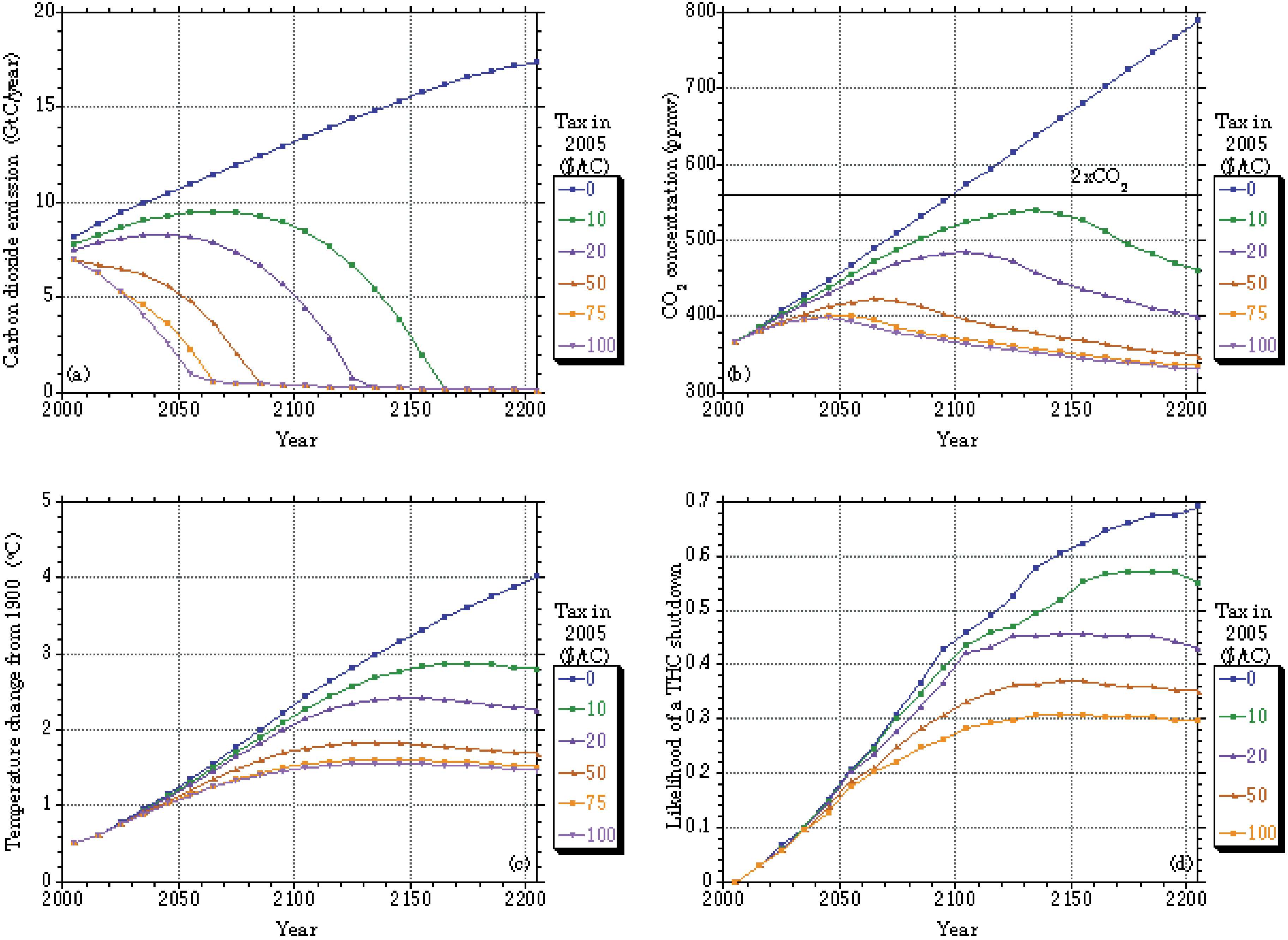
and 2205, contingent on specific values for specific sources of uncertainty, are plotted against various carbon taxes initiated in 2005. The probabilities associated with each uncertain variable were computed across a complete sample of scenarios defined by spanning the remaining three sources of uncertainty. Panel A displays probabilities for the complete set of climate sensitivities; Panel B, for seven critical temperature thresholds ΔT_c; Panel C, for five values of the parameter α; and Panel D, for six values of the parameter K.

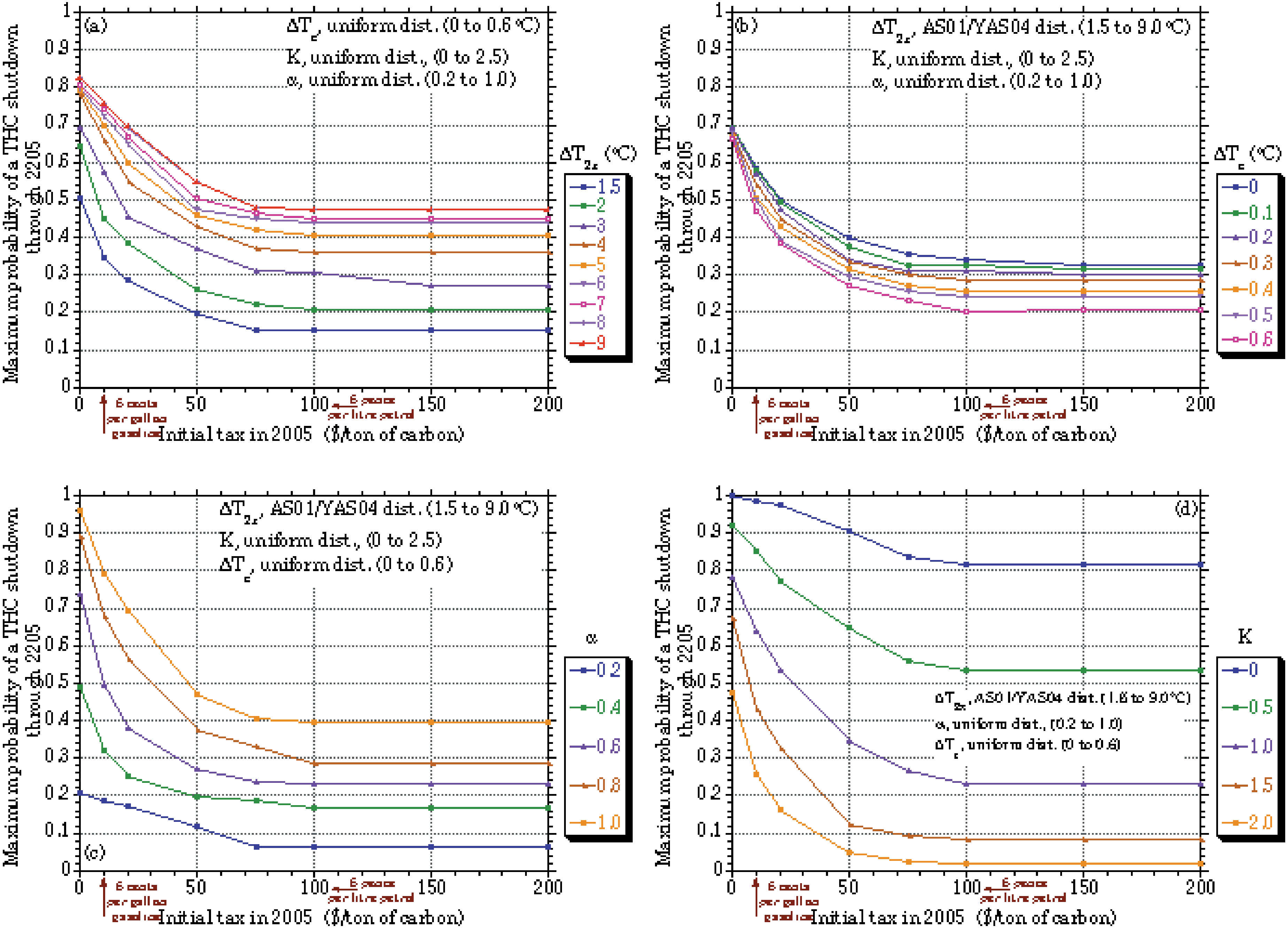

Dynamic Integrated Climate Economy (DICE) Model
Base case GHG emissions
+
IPCC-Bern Model
GHG Concentration
Temperature Change (ΔT_{2x})
Stommel-Saltzman Model
Freshwater Addition To North Atlantic (ΔT_c, α)
Change in THC Intensity (K)
Change in GHG emissions
Tax on Carbon


20
15
10
5
0
-5
-10
-15
-20
THC intensity (Sv)
0.5
1
1.5
2
2.5
3
3.5
4
Maximum temperature increase from 1900 (°C)
5%
25%
50%
75%
95%



Maximum probability of a THC shutdown through 2205
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
5 cents per gallon gasoline
6 pence per litre petrol
Initial tax ($/ton of carbon)
IT Year
2005
2035


Carbon dioxide emission (GtC/year)
20
15
10
5
0
2000
2050
2100
2150
2200
Year
(a)
Tax in 2005 ($/tC)
0
10
20
50
75
100
CO$_2$ concentration (ppmv)
800
700
600
500
400
300
2xCO$_2$
(b)
Temperature change from 1900 (°C)
5
4
3
2
1
0
(c)
Likelihood of a THC shutdown
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(d)


(a)
ΔT_c, uniform dist. (0 to 0.6 °C)
K, uniform dist., (0 to 2.5)
α, uniform dist. (0.2 to 1.0)
ΔT_{2x} (°C)
1.5
2
3
4
5
6
7
8
9
(b)
ΔT_{2x}, AS01/YAS04 dist. (1.5 to 9.0 °C)
K, uniform dist., (0 to 2.5)
α, uniform dist. (0.2 to 1.0)
ΔT_c (°C)
0
0.1
0.2
0.3
0.4
0.5
0.6
(c)
ΔT_{2x}, AS01/YAS04 dist. (1.5 to 9.0 °C)
K, uniform dist., (0 to 2.5)
ΔT_c, uniform dist. (0 to 0.6)
α
0.2
0.4
0.6
0.8
1.0
(d)
ΔT_{2x}, AS01/YAS04 dist. (1.5 to 9.0°C)
α, uniform dist., (0.2 to 1.0)
ΔT_c, uniform dist. (0 to 0.6)
K
0
0.5
1.0
1.5
2.0
Maximum probability of a THC shutdown through 2205
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Initial tax in 2005 ($/ton of carbon)
0
50
100
150
200
6 cents per gallon gasoline
6 pence per litre petrol