Reducing the Risk of a Collapse of the Atlantic Thermohaline Circulation

Avoiding Dangerous Climate Change
A Scientific Symposium on Stabilisation of Greenhouse Gases
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Conclusions

• Absent climate policy, the likelihood of a THC collapse sometime over the next 200 years is more than 2 chances in 3.
• The likelihood declines with mitigation, but even the most rigorous immediate climate policy would leave a 1 in 4 chance of a THC collapse.
• Waiting 30 years to act increases the odds to more than 1 chance in 3.
Outline

• Introduction to the Thermohaline Circulation

• Avoiding a Shutdown of the THC
Simulated THC, Control Run
The Ocean Currents (simulation)

Upper ocean (0~1000 m)  Deep ocean (1000~3000m)
Simulated THC, Control Run

30° N

50° N

N. America  Europe  N. America  Europe
The importance of the THC in the present climate

Trenberth et al. 2001
The importance of the THC in the present climate
Introduction

• Article 2 of the UN Framework Convention on Climate Change calls for the avoidance of “dangerous anthropogenic interference with the climate system”.

• Some climate models have shown that a slowdown/shutdown of the thermohaline circulation (THC) is one such possible dangerous interference.
Stommel Model

Figure 11.4  The two-box ocean system comprising a low-latitude box (o) and a polar box (p) connected by a volume exchange Q.

Figure 11.5  Bifurcation diagram showing the equilibrium values of the nondimensionalized volume flux by the T11 circulation, ψ, for the two-box ocean system, as a function of the "external" forcing function Π(λ, μ, θ).
The THC is a key factor to explain past abrupt climate changes

Alley (2000)
Figure 9.21: Simulated water-volume transport change of the Atlantic "conveyor belt" (Atlantic overturning) in a range of global warming scenarios computed by different climate research centres. Shown is the annual mean relative to the mean of the years (1961 to 1990) (Unit: SV, $10^6$ m$^3$/s$^{-1}$). The past forcings are only due to greenhouse gases and aerosols. The future-forcing scenario is the IS92a scenario. See Table 9.1 for more information on the individual models used here.
An Abrupt Climate Change Scenario and Its Implications for United States National Security
October 2003

By Peter Schwartz and Doug Randall

Imagining the Unthinkable

The purpose of this report is to imagine the unthinkable – to push the boundaries of current research on climate change so we may better understand the potential implications on United States national security.

We have interviewed leading climate change scientists, conducted additional research, and reviewed several iterations of the scenario with these experts. The scientists support this project, but caution that the scenario depicted is extreme in two fundamental ways. First, they suggest the occurrences we outline would most likely happen in a few regions, rather than globally. Second, they say the magnitude of the event may be considerably smaller.

We have created a climate change scenario that although not the most likely, is plausible, and would challenge United States national security in ways that should be considered immediately.

Executive Summary

There is substantial evidence to indicate that significant global warming will occur during the 21st century. Because changes have been gradual so far, and are projected to be similarly gradual in the future, the effects of global warming have the potential to be manageable for most nations. Recent research, however, suggests that there is a possibility that this gradual global warming could lead to a relatively abrupt slowing of the ocean’s thermohaline conveyor, which could lead to harsher winter weather conditions, sharply reduced soil moisture, and more intense winds in certain regions that currently provide a significant fraction of the world’s food production. With inadequate preparation, the result could be a significant drop in the human carrying capacity of the Earth’s environment.

The research suggests that once temperature rises above some threshold, adverse weather conditions could develop relatively abruptly, with persistent changes in the atmospheric circulation causing drops in some regions of 5-10 degrees Fahrenheit in a single decade. Paleoecological evidence suggests that altered climatic patterns could last for as much as a century, as they did when the ocean conveyor collapsed 8,200 years ago, or, at the extreme, could last as long as 1,000 years as they did during the Younger Dryas, which began about 12,700 years ago.
THE DAY AFTER TOMORROW
WHERE WILL YOU BE?
IN THEATRES WORLDWIDE MAY 28, 2004
THC Intensity Versus Freshwater Addition

(a) Uncoupled OGCM with prescribed heat & salinity fluxes

(c) A/O GCM

\[ Y = M_0 + M_1 X \]

- \( M_0 = 16.199 \)
- \( M_1 = -25.101 \)
- \( R = 0.97866 \)
Simulated THC, Control Run
Simulated THC, 0.6 Sv Run
0–1000m and 1000-2500m
Currents in the Control Run
0–1000 m and 1000-2500m
Currents in the 0.6 Sv Run
SAT Difference, Jan

SAT DIF 0.6 Sv Jan

[Map showing SAT difference]
SAT Difference, July
K is the ratio of the transport coefficient for the gyre circulation and eddies, to that for the THC.
Stommel/Saltzman Model

\[ \frac{ds}{dt^*} = \Pi - |1 - s| s - Ks \]

s is dimensionless difference in salinity between tropical and polar boxes, 
t\( t^* \) is dimensionless time, 
\( \Pi \) is the dimensionless freshwater addition, 
\( K \) is the ratio of the transport coefficient for the gyre circulation and eddies, \( k_\phi \), to that for the THC, \( k_\psi \). 
In the Stommel model, \( K = 0 \). In the Saltzman model, \( 0 \leq K \leq 1 \).
The maximum streamfunction of the THC is 
\[ \Psi = k_\psi \mu_T \delta T^* (1 - s) \]

where \( \mu_T \) is the thermal volume expansion coefficient, and \( \delta T^* \) is the temperature difference between the equatorial and polar boxes, taken to be constant.
Stommel–Saltzman Model Behavior

Stability Diagram

Hosing/De-Hosing
Outline

• Introduction to the Thermohaline Circulation

• Avoiding a Shutdown of the THC
To Hedge or Not Against an Uncertain Climate Future?

Gary Yohe, Natasha Andronova, Michael Schlesinger

It has been over a decade since Nordhaus (7) published his seminal paper on mitigation policy for climate change. His question was "To slow or not to slow?"; his answer was derived from a traditional cost-benefit approach. He found that a tax levied on fossil fuel in proportion to its carbon content, which would climb over time at roughly the rate of interest, maximized global welfare. Although many more analyses of the same question have since been published, his results are still robust if one assumes a deterministic world in which decision-makers are present. However, no decision-maker has perfect foresight, and the uncertainty that clouds our view of the future has led some to argue that near-term mitigation of greenhouse gas emissions would be foolish. Such policy would impose immediate costs, they argue, and have uncertain long-term benefits.

We take a different approach in this Policy Forum by assuming that decision-makers will someday become so concerned about the potential damages associated with climate change that they will take action. Even though it is impossible to determine exactly what sort of mitigation target these future policies might ultimately adopt, a "wait-and-see" approach may no longer be the best near-term policy choice. Should we move soon to intervene in global energy markets as a hedge against the expected cost of meeting a currently unknown policy target?

We follow the modeling approach adopted in the hedging experiments conducted by Munn (2) and Yohe (3) for the Energy Modeling Forum to explore the policy implications of extreme events. Our analysis is based on a modified version of DICE-99 (Dynamic Integrated Model of Climate and the Economy)—a widely respected model of global economic activity and the damages associated with greenhouse gas-induced temperature change (4). We assume that decision-makers evaluate the economic merits of implementing near-term global mitigation policies starting in 2005 that will be in force for 30 years. They know that they will be able to "correct" their policy in 2035, and we assume that decisions will be informed by perfect information about both the climate sensitivity and the policy target. Their goal will be to maximize the expected discounted value of gross world product (GWP, the global equivalent of gross domestic product) across the range of options that will be available at that time (see online material for details and definitions).

The uncertainty in our understanding of the climate system against which these policies will be framed is portrayed in the figure (below). It shows a continuous cumulative distribution function (CDF) of climate sensitivity estimated by Andronova and Schlesinger (5) (where climate sensitivity is the temperature increase that results from a doubling of atmospheric concentration of greenhouse gases relative to preindustrial levels). It also shows a version of the same CDF that allowed for, reasons of practicality, to work with a limited number of sensitivities that were nonetheless representative of the continuous CDF. Each sensitivity is associated with a probability, so that if it were used for the continuous version. Both representations show that climate sensitivities as high as 9°C are possible.

Several structural and calibration modifications of the DICE-99 model were required to accommodate the wide range displayed in the figure. Because responding to high sensitivities could be expected to put enormous pressure on the consumption of fossil fuel, for example, we limited the rate at which the global economy could "decarbonize" itself (i.e., reduce the ratio of carbon emissions to global economic output) to 1.5% per year.

Calibrating the DICE-99 model to alternative climate sensitivities that span the range displayed in the figure was more involved, because the DICE model includes a parameter that reflects the inverse thermal capacity of the atmospheric layer and the upper oceans. Larger climate sensitivities were associated with smaller inverse capacity values, so that the model could match observed temperature data when run in the historical past. The parameter was defined from optimization of the global temperature departures calculated by DICE and calibrated against the observed departures from Jones and Moberg (6) for the prescribed range of the climate sensitivities from 1.5°C to 6°C (7).

Modest near-term mitigation would maximize discounted GWP, even if no mitigation was done after 2035 (see the supporting online text). Achieving optimality or even meeting specific concentration targets would not, however, necessarily hold temperatures below the 2°C to 3°C range identified by Stain and Hitz (8) and the Intergovernmental Panel on Climate Change (IPCC) (9), as a threshold above which damages caused by gradual climate change would climb dramatically, and by Schneider (10) and the IPCC (9), as a threshold above which abrupt changes become much more likely. We therefore focused our attention on mitigation pathways designed to limit temperature increases to four targeted levels (recorded in the first row of the table, next page) that straddle this critical threshold.

We assumed that global policy-makers would choose among these options in 2035, when the true climate sensitivity would be revealed: but each target was assumed to be equally likely for the purposes of setting near-term policy in 2005. Maximum discounted GWP was computed using the modified DICE-99 framework for initial 2005 taxes ranging from $0 to $50 per ton of carbon. Some combinations involved doing too little in the near term, so GWP fell as downstream mitigation "ramped-up" to achieve the prescribed temperature limit. Other combinations involved doing too much in the near term, so GWP fell even though mitigation could be "turned down" after 2035. An in-
Integrated Assessment Model

Base case GHG emissions

Dynamic Integrated Climate Economy (DICE) Model

IPCC-Bern Model

Change in GHG emissions

Temperature Change ($\Delta T_{2x}$)

Freshwater Addition To North Atlantic ($\Delta T_{c, \alpha}$)

Stommel-Saltzman Model

Change in THC Intensity (K)

Tax on Carbon
Uncertain Quantities

$\Delta T_{2x}$, climate sensitivity: 9 values from 1.5°C to 9.0°C taken with probability $p_i$, $i = 1, \ldots, 9$ given by Andronova & Schlesinger (2001, Geophys Res. Let.);

$\Delta T_c$, threshold of temperature change since 1856 for onset of a THC slowdown: 7 values taken from 0°C and 0.6°C in 0.1°C increments, each with equally likely probability;

$\alpha$, hydraulic sensitivity – amount of freshwater added to North Atlantic per degree of global warming: 5 values from 0.2 to 1.0 in 0.2 increments, each with equally likely probability;

$K$, ratio of poleward salt transport by non-THC (gyre & eddies) to that by THC: 5 values from 0 to 2.5 in 0.5 increments, each with equally likely probability;

All $9 \times 7 \times 5 \times 5 = 1575$ combinations run. The relative likelihood of any combination depends on the underlying $\Delta T_{2x}$ according to $\{p_i / 1575\}$. 
Climate Sensitivity, $\Delta T_{2x}$

Andronova & Schlesinger (S2)

This paper
Maximum probability of a THC shutdown through 2205

Initial tax ($/ton of carbon)

IT Year

- 2005
- 2035

5 cents per gallon gasoline

6 pence per litre petrol

Climate Research Group
Expected value of minimum THC intensity over 2005 to 2205 (Sv)

Maximum temperature increase from 1900 (°C)
Conclusions

• Absent climate policy, the likelihood of a THC collapse sometime over the next 200 years is more than 2 chances in 3.

• The likelihood declines with mitigation, but even the most rigorous immediate climate policy would leave a 1 in 4 chance of a THC collapse.

• Waiting 30 years to act increases the odds to more than 1 chance in 3.
Nice Planet We Have. Let’s Keep It That Way. Shall We? Thank you!
Changes in the THC Intensity
Stommel/Saltzman Model

\[
\frac{ds}{dt^*} = \Pi - |1-s| s - Ks
\]

s is dimensionless difference in salinity between tropical and polar boxes, 
t* is dimensionless time, 
\(\Pi\) is the dimensionless freshwater addition, 
K is the ratio of the transport coefficient for the gyre circulation and eddies, \(k_\phi\), to that for the THC, \(k_\psi\). 
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