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Reducing the risk of a collapse of the Atlantic thermohaline circulation: A comment

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Abstract

Yohe et al. (2006) use a collection of reduced-form models to estimate the likelihood of a collapse of the thermohaline ocean circulation (THC) under different levels and timings of climate mitigation policy considering four sources of uncertainty in the climate system. The representation of uncertainty about future global mean temperature change in this study assumes a deterministic relationship between climate sensitivity and a model parameter related to ocean heat uptake. This assumption leads to an underestimation of the uncertainty and magnitude of transient climate change. As a result, both the importance of climate sensitivity compared to other uncertain model parameters and the likelihood of a THC breakdown are significantly underestimated in this study.

1 Introduction

Yohe et al. (2006) use a collection of reduced-form models to estimate the likelihood of a collapse of the thermohaline ocean circulation (THC) under different levels and timings of climate mitigation policy. They consider four sources of uncertainty by including an empirical probability distribution for climate sensitivity and uniform distributions for three uncertain parameters of the THC model. I welcome the general approach of this study, which is an innovative contribution to the debate how to avoid 'dangerous' climate change. However, the specific representation of uncertainty about future climate change in this study wrongly excludes high estimates of transient climate change, with significant implications for its quantitative results. I will substantiate this claim by (a) sketching the representation of uncertainty about future climate change in Yohe et al. (2006), (b) comparing projections of 21st-century climate change in Yohe et al. (2006) with other published studies, and (c) discussing the relevance of this deviation.

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2 Probabilistic application of the DICE climate model

There is some vagueness about the climate model applied in Yohe et al. (2006). Figure 1 depicts the IPCC-Bern Model as a component of the Dynamic Integrated Climate Economy (DICE) model, which is not the case. In contrast, the text states *"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"* (p. 58), suggesting that a (recalibrated) version of the DICE-99 climate model was applied. This interpretation is also supported by the description of the probabilistic representation of the climate system, which closely links the analysis discussed here to an earlier analysis by the same authors: *"The discrete version of this density function [of climate sensitivity] employed by Yohe et al. (2004) was imported here to span a range from 1.5*°C *to 9*°C.*"* Since the global mean temperature (GMT) projections for the DICE-99 reference emissions scenario in Yohe et al. (2004, Figure S1) and Yohe et al. (2006, Figure 2) are very similar, I assume in the following discussion that the detailed description of the probabilistic representation of climate change in Yohe et al. (2004, Supporting Online Material) applies to Yohe et al. (2006) as well.

DICE-94 and DICE-99 apply the same climate model, except for various changes in the names of model variables and parameters (Nordhaus & Boyer, 2000, p. 62–67). This climate model is based on a two-box model by Schneider & Thompson (1981):

$$\dot{T}_{up} = \frac{1}{R_1}\cdot\left(F - \frac{F_{2\times}}{T_{2\times}}\cdot T_{up} - \frac{R_2}{\tau_{12}}\cdot\left(T_{up}-T_{lo}\right)\right) \tag{1}$$

$$\dot{T}_{lo} = \frac{1}{\tau_{12}}\cdot\left(T_{up}-T_{lo}\right) \tag{2}$$

The three time-dependent variables and five parameters of this model are:

$T_{up}(t)$	$[^\circ\mathrm{C}]$	temperature of the atmosphere and upper ocean
$T_{lo}(t)$	$[^\circ\mathrm{C}]$	temperature of the deep ocean
$F(t)$	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$	net change in radiative forcing
$T_{2\times}$	$[^\circ\mathrm{C}]$	equilibrium increase in GMT from a CO_2 doubling
$F_{2\times}$	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$	increase in radiative forcing from a CO_2 doubling
R_1	$\left[\frac{\mathrm{W\,yr}}{^\circ\mathrm{C\,m}^2}\right]$	thermal capacity of the atmosphere and upper ocean
R_2	$\left[\frac{\mathrm{W\,yr}}{^\circ\mathrm{C\,m}^2}\right]$	thermal capacity of the deep ocean
τ_{12}	[yr]	time scale of heat transfer from upper to deep ocean

The two most uncertain parameters in this model are $T_{2\times}$, which determines the equilibrium change in GMT, and τ_{12}, which determines the speed of adjustment

(Allen et al., 2000; Wigley & Raper, 2001; Knutti et al., 2005). The values of the other three parameters are relatively well known. In particular, R_1 can be easily determined from mixed layer depth.

The DICE climate model combines the five physical parameters of the original model into four parameters, most of which can no longer be interpreted physically: $C1 = \frac{1}{R_1}$, $LAM = \frac{F_{2\times}}{T_{2\times}}$, $C3 = \frac{R_2}{\tau_{12}}$, and $C4 = \frac{1}{\tau_{12}}$. In this formulation, LAM, $C3$, and $C4$ are associated with large uncertainty (since they depend on the highly uncertain parameters $T_{2\times}$ or τ_{12}), whereas $C1$ is much less uncertain (since it depends only on the relatively well known parameter R_1). Hall & Behl (2006, p. 458) point out that $C3$ and $C4$, described as "the two least important parameters" by Nordhaus (1994, p. 40), "are important for understanding even short-term climate change".

Even though $C1$ is much less uncertain than $C3$ and $C4$, Nordhaus (1994, Chapter 3) sets out to calibrate $T_{2\times}$ and $C1$, using historical data as well as results from GCM experiments. The joint probability density function (PDF) for these two parameters constrained by historical forcing and temperature data shows a negative correlation between $T_{2\times}$ (varied from 1–5 °C) and $C1$ (varied from 0.01–0.1 $\frac{{}^\circ\mathrm{C}\,\mathrm{m}^2}{\mathrm{W}\,\mathrm{yr}}$), but the conditional PDF for $C1$ given $T_{2\times}$ is often rather flat (Nordhaus, 1994, p. 43). The variation of $C1$ by a factor 10 is inconsistent with established knowledge about the physically plausible range of R_1, where upper and lower estimates differ by a factor 2 at best (de Boyer Montégut et al., 2004).

Several factors contribute to the calibration of $C1$ outside its physically plausible range. First, Nordhaus (1994) reformulated the climate model by Schneider & Thompson (1981) in such a way that most parameters can no longer be physically interpreted. As a result, it became more difficult to focus on the main sources of uncertainty, and to identify all available data for constraining the range of individual parameters. Second, Nordhaus (1994) calibrated a parameter with small uncertainty while prescribing parameters with larger uncertainty. As a result, the observed data could only be reproduced when the less uncertain parameter was varied outside its physically plausible range. Third, Nordhaus (1994) attempted to explain all variations in GMT by rising concentrations of GHG since the cooling effect of aerosols was less well established at that time.

I have devoted so much attention to the description of the DICE climate model because the problems mentioned above were instrumental for the introduction of an additional flaw in the probabilistic analyses with DICE-99 by Yohe et al. (2004) and Yohe et al. (2006). These analyses represent the uncertainty about future GMT change by a single uncertain parameter. Analogous to the approach in Nordhaus (1994, Chapter 3), $T_{2\times}$ and $C1$ are calibrated using a large ensemble of climate projections. Yohe et al. assign a single value for $C1$ to each value of $T_{2\times}$ (Yohe et al., 2004, Table S1), whereby high climate sensitivities are always combined with very long response times of the climate system. This decision

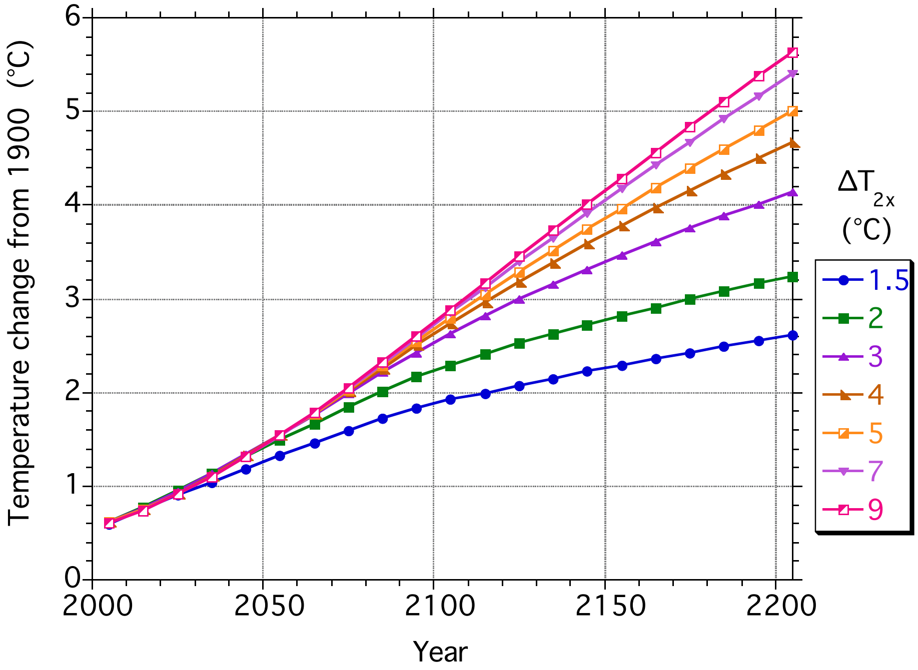

Figure 1: Global mean temperature trajectories for the DICE-99 baseline emissions scenario determined by the modified DICE-99 climate model for alternative climate sensitivities from 1.5 °C to 9 °C and associated calibrations of the heat capacity of the atmosphere and the upper ocean layer (reprinted from Yohe et al., 2006, Fig. 2).

was made despite clear evidence (including from Nordhaus, 1994, Table 3.5) that $C1$ and $T_{2\times}$ are *not* perfectly correlated.

3 Probabilistic projections of future climate change

Figure 1 depicts GMT trajectories calculated with the modified DICE climate model for the DICE-99 baseline emissions scenario, which closely resembles the medium-low SRES B2 scenario (Nakicenovic & Swart, 2000). As noted above, this figure from Yohe et al. (2006, Fig. 2) is essentially equivalent with Yohe et al. (2004, Fig. S1). The calculations consider a wide range of climate sensitivities from 1.5 °C to 9 °C, which covers more than the 5–95% range of most published climate sensitivity PDFs (Meinshausen, 2006). Nevertheless, the associated range of GMT change is only 0.2 °C and 0.8 °C in 2050 and in 2100, respectively.

Detailed probabilistic analyses find a much larger uncertainty range for 21$^{\text{st}}$-century climate change. The width of the 5–95% range of GMT increase is

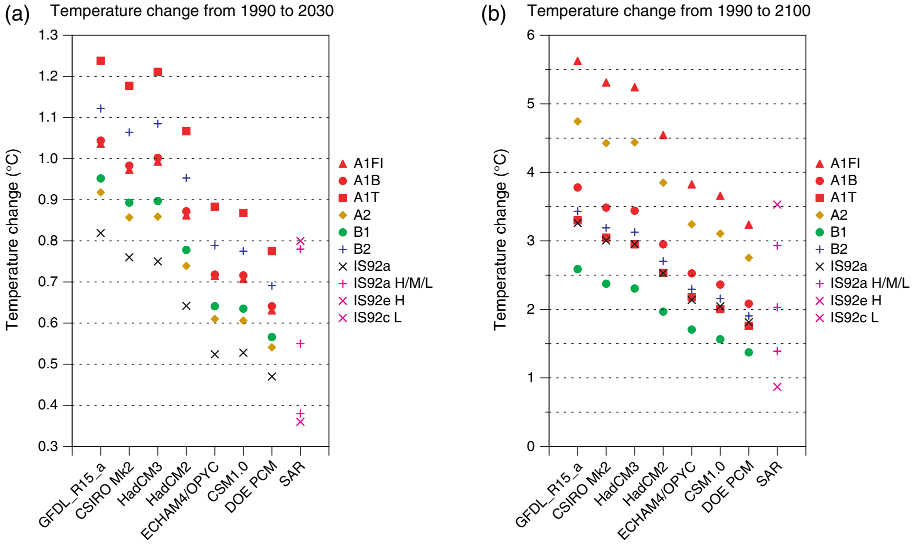

Figure 2: Global mean temperature projections for the six illustrative SRES emissions scenarios determined by the simple climate model MAGICC tuned to several GCMs from 1990 to 2030 (left plate) and 2100 (right plate) (reprinted from Cubasch et al., 2001, Fig. 9.15).

estimated at 1.0 °C by the 2020s independent of the emissions scenario (Stott & Kettleborough, 2002), at 1.5 °C by the 2040s for the medium IS92a scenario (Allen et al., 2000), at 2.1 °C (Stott & Kettleborough, 2002) and 2.2 °C (Knutti et al., 2002) by 2100 for the low SRES B1 scenario, and at 3.9 °C by 2100 for the high SRES A1FI scenario (Stott & Kettleborough, 2002). Similar results have been found by Wigley & Raper (2001), Webster et al. (2003) and Knutti et al. (2005).

Figure 2 (Cubasch et al., 2001, Fig. 9.15) depicts GMT projections determined by the simple climate model MAGICC tuned to several GCMs for the six illustrative SRES emissions scenarios. The GMT increase projected for the SRES B2 scenario (which is similar to the scenario underlying Figure 1) is approximately 0.7–1.1 °C from 1990 to 2030 and 1.9–3.4 °C from 1990 to 2100. The corresponding projections in Figure 1 are only 0.6 °C and 1.4–2.2 °C, respectively, even though the range of climate sensitivity considered is much higher than in Figure 2.

Summarizing the results from this wide range of studies, it is obvious that Yohe et al. (2004) and Yohe et al. (2006) substantially underestimate the uncertainty about 21st-century climate change. Many factors can potentially contribute to this biased result, including the lack of consideration of uncertain factors such as aerosol forcing in the DICE climate model. However, the main distinguishing factor of the analyses by Yohe et al. and other probabilistic analyses is the as-

THC collapse before	2105	2205
Kappa (K)	1–97%	30–100%
Alpha (α)	14–70%	25– 88%
Climate sensitivity (ΔT_{2x})	**38–50%**	**44– 78%**
Critical temperature (ΔT_c)	38–49%	45– 65%

Table 1: Sensitivity of the maximum likelihoods of THC collapse through 2105 and 2205, respectively, to the ranges of four uncertain parameters in the absence of a carbon tax (adapted from Yohe et al., 2006, Table 3 and 4).

sumption of a perfect correlation between the two uncertain climate parameters $C1$ and $T_{2\times}$ in the former. Since these two uncertain parameters show only a modest correlation, their uncertainty should preferably have been represented by their joint PDF. In this particular case, the uncertainty range for transient climate change determined in the detailed studies is much better reproduced when only $T_{2\times}$ is varied and $C1$ is held fixed at its default value (as in Keller et al., 2004; Mastrandrea & Schneider, 2004; Keller et al., 2005) than when $T_{2\times}$ and $C1$ are varied assuming a deterministic relationship (as in Yohe et al., 2004; Yohe et al., 2006).

4 Validity of the results

What are the implications of the overconfident GMT projections for the policy conclusions drawn in Yohe et al. (2006)? While the qualitative conclusions mentioned in the abstract of this study are not affected by the underestimation of the uncertainty and magnitude of transient climate change, the same is not true for the quantitative results.

Table 1 shows selected results from the importance analysis, which is one of the key quantitative analyses presented in Yohe et al. (2006).

According to this table, the uncertainty about climate sensitivity is much less important for estimating the risk of a THC collapse than the uncertainty about two uncertain parameters of the THC model, K and α. It is further suggested that the likelihood of a THC collapse before 2105 is 50% for the highest values of climate sensitivity. As argued above, these results are based on a substantial underestimation of the uncertainty and magnitude of transient climate change. Consequently, a more accurate probabilistic representation would reveal a higher importance of the uncertainty about climate sensitivity, and it would result in higher estimates of the likelihood of a THC collapse. A rough estimate of the magnitude of the effect can be based on the observation that the range of GMT change projected in Figure 1 for 2200 is reached in the detailed probabilistic analyses cited above already around 2100. Hence, it is reasonable to assume that the high estimates for the likelihood of a THC collapse before 2205 reported in Table 1 (*i.e.*, 78% for a climate sensitivity of 9 °C) are more indicative of the risk up to 2105 (which is estimated at a maximum of 50%).

The main conclusion from the reanalysis presented here is that weaknesses in the specification and calibration of a model may strongly affect the results of probabilistic analyses even if deterministic analyses produce reasonable results. Hence, models developed for deterministic application should not be uncritically applied in a probabilistic context.

The discussion in this comment has concentrated on a specific weakness of the probabilistic analysis by Yohe et al. (2006). It should be noted that the modelling framework applied in that analysis may be inadequate for calculating the likelihood of a THC collapse since coupled GCMs do not show the abrupt collapse simulated by simple box models (Gregory et al., 2005).

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