

Reducing the risk of a collapse of the Atlantic thermohaline circulation

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Running title: Reducing the risk of a THC collapse

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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, this uncertainty puts likelihood of a collapse sometime over the next 200 years to be more than 2 chances in 3 without mitigation from a single baseline emissions trajectory produced by the Nordhaus and Boyer DICE-99 economic model. The likelihood declines with mitigation, but the immediate imposition of extremely stringent climate policy would leave a 1 in 4 chance of a THC collapse. Waiting 30 years to act increases the odds to more than a 1 chance in 3.

Key Words: climate policy, thermohaline circulation collapse, profound uncertainty

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” [IPCC (2001)]. Alley, et al. (2003) report that the authors of the U.S. National Research Council report on abrupt climate change [NRC (2002)] reaffirmed this concern in their more recent assessment of the current 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 persisted in an equilibrium that did not support the THC. 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.

Section 1 presents a brief description of our modeling approach before four major sources of uncertainty are identified explicitly in Section 2. Simulation results across all four sources are presented in Section 3, and the relative strengths of these sources are explored in the fourth section. Concluding remarks offered in a final section place the results into the context of the current state of knowledge about the THC process. 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, though, allow us to conclude that we do not yet know enough about the THC to assert that a collapse would not be as likely as seeing “heads” emerge from a single toss of a single coin.

1. 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. 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 in the DICE-99 framework 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 mitigation intervention 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 endogenously determined rate of interest.

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 (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.

2. 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 range of temperature trajectories. Andronova and Schlesinger (2001) produced a cumulative probability distribution of climate sensitivity from the historical record of surface air temperature; the discrete version employed by Yohe, et al. (2004) 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 of the THC modelling framework. The governing equation of the Stommel-Saltzman (S-S) 2-box ocean model for nondimensional variables is

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

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 k_ϕ) to that for the THC (denoted 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

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

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 ($10^6 \text{ m}^3/\text{sec}$) between 50°N to 70°N in the Atlantic to shut down the THC [Yin (2004); Yin, et al. (2005)]. 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 [Yin (2004); Yin, et al. (2005)]. Taking $F = 0.6 \text{ Sv}$ for $K = 2.5$ yields $\beta = 0.24 \text{ Sv}$.

Schlesinger (2000) and Schlesinger, et al. (2006) 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, $\Delta\bar{T}$,

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

where

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

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

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

$$\alpha = \frac{F}{\beta [\Delta\bar{T} - \Delta\bar{T}_c] H[\Delta\bar{T} - \Delta\bar{T}_c]} . \quad (5)$$

If we assume that $\Delta\bar{T} - \Delta\bar{T}_c = 2.5^\circ\text{C}$ for $F = 0.6 \text{ Sv}$, then $\alpha = 1.0 (\text{°C})^{-1}$ for $\beta = 0.24 \text{ Sv}$. The values of α and $\Delta\bar{T}_c$ are highly uncertain, though. Accordingly, we took these quantities to have uniform probability distributions between 0.2 and $1.0 (\text{°C})^{-1}$ (in increments of 0.2) for α and between 0.0°C and 0.6°C (in 0.1 degree increments) for $\Delta\bar{T}_c$.

Finally, the S-S model translates freshwater addition to flow in the THC. Yin (2004) and Yin, et al. (2005) show that this depends critically on the ratio of salinity transports by the gyre/eddies and the THC, represented by K . 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 $(\pi_i / 210)$, where π_i represents the likelihood of the various climate sensitivities.

A uniform prior on K was chosen based on the study by Yin (2004) and Yin et al. (2005) which 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 a coupled UIUC atmosphere-ocean general circulation model.

3. Some Simulation Results.

Figure 2 displays summary results in terms of 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.

Figure 3 presents the results in terms of an association between the expected value of the minimum THC intensity between now and 2205 and the maximum 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 degrees centigrade.

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 Figures 2 and 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.

4. Some Diagnostics.

Figure 5 displays the results of some contingent simulations that were conducted to identify the most important sources of uncertainty. 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 panels also 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. On the other side of the coin, however, the panels show, as well, that a value for K less than 0.5 would put the likelihood of a THC collapse at no less than 50%.

5. 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 a reason not to act.

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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 – 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 sources of uncertainty.

Figure 3 – 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.

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 .

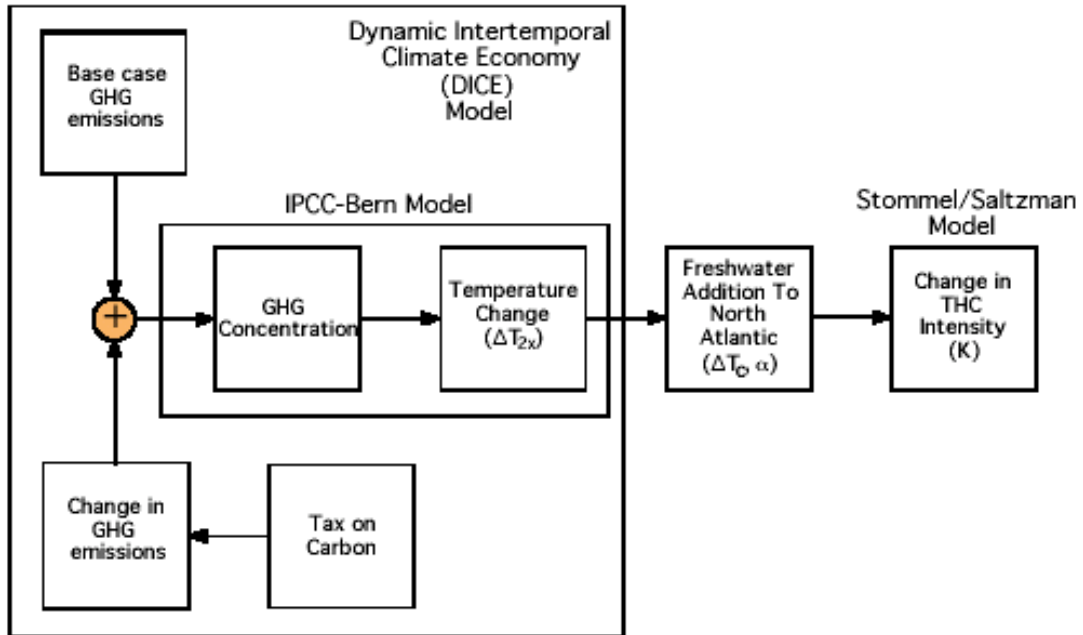


Fig.1

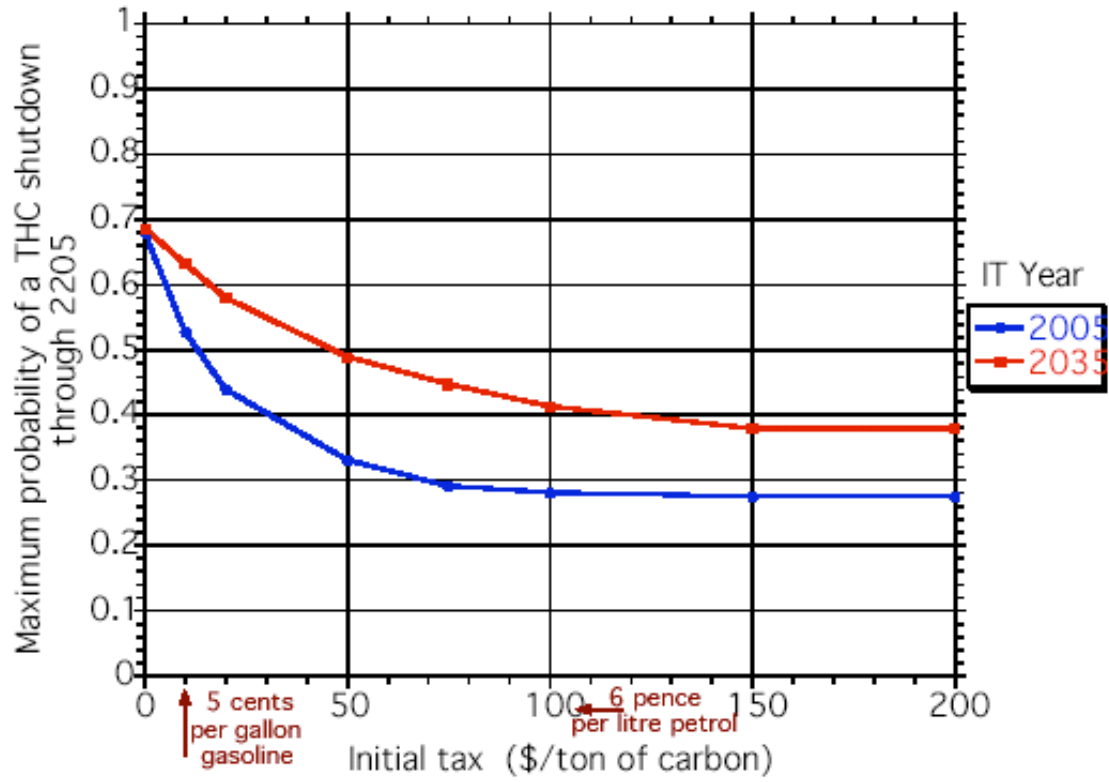


Fig.2

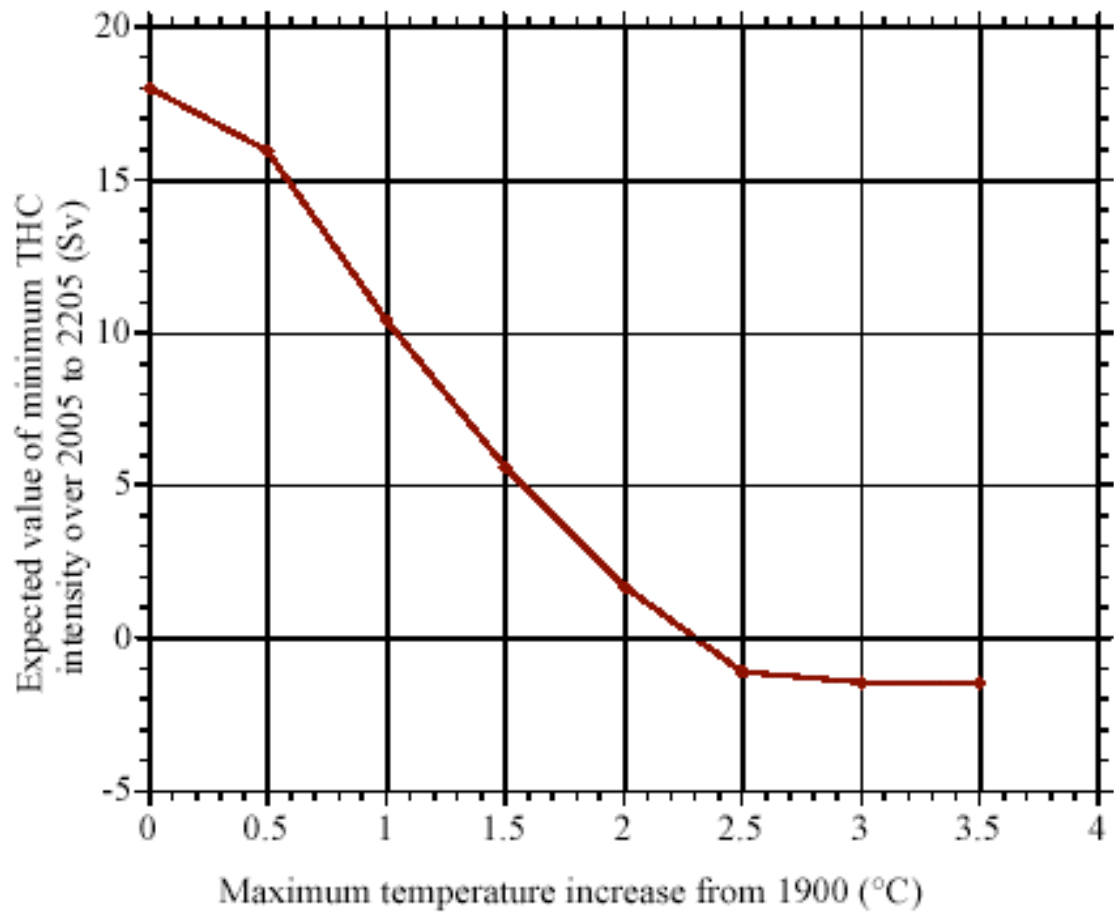


Fig.3

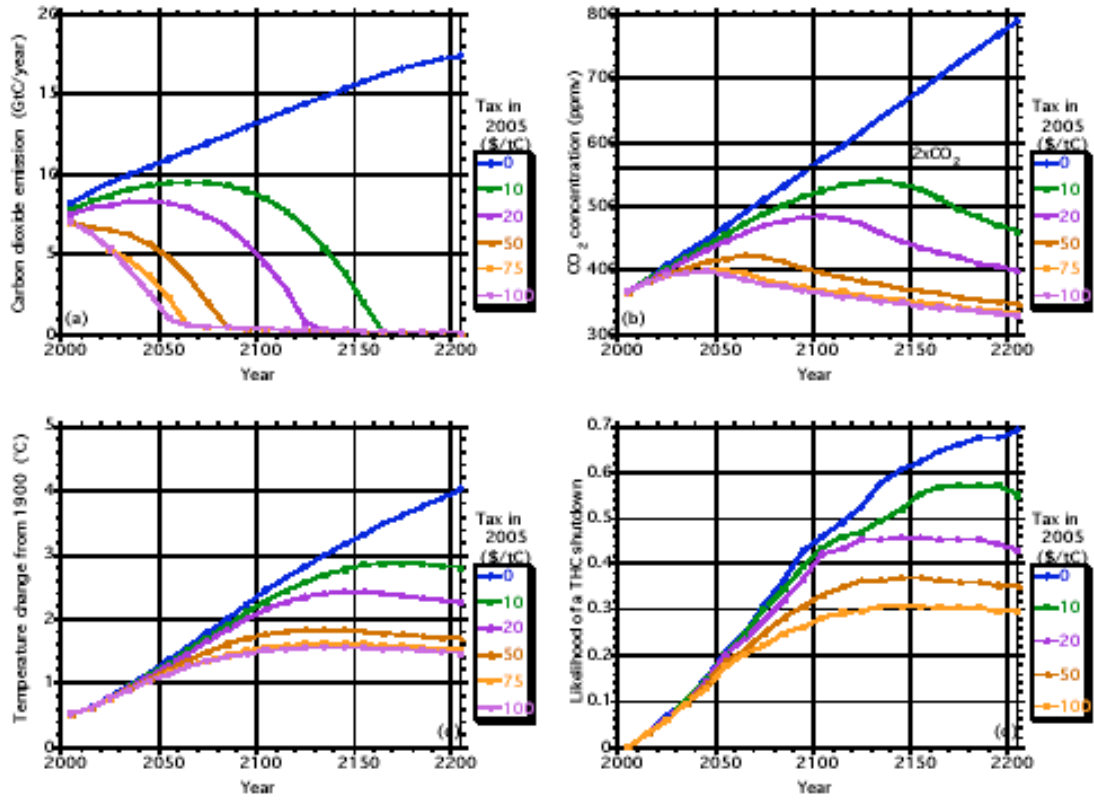


Fig.4

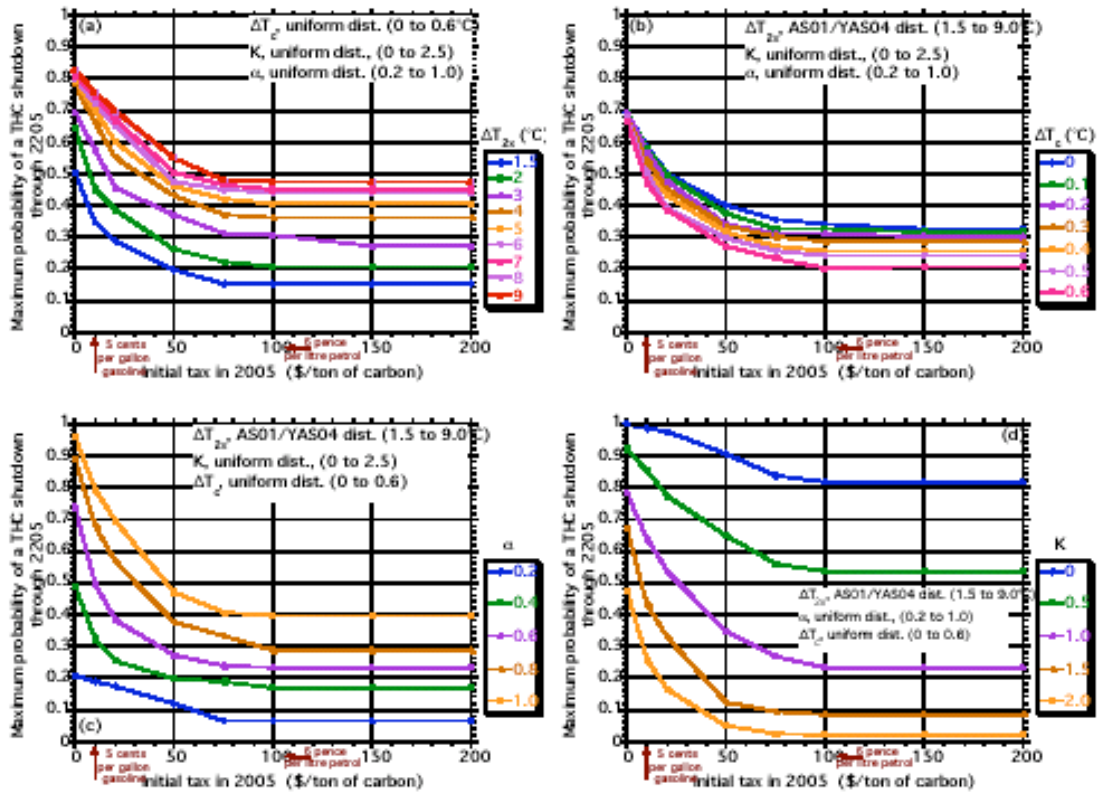


Fig.5