Towards a Risk Assessment for Shutdown of the Atlantic Thermohaline Circulation

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Abstract

The possible shutdown of the Atlantic Ocean Thermohaline Circulation (THC) has attracted considerable attention as a possible form of dangerous climate change. We review evidence for and against three common assertions, which imply that THC shutdown could pose particular problems for adaptation: first, associated climate changes would be in the opposite direction to those expected from global warming; secondly, such changes could be rapid (timescale one or two decades); and thirdly the change could be irreversible. THC shutdown is generally considered a high impact, low probability event. Assessing the likelihood of such an event is hampered by a high level of modelling uncertainty. One way to tackle this is to develop an ensemble of model projections which cover the range of possible outcomes. We present early results from a coupled GCM ensemble, demonstrating the feasibility of this approach, and discuss prospects for a more objective THC risk assessment in future.

1. Review of current knowledge

1.1 Impact of the THC on climate

The THC, or more precisely the meridional overturning circulation (MOC), transports around 10^{15}W of heat northwards in the North Atlantic [1]. This heat is lost to the atmosphere northwards of about 24°N, and represents a substantial heat source for the northern hemisphere climate. The impact of this heat transport on the atmosphere has been estimated using coupled climate models. The THC can be artificially suppressed in such models by adding large amounts of fresh water to the North Atlantic to suppress deep water formation there [e.g. 2,3,4]. The resulting climate response varies in detail between models, but robust features include substantial cooling of the northern hemisphere (strongest in regions close to the North Atlantic) and major changes in precipitation, particularly in regions bordering the tropical Atlantic. Impacts of THC shutdown on net primary production of carbon by terrestrial vegetation are shown in Fig. 1. General cooling and drying of the Northern Hemisphere results in a reduction of 11% in hemispheric primary production. Regionally, changes are larger, and in some regions current vegetation types become unsustainable, leading to large scale ecosystem change [5].

While downscaling of the impacts of THC shutdown from global models to local scale has not been widely performed as yet, and model estimates vary in detail, there is sufficient evidence that the impacts of such a shutdown would be substantial. Fig. 2 shows the modelled effect on surface temperature of a hypothetical THC shutdown in 2049, after following a scenario of global warming up to that point [6]. We see that around the North Atlantic, the cooling effect of the THC change more than outweighs the effects of global warming, leading to a net cooling relative to the preindustrial climate in those regions. The resulting climate in the UK, for example, would be substantially colder than that experienced during the 'Little Ice Age' of the 17th and 18th Centuries. It should be stressed that this is a 'what if?' scenario, and the model does not predict that this would actually occur.

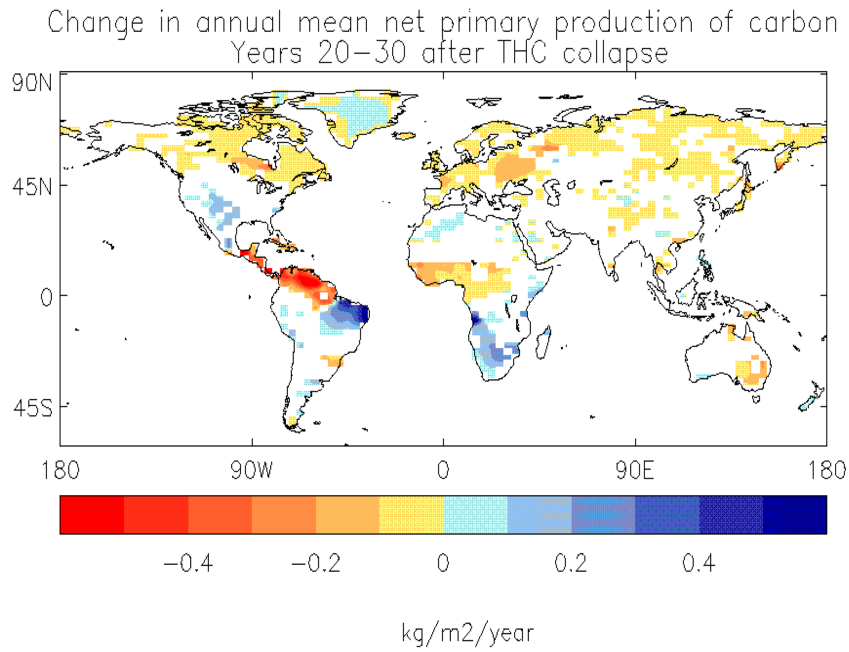

Fig. 1: Change in net primary productivity (kg carbon per m^2 per year) when the THC is artificially turned off in the HadCM3 climate model [4]. Reductions are seen over Europe (-16%), Asia (-10%), the Indian subcontinent (-36%) and Central America (-106%). The latter figure implies that present vegetation types would become unsustainable and large scale ecosystem adjustment could be expected [5].

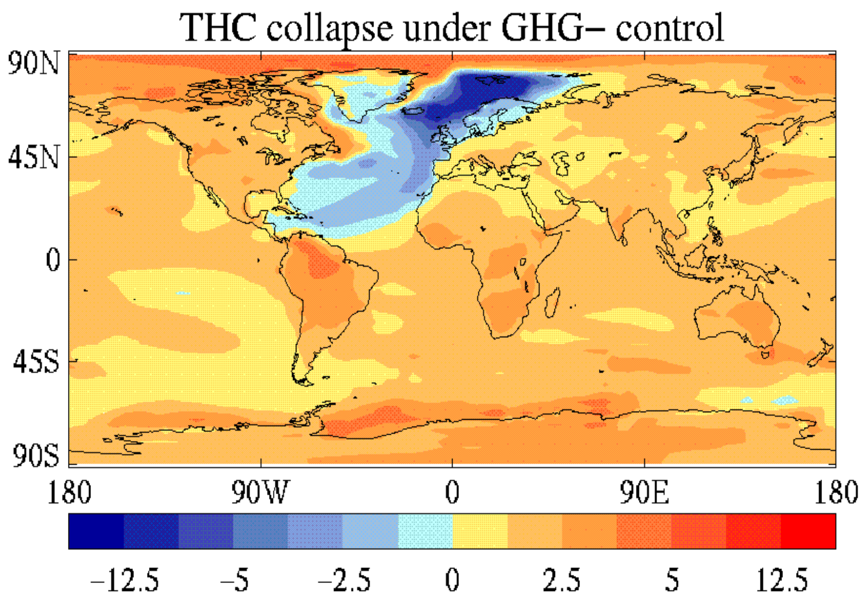

Fig. 2: Change in surface air temperature (°C) relative to preindustrial values, in a HadCM3 experiment in which the THC is artificially turned off in 2049, after following the IS92a greenhouse gas emission scenario up to that point [6]. Note that this is a 'what if?' scenario; the model does not actually predict a THC shutdown at that time.

1.2 Past rapid climate changes

A number of palaeoclimatic records point to the occurrence of rapid changes in the past. Particular events, which have been argued to show spatial coherence over a wide region, include the Dansgaard-Oeschger events during glacial periods, and more recently the so-called '8.2 kbp cold event', seen in Greenland ice cores and other proxies. These events appear to have timescales of decades or even shorter, and their amplitudes are well in excess of variability seen in the later Holocene (last 8000 years). A *prima facie* case has been made for a link between these events and major reorganisations of the THC. See [21] for a review of the palaeoclimatic evidence.

1.3 Can the present THC exhibit multiple equilibria and rapid change?

The climatic state of the late Holocene (last few thousand years) is substantially different from the state during glacial or early post-glacial periods, when ice sheets and sea ice covered much of the northern high latitudes, allowing for strong ice-albedo feedback and potential for substantial fresh water input to the North Atlantic through ice melt. Since there is no evidence of any O(1) changes in the THC over the past 8000 years at least, it needs to be asked whether the present (and likely future) climate states do in fact have a potential for THC shutdown.

Many simpler climate models, ranging from the box model of [7] to climate models of intermediate complexity [8,9], suggest that the present climate state may possess an alternative mode of operation with the THC weaker or absent. In many such studies increased greenhouse gas forcing can take the system beyond some threshold, after which only the 'THC off' state is stable. In that case, even if greenhouse gas forcing is returned to present day values, the THC remains off. Once the threshold is passed, the THC shutdown is effectively irreversible. Since the evidence for such hysteresis behaviour is largely based on more or less simplified models, it is important to ask whether such bistable behaviour exists in the most comprehensive climate models used to make climate projections (GCMs). The computational cost of coupled GCMs prohibits a complete exploration of the hysteresis curve. Experimentation has therefore concentrated on applying a temporary perturbation (usually a fresh water flux) to the models in order to turn off the THC. In most cases when the perturbation is removed, the THC recovers, implying that a stable 'THC off' state has not been found in that model (though it may nevertheless exist) [10-12]. However, a stable 'THC off' state has been demonstrated in two models [11,13]. A number of factors have been proposed as influencing the stability of the 'off' state, including ocean mixing [11], atmospheric feedbacks through wind stress [10] and the hydrological cycle [10,12,14]. At present it is not possible to say definitively from these model studies whether the present day THC is bistable, or whether there is a threshold beyond which irreversible shutdown would occur.

1.4 Why is modelling the future THC so difficult?

The current state of uncertainty in modelling the future behaviour of the THC can be illustrated by comparing the THC response of a number of different climate models used in the IPCC 3rd Assessment Report, under a common greenhouse gas forcing scenario ([15], see Fig. 9.21). Under this scenario, the models suggest changes in the maximum strength of the overturning circulation, ranging from a slight strengthening to a weakening of around 50%. Even two models which show a similar response can be shown to obtain that response for different reasons, dominated in one case by thermal forcing and in the other by fresh water forcing ([15], Fig. 9.22). The response is likely to be the net result of a number of positive and negative feedbacks. To obtain the correct net outcome it may be necessary to model each of the key feedbacks quite accurately.

Simplified models which do show the THC crossing a threshold suggest that near the threshold predictability becomes very poor, i.e. even if we could accurately determine that the THC was near a threshold, it could be difficult to predict the timing of a shutdown (e.g. [16], [17]). At present it is not possible to identify a 'safe' CO_2 stabilisation level that would prevent THC shutdown. It is possible that the *rate* of CO_2 increase, as well as the final concentration, may determine the outcome [18].

1.5 Summary: where are we now?

Comprehensive GCM climate projections suggest that the most likely response of the THC to global warming over the next century is a slowdown of around 0-50%. No models have shown a complete shutdown, or a net cooling over land areas. Hence a shutdown during the 21st Century is regarded as unlikely. Nonetheless a range of theoretical, modelling and and palaeoclimate studies shows that large, rapid changes are a possibility.

To produce a risk assessment for THC shutdown requires an understanding of both the impacts of a shutdown and the probability of occurrence. The evidence of 1.1 above points to substantial impacts (although these have not been assessed in detail). However, little can currently be said about the probability, except that it is subjectively considered low during the 21st Century, based on the results of section 1.4. To work towards a more quantitative probabilistic assessment, including information about 'safe' stabilisation levels, requires further development of models and methods. Some promising progress has recently been made towards this goal, and this is described in section 2 below.

2. Towards quantifying and reducing uncertainty in THC projections

2.1 Understanding what drives THC changes

The first step to reducing uncertainty is to understand the processes which contribute to the wide range of THC responses currently seen in models. A recent international initiative under the auspices of the Coupled Model Intercomparison Project (CMIP) addresses this goal by analysing a number of climate models, all subject to a number of standardised forcing experiments. Fig. 3 shows the roles of heat and water forcing in the response of the THC to 1% p.a. CO_2 increase, across this range of models. The large variation in the forcing processes is apparent, although it can be seen that in all models except one the heat forcing dominates the fresh water forcing over the timescale of this experiment. More detailed analysis is required to obtain a full picture of the processes determining the THC response in each model (e.g. [18]), but we can expect this process eventually to allow a good understanding to be developed of why the model responses are so different. This in turn will suggest targeted observational constraints than can be used to determine how much weight to give to particular model THC projections.

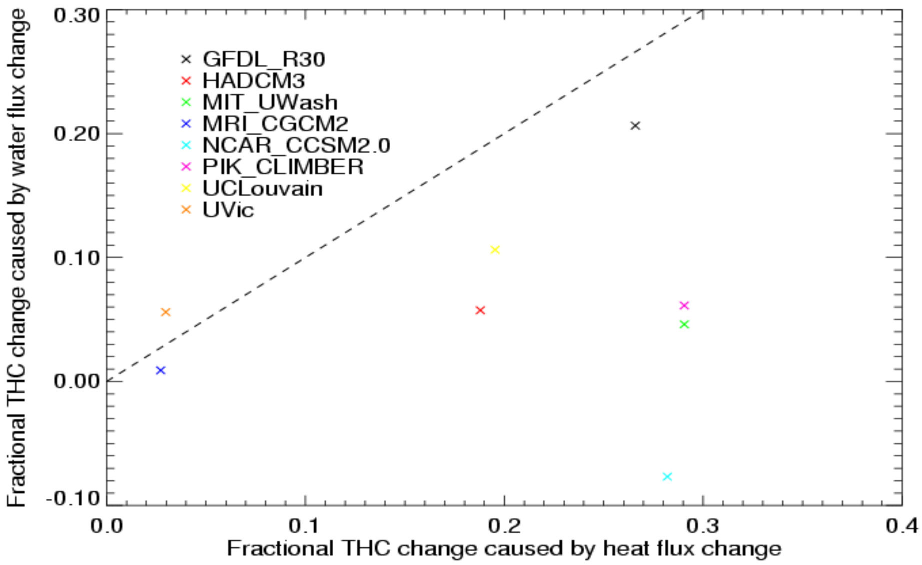

Fig. 3: Contributions of changes in thermal and fresh water forcing to the total THC change, following a 1% per annum CO_2 increase up to four times the initial concentration, in a range of climate models. Changes are expressed as a fraction of the THC strength in the control run. The dashed line divides the regions where thermal and haline forcing dominate. Data courtesy of partners in the CMIP coordinated experiment on THC stability.

2.2 Probabilistic estimation of the future THC

Some uncertainty will inevitably remain, and in order to obtain some form of objective assessment of the likelihood of major THC changes, it will be necessary to sample the range of possible model outcomes more systematically than is possible using the few model runs shown in [15] or in Fig.3. Recent progress has been made in this area by generating 'perturbed physics' model ensembles (e.g. [19,20]). An ensemble of models is generated by varying a set of model parameters within a defined range. The parameter settings are chosen from a prior distribution based on expert judgement about reasonable allowable ranges.

Climate projections made using each ensemble member may then be weighted according to some chosen set of observational constraints [20], or the ensemble may be generated in such a way as to ensure a predefined goodness of fit to the observations [19]. Studies to date have used either highly simplified models [19] or atmosphere-only GCMs [20]. Here we demonstrate the feasibility of generating a coupled GCM ensemble which can exhibit a range of THC responses to a given forcing. We use an existing ensemble of atmosphere-only model runs using the HadAM3 atmospheric model [20] to generate a set of atmospheric model parameters that are likely to result in a range of different THC responses, based on detailed analysis of the coupled model HadCM3 (with standard parameter settings) [18]. An ensemble of coupled models is thus produced, and a range of THC responses can be seen. The problem of climate drift in the coupled models is overcome by one of two methods: either flux adjustment or pre-selection of parameter settings to minimise climate drift without using flux adjustment. The latter pre-selection is made on the basis of global heat budgets in the atmosphere-only ensemble. Early results show that a range of THC responses can be produced. The ensemble will now be expanded to cover as wide a region of parameter space as possible, thus allowing a plausible range of THC behaviour to be quantified. The longer term goal is to add a range of models to the ensemble (thus transcending structural constraints of any given model). This should include a spectrum of models, including computationally cheaper models to allow thorough exploration of a wide parameter space (including a plausible range of stabilisation scenarios). This will allow for the first time an objective estimate of the likelihood of major THC change and identification of 'safe' stabilisation pathways.

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