Assessing the Risk of a Collapse of the Atlantic Thermohaline Circulation

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Abstract

In this paper we summarize work performed by the Climate Research Group within the Department of Atmospheric Sciences at the University of Illinois at Urbana-Champaign (UIUC) and colleagues on simulating and understanding the Atlantic thermohaline circulation (THC). We have used our uncoupled ocean general circulation model (OGCM) and our coupled atmosphere-ocean general circulation model (AOGCM) to simulate the present-day THC and how it would behave in response to the addition of freshwater to the North Atlantic Ocean. We have found that the THC shuts down 'irreversibly' in the uncoupled OGCM but 'reversibly' in the coupled AOGCM, the latter because of a negative feedback that cannot exist in the uncoupled OGCM. We have represented this wide range of behaviour of the THC with an extended and simplified version of the original simple model that gave rise to the concern about the THC shutdown. We have used this simple model of the THC together with the DICE-99 integrated assessment model to estimate the likelihood of a THC shutdown between now and 2205, both without and with the policy intervention of a carbon tax on fossil fuels. We find that absent any climate policy, there is a greater than 50% likelihood of a THC collapse. This likelihood can be reduced by the policy intervention, but still exceeds 25%. It would therefore seem that the risk of a THC collapse is unacceptably large and that measures over and above the policy intervention of a carbon tax should be given serious consideration.

1. Introduction

The thermohaline circulation (THC) is the circulation in the Atlantic Ocean that is driven by temperature (thermo) and salt (haline) forcing over the ocean surface [1]. The zonally integrated meridional circulation in the Atlantic Ocean simulated by the UIUC coupled atmosphere/ocean general circulation model (AOGCM) in its control simulation for present-day conditions has sinking motion down to about 2500 m located near 60°N, with a clockwise circulation to the south and a counterclockwise circulation to the north (as viewed from Europe). In the clockwise circulation, water is transported from the Southern Hemisphere across the equator into the Northern Hemisphere above about 1000 m, with a return flow located below. For this reason the THC is often called the meridional overturning circulation (MOC). But this appellation is somewhat misleading. The ocean currents simulated by the AOGCM in the upper (0-1000 m) and deep (1000-3000 m) Atlantic Ocean are comprised of a western boundary current with flow toward the North Atlantic in the upper

ocean and flow toward the South Atlantic in the deep ocean. The MOC is the result of zonally integrating these strong currents across the Atlantic with the much weaker flow over most of the ocean basin. A longitude-depth cross-section of currents at 30°N has not only a strong southward current at depth off the east coast of North America, with the associated northward current above, but also a strong southward flow at the surface to the east. This is the southward flowing branch of the gyre circulation that is driven by the westerly winds in northern midlatitudes and easterly winds in the tropics. In fact, this gyre circulation contributes to the surface poleward flow off the east coast. As a result, it is difficult to completely separate the THC and gyre circulations.

The importance of the THC in the present climate is due to its net transport of heat northward at all latitudes in the Atlantic – the only ocean for which this is the case – with a maximum value of about a million billion watts (10^{15} watts, a petawatt). As a result of this northward heat transport, at least in part, Europe is up to 8°C warmer than other longitudes at its latitude, with the largest effect in winter. It is this comparatively mild European climate, as well as the interrelated climates elsewhere, that has given concern about the possible effect of a collapse of the THC, in terms of political and economic instability [2] and the onset of an ice age [3].

Why would the THC collapse? There are two threads of evidence that suggest this possibility. One is based on modelling and the other is drawn from paleoclimate evidence. The first model of the THC was developed by Henry Stommel [1]. In this very simple model, 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 for the present-day THC configuration or counterclockwise – a reversed THC. Many years later Barry Saltzman [4] simplified the model to consider only salt transport. He took the temperature difference between the boxes as being constant and extended the model to include 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.

As freshwater is added in the Stommel-Saltzman (S-S) model the THC intensity weakens because the density of the surface water in the polar box diminishes making it less able to sink. As increasing amounts of freshwater are added, the intensity continues to decrease, but only to a point. At this threshold or bifurcation point, this continuous behaviour ceases and is replaced by a nonlinear abrupt change to a counterclockwise reversed THC (RTHC). Further addition of freshwater enhances the intensity of this RTHC. More importantly, a reduction of the freshwater addition does not cause the circulation to return to the bifurcation point from which it came. Rather it weakens the RTHC. Eventually, if the freshwater addition is reduced sufficiently, another bifurcation point is reached such that the THC abruptly restarts. This irreversible behaviour of the THC in the S-S model results in hysteresis – the change in the system from one stable equilibrium to another and then back along a different path.

Why should there be an additional freshwater addition to the North Atlantic Ocean? The surface air temperature of central Greenland has been reconstructed as a function of time from about 15,000 years ago to the present based on the isotopic composition of an ice core that was drilled in the Greenland ice sheet [5]. The reconstruction shows a rise in surface air temperature at the end of the last Ice Age nearly 15,000 years ago followed by a return to Ice Age conditions thereafter for about 2000 years. During this episode an Arctic plant called Dryas arrived in Europe, hence the appellation Younger Dryas (Older and Oldest Dryas events having taken place earlier, 13,540–13,350 and 13,800–13,670 years before present, respectively [6]). Additional evidence of the Younger Dryas has been provided by terrestrial pollen records, glacial-geological data and marine sediments [7]. One of the seemingly more arcane indicators of the Younger Dryas has been provided by the remains of scarabs (beetles, not the Beatles) in the UK over the past 22,000 years [8]. All this evidence of abrupt cooling in the North Atlantic and Europe has been taken as being due to a collapse of the THC. This THC shutdown appears to have occurred as the meltwater from the retreating Laurentide ice sheet on North America, which had previously flowed to the Gulf of Mexico via the Mississippi River, instead flowed out the St. Lawrence waterway to the North Atlantic Ocean thereby freshening it sufficiently to halt the THC circulation.

So the THC has apparently collapsed in the past. Might it do so in the future as a result of global warming? The THC intensity simulated by 9 AOGCMs for a scenario of future greenhouse gas emissions [IS92a; 9] slows down or shuts down for all models but one [10]. As the world warms, both precipitation (P) and evaporation (E) increase over the North Atlantic, but the difference (P – E) also increases there. Freshwater is thereby added to the ocean and reduces the density of the surface water and thus its ability to sink [11].

In the AOGCM simulations of a greenhouse-gas (GHG)-induced slowdown or shutdown of the THC, the resulting climate change is due to both the increased concentrations of GHGs and to the THC shutdown. However, the magnitude of GHG-induced climate change required to slowdown or shutdown the THC is highly uncertain. Thus it is desirable to separate the THC-induced climate change from the GHG-induced climate change so that they can subsequently be combined to address a series of critical questions. Suppose the THC begins to slowdown for a change of global-mean surface air temperature of x°C due to increased concentrations of GHGs. (1) What would the resulting climate changes look like? (2) What would the impacts of those changes look like?, and (3) What near-term policies are robust against the uncertainty of a THC slowdown/shutdown [12]?

We began a program of research in 1999 that would allow us to answer the first of these questions by simulating the slowdown and shutdown of the THC using our AOGCM. This work is described by Yin [13] and Yin et al. [14], and the construction of geographical distributions of THC-shutdown-induced climate change by Schlesinger et al. [15]. In performing our THC-shutdown simulations, first with our uncoupled ocean GCM (OGCM) and then with it coupled to our atmospheric GCM, we obtained an unanticipated result. Like all other simple models [16-22] beginning with that of Stommel [1], the OGCM simulated an irreversible THC shutdown. By way of contrast, though, the AOGCM simulated a reversible THC shutdown. Below we describe this finding and note that the S-S model can reproduce not only the irreversible THC shutdown, but also the reversible THC shutdown. We shall also discuss some of the climate changes induced by the THC collapse simulated by our AOGCM. Subsequently we shall use the S-S model with wide-ranging behavior to examine how to reduce the risk of a THC collapse.

2. Simulations of the THC Shutdown with the UIUC OGCM and AOGCM

In this section we describe the freshwater perturbation experiments that we have performed with our OGCM and AOGCM, discuss the climate changes induced by a collapse of the THC, and describe how the S-S model is capable of simulating a range of THC shutdown behaviour, from an irreversible collapse to a reversible one.

2.1: Freshwater Perturbation Experiments

The freshwater perturbation experiments with the uncoupled OGCM were performed by very slowly increasing and then decreasing the external freshwater addition to the North Atlantic between 50°~70°N latitudes [22]. The freshwater perturbation changes at a rate of 0.2 Sv (Sv = 10^6 m^3/sec) per 1000 years. Although the setup of the experiment is a transient run, the THC is always in quasi-equilibrium with the external freshwater forcing due to the extremely slow change of the freshwater perturbation flux. To facilitate comparison with the AOGCM simulations, several steady-state runs with fixed freshwater perturbations were also carried out using the uncoupled OGCM.

The set of the AOGCM simulations was performed for fixed freshwater addition ("hosing") and removal ("dehosing") rates over the same latitude band in the North Atlantic as for the OGCM-only simulations. Two groups of freshwater perturbation experiments were carried out to test the response of the THC. The first group included three "hosing" experiments starting from the 30th year of the control run. Perturbation freshwater fluxes of 0.05, 0.1, 0.3 Sv were uniformly input into the perturbation region in separate experiments. The 110th year of the control run was chosen as the initial condition for the second group. This group consisted of three "hosing" experiments (0.1, 0.3 and 0.6 Sv) and two "dehosing" experiments. The

two "dehosing" experiments started from the shutdown state of the THC induced by 0.6 Sv freshwater addition, and included a moderate reduction of the perturbation flux from 0.6 to 0.3 Sv and the total elimination of the 0.6 Sv freshwater addition.

The strength of the THC simulated by the uncoupled OGCM with boundary conditions of prescribed heat and freshwater fluxes from the atmosphere has a pronounced hysteresis loop in which the THC, after shutdown, can be restarted only after the freshwater addition is eliminated and changed into a freshwater extraction. This irreversibility of the THC shutdown, if true, would warrant the use of precaution in formulating climate policy.

In contrast, the strength of the THC simulated by the AOGCM does not have a hysteresis loop when the freshwater added to the North Atlantic is increased until shutdown occurs and is then reduced. Instead, once the freshwater addition is reduced from its shutdown value, the THC restarts. Furthermore, the relation between the THC intensity and the change in freshwater addition is roughly linear throughout the entire range of freshwater addition. Moreover, the freshwater addition required to shut down the THC is much larger for the AOGCM than for the uncoupled OGCM.

Why does the THC behave differently in the uncoupled OGCM and the AOGCM? Yin [13] and Yin et al. [14] investigated this question and found that the salinity increases in the Caribbean in the AOGCM simulation of the THC shutdown because the intertropical convergence zone shifts from the Northern Hemisphere into the Southern Hemisphere, thereby decreasing the precipitation over the Caribbean. The resulting more dense, salty water is then transported poleward by the gyre circulation in the North Atlantic. This acts as a negative feedback on the THC shutdown which works both to make it more difficult to shut down the THC – a larger freshwater addition is required than in the uncoupled OGCM – and help restart the THC when the freshwater added to shut down the THC is reduced. This negative feedback cannot exist in the uncoupled OGCM simulations because of the need therein to prescribe boundary conditions in the atmosphere.

2.2: Climate Changes Induced by a THC Shutdown

In the 0.6 Sv hosing experiment simulated by the AOGCM, the clockwise meridional circulation of the control run is eliminated. A clockwise circulation near 15°N latitude at the surface remains due to the wind-driven gyre circulation. The ocean currents in the upper (0-1000 m) and deep (1000-3000 m) Atlantic Ocean simulated by the AOGCM of the control run both collapse in the 0.6 Sv hosing simulation. The counterclockwise Antarctic Bottom Water (AABW) circulation centered near 3000 m that is caused by water sinking off the West Antarctic coast is little influenced by the shutdown of the THC in the North Atlantic.

The January and July surface air temperatures resulting from the THC shutdown in the 0.6 Sv simulation is lower over the U.S. midwest, Greenland, the North Atlantic Ocean and Europe, with larger cooling in winter than in summer. Interestingly, strong warming occurs over Alaska and the Palmer Peninsula in Northern Hemisphere and Southern Hemisphere winter, respectively. If such a simulated warming were to occur, it would likely harm the Alaskan permafrost and the West Antarctic ice sheet which is grounded on the ocean floor.

2.3: Replication of the THC Shutdown by a Simple Model

As noted in the Introduction, it was the simple two-box model proposed by Stommel [1] that raised the first alert that the Atlantic thermohaline circulation could collapse irreversibly if sufficient freshwater were added there to reach its threshold bifurcation point. Here we describe how this model, as generalized by Saltzman [4], can replicate not only an irreversible THC collapse, as obtained by all simple models, but also the reversible THC shutdown described above which is obtained by most AOGCMs [13].

The THC simulated by the S-S model exhibits sharply different behaviour for different values of the ratio of the transport coefficient for the gyre circulation and eddies to that for the THC, characterized by K. For K = 0 (the case examined by Stommel [1]) there is an unstable equilibrium circulation connecting two stable equilibrium circulations; one displays sinking in high latitudes and upwelling in low latitudes while the other moves in the opposite direction. As K increases from zero to unity, the range examined by Saltzman [4], the region of the unstable equilibrium shrinks. Larger values of freshwater addition are required to weaken the THC intensity to any particular value. When K takes the value of unity, the unstable equilibrium circulation disappears, and the two stable equilibrium circulations merge. In this case the flow between the two boxes is the combination of wind-driven flow and thermohaline flow. The contribution of the wind-driven flow to the poleward salinity transport is significant. As K is increased above unity – a case examined by Yin [13] and Yin et al. [14] – still larger values of freshwater addition are required to weaken the THC to any particular intensity, and the discontinuity in slope between the two stable circulations decreases. The curve gradually approaches a straight line with increasing K. In this case, the contribution of the non-THC flow to the mass exchange dominates that of the thermohaline flow.

When the S-S model is run in a hosing–dehosing simulation like that of the OGCM and AOGCM, the result for K = 0 shows the classical hysteresis loop of the Stommel model. Much weaker hysteresis is obtained for K = 1, and it is shifted toward larger values of freshwater addition. As K increases upward from unity the slopes of the two stable modes approach each other and the hysteresis disappears at about K = 2.5. This behaviour is remarkably similar to the transition from the hysteresis loop simulated by the uncoupled OGCM to the single curve simulated by the coupled AOGCM.

3. Assessing the Risk of a THC Collapse

We are now in a position to ask 'How likely is a collapse of the Atlantic thermohaline circulation?', and if not highly unlikely, 'How can we reduce the risk of a THC shutdown?' We will use the S-S model together with a simple Integrated Assessment Model, the Dynamic Integrated Climate Economy (DICE) model developed by Bill Nordhaus [23]; the version we use is DICE-99 [24].

DICE-99 uses a submodel (the IPCC-Bern model) to calculate time-dependent GHG concentrations, radiative forcings, and change in global-mean surface air temperature from a base-case of greenhouse-gas emissions. For the latter, the climate sensitivity (the change in the equilibrium global-mean surface air temperature due to a doubling of the pre-industrial CO_2 concentration, ΔT_{2x}) must be prescribed. For this we use the probability density function (pdf) calculated by Andronova and Schlesinger [25] from the observed record of surface air temperature from 1856 through 1997, as discretized by Yohe et al. [26]. Because simple climate models have simulated an irreversible THC shutdown, akin to K = 0 in the S-S model, while our and other AOGCM's simulate a reversible THC shutdown, akin to K = 2.5 in the S-S model, we take K in the S-S model to be uncertain with a uniform pdf between these values. To close the problem we specify the (non-dimensional) amount of freshwater added to the North Atlantic, $\Pi(t)$, as a function of the change in global-mean surface air temperature simulated by DICE-99, $\Delta \overline{T}(t)$. Results from simulations by our atmospheric GCM coupled to a 60 m deep mixed-layer ocean model for several different radiative forcings [15, 27] suggest the linear relationship,

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

where

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

is the Heaviside step function and α is the 'hydraulic sensitivity". The Heaviside step function is introduced to prevent any freshwater addition until a critical temperature change is reached, $\Delta \overline{T}_c$. We treat both α and $\Delta \overline{T}_c$ as uncertain independent quantities with uniform pdf's between 0.2 and 1.0 $\left(1/^{\circ}C\right)$ and between 0 and 0.6°C, respectively [28]. The policy instrument within DICE is a tax on the carbon content of fossil fuels, from an initial tax of $10 a ton of carbon (tC) – about 5 cents a gallon of gasoline – to $100 per tC – about 6 pence per liter of petrol. This carbon tax rises in time at the then prevailing interest rate that is determined by the model. The tax can be considered as economic "shorthand" for a wide range of possible policy interventions such as the Clean Development Mechanism and Joint Implementation.

We now address the question: 'How likely is a collapse of the Atlantic thermohaline circulation?' For the base-case CO_2 emission from 2005 to 2205 and $\Delta T_{2x} = 3^{\circ}C$, the likelihood of a THC shutdown obtained over the uniform probability distributions for K, α and $\Delta \overline{T}_c$ rises monotonically to 4 in 10 in 2100 and 65 in 100 in 2200.

Having found that the collapse of the Atlantic thermohaline circulation is not highly unlikely, we now address the question: 'How can we reduce the risk of a THC shutdown?' Policy intervention in the form of a carbon tax: (1) reduces the CO_2 emission to zero, earlier the larger the initial tax; (2) causes the CO_2 concentration to peak and then decrease as the carbon sinks begin to dominate the declining CO_2 emission, earlier the larger the initial tax; and (3) causes the global-mean surface temperature change to peak and then decrease in response to the declining CO_2 concentration, to lower values the larger the initial tax. As a result, mitigation can cause the likelihood of a THC shutdown to peak, with lower maximum probabilities (MP) associated with larger initial taxes.

We now consider MP as a function of the initial tax in 2005 (IT) contingent on: (a) climate sensitivity, ΔT_{2x}; (b) the critical temperature threshold for the input of freshwater into the North Atlantic, $\Delta \overline{T}_c$; (c) the hydraulic sensitivity, α; and (d) the ratio of the salt transport by the non-THC oceanic motions to that by the THC, K. Each of these likelihoods is obtained over the probability distributions of the three non-contingent quantities. For example, for the contingency on ΔT_{2x}, the likelihood is calculated over the probability distributions for $\Delta \overline{T}_c$, K and α. It is found that MP decreases with increasing IT, but at a decreasing rate that falls to zero when IT reaches $100/tC. Also, the MP for any IT is most sensitive to K; that is, whether the shutdown of the THC is irreversible (small K) or reversible (large K). The MP–IT relationship is also sensitive to the uncertainty in hydraulic sensitivity, α, and climate sensitivity, ΔT_{2x}, but less so than to the uncertainty in K. Lastly, the MP–IT relationship is relatively insensitive to the uncertainty in the threshold, $\Delta \overline{T}_c$.

MP as a function of IT beginning in 2005, obtained over the probability distributions of all four uncertain quantities K, α, ΔT_{2x} and $\Delta \overline{T}_c$, is reduced from a 65 in 100 occurrence for no initial tax to a 28 in 100 occurrence for an initial tax of $100/tC. If the tax is initiated 30 years later in 2035, then the $100/tC tax reduces the 65 in 100 likelihood to a 42 in 100 likelihood, and a $200/tC tax somewhat further to a 38 in 100 occurrence. These are disquieting findings.

4. Conclusion

At this stage in a scientific paper it is customary to mention the caveats of the study, and we do so here. We have used, of necessity, very simple models of the Earth's climate system, within DICE-99, and of the Atlantic thermohaline circulation, the S-S model. Note, though, that the latter does contain the original Stommel model (for $K = 0$) that gave rise to the concern about the possible collapse of the THC. Accordingly, one should take the quantitative results with caution. Having so said, one cannot but be taken by the fact that absent any climate policy, there appears to be a greater than 50% likelihood of a collapse of the Atlantic THC. Furthermore, even with the policy intervention of a carbon tax there appears to be a greater than 25% likelihood of a collapse. Such high probabilities are worrisome. Of course they should be

checked by additional modelling studies. But, if these future studies find similar results, it would seem that the risk of a THC collapse is unacceptably large and, therefore, that measures over and above the policy intervention of a carbon tax be given serious consideration.

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