

# Global warming and thermohaline circulation stability

BY RICHARD A. WOOD, MICHAEL VELLINGA AND ROBERT THORPE  
*Hadley Centre for Climate Prediction and Research, Met Office, London Road,  
Bracknell RG42 3TQ, UK (richard.wood@metoffice.com)*

*Published online 22 July 2003*

The Atlantic thermohaline circulation (THC) plays an important role in global climate. Theoretical and palaeoclimatic evidence points to the possibility of rapid changes in the strength of the THC, including a possible quasi-permanent shutdown. The climatic impacts of such a shutdown would be severe, including a cooling throughout the Northern Hemisphere, which in some regions is greater in magnitude than the changes expected from global warming in the next 50 years. Other climatic impacts would likely include a severe alteration of rainfall patterns in the tropics, the Indian subcontinent and Europe.

Modelling the future behaviour of the THC focuses on two key questions.

- (i) Is a gradual weakening of the THC likely in response to global warming, and if so by how much?
- (ii) Are there thresholds beyond which rapid or irreversible changes in the THC are likely?

Most projections of the response of the THC to increasing concentrations of greenhouse gases suggest a gradual weakening over the twenty-first century. However, there is a wide variation between different models over the size of the weakening. Rapid or irreversible THC shutdown is considered a low-probability (but high-impact) outcome; however, some climate models of intermediate complexity do show the possibility of such events. The question of the future of the THC is beset with conceptual, modelling and observational uncertainties, but some current and planned projects show promise to make substantial progress in tackling these uncertainties in future.

**Keywords:** climate change; global warming; ocean circulation;  
thermohaline circulation; Gulf Stream

---

## 1. Introduction

The future evolution of the Atlantic thermohaline circulation (THC) and its influence on climate are the subject of much debate both in the scientific literature and in the media. This has arisen for a number of reasons. First, the idea of a rapid regional *cooling* of climate, such as would result from a shutdown of the THC, naturally

One contribution of 14 to a Discussion Meeting 'Abrupt climate change: evidence, mechanisms and implications'.

catches attention in the context of widespread discussion of global warming. Second, the palaeoclimatic evidence for large, rapid climate shifts in the past, linked to the THC (see Alley 2003) emphasizes the potentially large climate changes involved. Third, a number of more-or-less simple models of the THC have been constructed which show the possibility of rapid changes of state. In this paper we attempt to summarize the current state of knowledge in this area. The outcome is not a single ‘prediction’ (not even in a probabilistic sense), because a number of qualitatively different behaviours are possible. In particular both a ‘smooth’ response to increasing greenhouse gases and various shifts of state (possibly abrupt) are possible.

Attempts to understand future climate inevitably depend on models, and over the past 15 years a large body of literature has emerged in this area. However, despite considerable progress in our understanding, we are still some way from being able to make reliable predictions of the fate of the THC over the next 100 years. A wide range of model types has been used to tackle the problem. Very simple models emphasize the role of one or two key processes and can often be analysed analytically to give conceptual understanding. Intermediate complexity models (often called ‘Earth System Models of Intermediate Complexity’ or ‘EMICs’) include more processes, albeit often in highly parametrized ways, but are computationally cheap and so can be used to explore parameter space and make a bridge between qualitative and quantitative understanding. General circulation models (GCMs) are the most comprehensive models available, but their computational cost limits the amount of experimentation that can be done. Eventual quantitative prediction is likely to depend on GCMs, and we focus largely on GCM work below.

In §2 we discuss the importance of the THC in the global climate. Section 3 introduces a simple conceptual framework to understand THC predictions, and §§4 and 5 summarize work on two classes of THC evolution: respectively, a ‘smooth’ response to greenhouse-gas forcing and rapid or ‘non-smooth’ changes. Section 6 draws some conclusions and looks at the way forward.

## 2. Importance of the THC for climate

The ocean circulation transports of the order of 1 PW ( $10^{15}$  W) of heat northwards across  $24^\circ$  N in the Atlantic (Trenberth & Solomon 1994; Ganachaud & Wunsch 2000; Bryden & Imawaki 2001). Most of this heat transport is carried by the Atlantic MOC<sup>†</sup>, and much of the Atlantic MOC can be identified with the THC (see footnote). On interannual and longer time-scales, this heat is lost to the atmosphere, with a consequent modification of the climate throughout the Northern Hemisphere. The

<sup>†</sup> We use the term ‘meridional overturning circulation’ (MOC) to mean the zonal integral across an ocean basin of the meridional flow. Given a flow field, the MOC can be precisely defined as a function of depth (or potential density) and latitude. The THC, on the other hand, is a less precise concept. We take it here to mean, broadly, that part of the ocean circulation which is driven directly by density contrasts rather than by wind forcing. It should be remembered that there are conceptual difficulties in disentangling which forcings are ‘responsible’ for a given aspect of the circulation (see, for example, Wunsch (2002) for further discussion), and in any case the MOC is not purely a manifestation of the THC: the wind-driven gyre circulation has a projection onto the MOC and, conversely, some largely horizontal circulations (e.g. in the subpolar gyre) may have a strong element of driving by density contrasts. In many cases the conceptual difficulties may be less severe when considering *changes* to circulation (as in this paper), rather than ascribing causes to the mean circulation itself. In this paper we attempt to use the terms precisely but pragmatically, recognizing that in some cases either term is appropriate.

impact of the THC on climate is most clearly seen by artificially shutting down the THC in a coupled climate model (Manabe & Stouffer 1988; Schiller *et al.* 1997; Rind *et al.* 2001; Vellinga & Wood 2002). In the study of Vellinga & Wood (2002) this was achieved in the HadCM3 climate model (Gordon *et al.* 2000) by an instantaneous freshening of a large region of the North Atlantic, reducing the mean density of the water column and inhibiting convective deep-water formation. The strength of the North Atlantic overturning reduces to near zero very quickly, and then recovers to its original strength over a period of *ca.* 120 years (the recovery process is discussed further in §5). The atmosphere responds quickly to the change in ocean circulation. A cooling of the Northern Hemisphere is rapidly established (figure 1a), which is strongest over and adjacent to the North Atlantic.

Over the first three decades the response develops to include a warming in the Southern Hemisphere. This is probably partly a consequence of the loss of northward heat transport, normally carried by the MOC, across the Equator (Ganachaud & Wunsch 2000). By the third decade, the maximum cooling over western Europe has reduced somewhat. Over the UK the *mean* cooling is 3–5 °C in the first decade, and 2–3 °C in the third decade. The cooling is fairly uniform through the seasons. To put such a cooling in context, a typical decadal mean cooling during the ‘Little Ice Age’ period of the late seventeenth and eighteenth centuries, as seen in the Central England temperature record (Parker *et al.* 1992), is of the order of 0.5 °C, and the coldest individual year in the record (which goes back to 1659) was 1740, with an anomaly of –2.5 °C (anomalies are taken relative to the 1961–1990 mean).

Note that the temperature *difference* between western Europe and eastern North America is not modified greatly by suppressing the THC. This contrast is due more to the difference between maritime and continental climates and large-scale atmospheric standing waves forced by the Rocky Mountains (Seager *et al.* 2002).

The climate response to suppression of the THC is not confined to surface temperature. As a response to the general cooling of the Northern Hemisphere, there is a widespread reduction in both surface evaporation and precipitation there. The net surface effect of changes in precipitation and evaporation is shown in figure 2. The tropical temperature changes result in a southward shift of the Atlantic Intertropical Convergence Zone (ITCZ) and a weakening of the Central American and East Pacific ITCZ and Indian monsoon (the latter is just below the significance level for many grid points so does not stand out strongly in the plot, but is significant when averaged over the Indian subcontinent).

The temperature and precipitation changes described above are broadly consistent with those found in other models (e.g. Manabe & Stouffer 1988; Schiller *et al.* 1997), although in the Schiller *et al.* model a stronger cooling is seen in some parts of the northeast Atlantic, due to a very strong sea-ice albedo feedback there and possibly associated with the use of heat-flux adjustments in that model.

The combined temperature and hydrological changes would be expected to have a significant impact on vegetation and agriculture. While these effects are not fully modelled here, the model does estimate the change in net primary productivity by land vegetation, on the assumption that the current mix of vegetation types is maintained. This is suggestive of the magnitude of changes that could be expected. There is reduction of 12% in the primary productivity of the Northern Hemisphere as a whole, with larger regional changes: –16% in Europe, –36% in the Indian

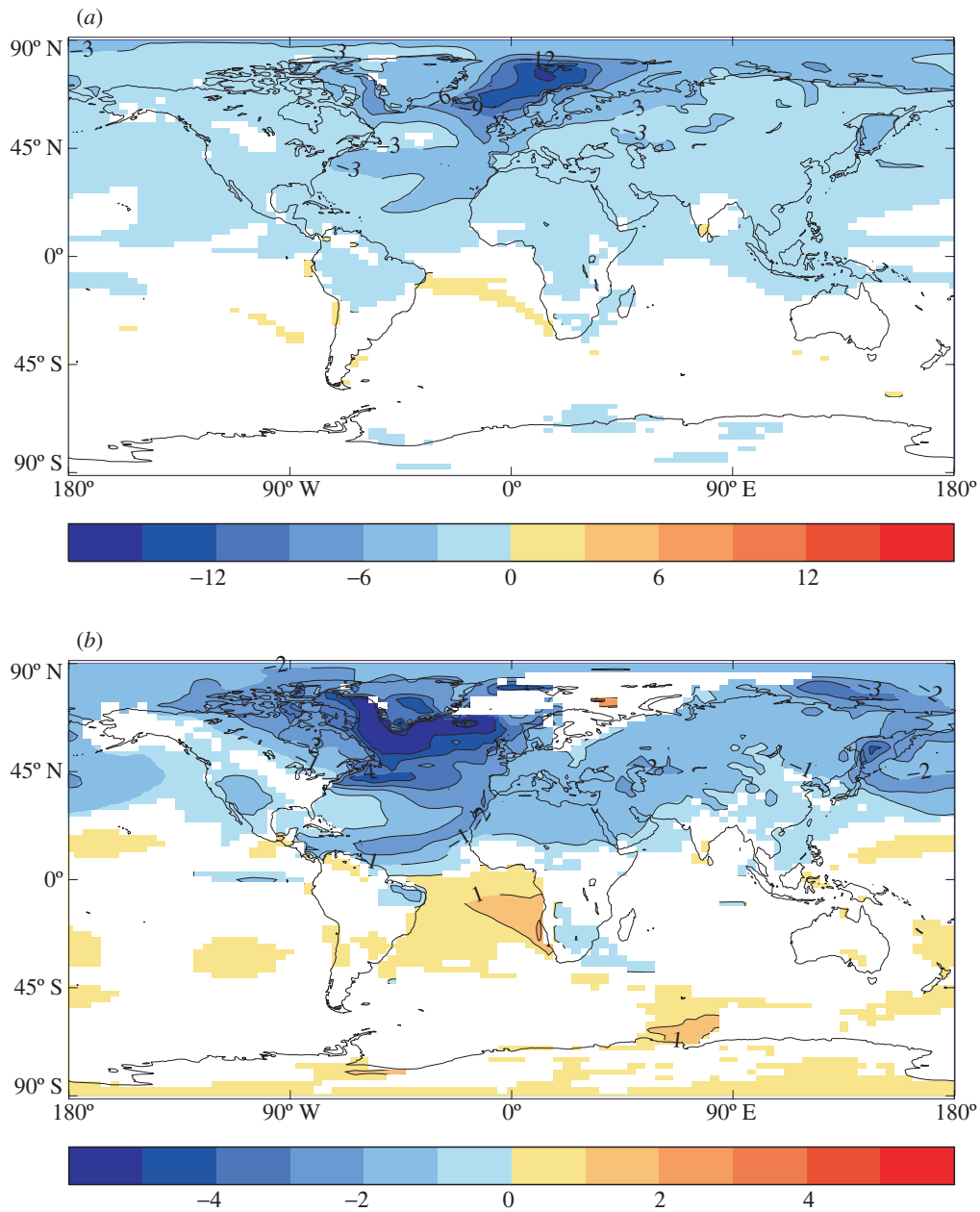


Figure 1. Response of decadal mean surface air temperature to an artificially induced shutdown of the THC in the HadCM3 model. Anomalies are relative to a control run with unperturbed THC. Greenhouse gases are kept fixed at pre-industrial values in all runs. Regions in which the anomaly is less than two standard deviations of the control run are not shaded. (a) Anomalies in the first decade after fresh-water perturbation; (b) anomalies in the third decade after fresh-water perturbation. Note different colour scales in (a) and (b). (Based on Vellinga & Wood (2002).)

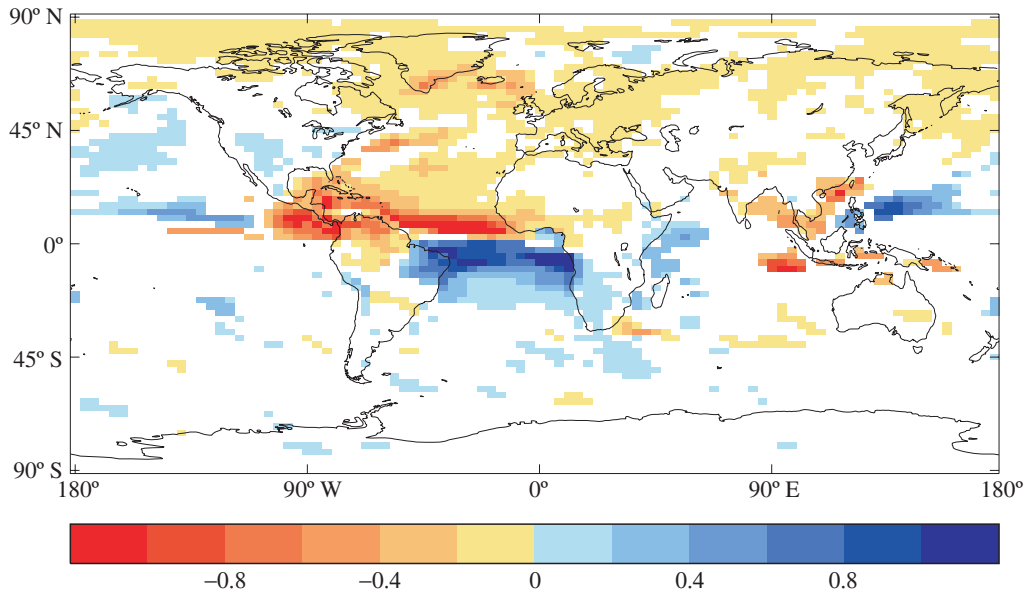


Figure 2. As in figure 1 but for changes in the surface fresh-water flux into the surface (precipitation minus evaporation, in  $\text{m yr}^{-1}$ ) in the third decade after fresh-water perturbation.

subcontinent and  $-109\%$  in Central America (the latter implying that the current mix of vegetation types is unsustainable).

### 3. Theoretical background

A wide range of theoretical models has been proposed for understanding the THC. A robust feature of many of the simple models is the hysteresis behaviour first noted by Stommel (1961). In its simplest form, Stommel's model consists of two boxes representing the high-latitude and low-latitude North Atlantic, with water exchanged between the two through an overturning circulation. The strength of the overturning is proportional to the density difference between the two boxes. The atmosphere is assumed to be able to damp large-scale sea-surface-temperature (SST) anomalies relatively quickly through radiation, whereas there is no such feedback on surface-salinity anomalies. Hence, in this model the allowable equilibrium states are determined primarily by the surface fresh-water forcing (i.e. the strength of the atmospheric water transports from box 1 to box 2).

Figure 3 shows possible equilibrium states of the overturning, as a function of the strength of the atmospheric water transport  $F$ . For  $F$  less than a critical value,  $F_{\text{crit}}$ , three solutions exist. The middle solution can be shown to be unstable, so in practice there are two realizable solutions, the upper branch with strong overturning and hence strong ocean heat transport, and the lower branch with weak reversed overturning and hence weak heat transport. For  $F > F_{\text{crit}}$  only the lower branch (weak) solution is possible. In this case the fresh-water forcing of the ocean is so strong that the density contrast is dominated by salinity, driving a reverse overturning (deep water flows towards the North Atlantic). The present-day circulation is assumed to be on the upper, thermally dominated branch.

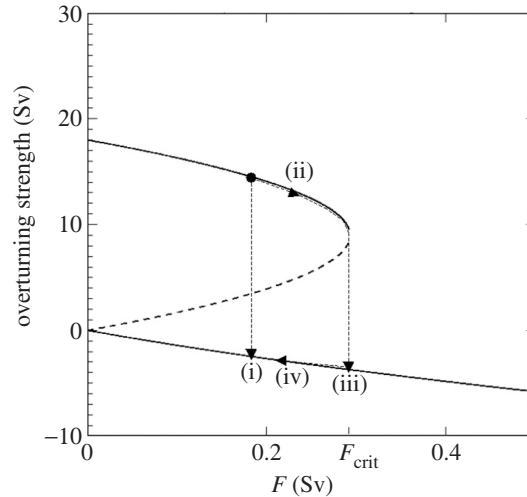


Figure 3. Equilibrium solutions of a simple model of the THC, based on Stommel (1961). Overturning strength is shown as a function of atmospheric meridional water transport  $F$ . For  $F < F_{crit}$ , three states are possible. The upper branch has strong overturning, the lower branch weak or reversed overturning. The middle branch (dashed) is unstable and so is of little practical significance. The present-day THC is considered to lie on the upper branch (shown by the dot). Three possible types of transition can occur: (i) a spontaneous ‘flip’ from the upper to the lower branch in response to internal climate ‘noise’ (not included in this model); (ii) a gradual weakening of the overturning in response to slow increase in  $F$  (or vice versa); (iii) if  $F$  is increased beyond  $F_{crit}$ , only the lower branch is a solution and the overturning transfers to that branch. In this case the change would be quasi-irreversible in the sense that subsequently reducing  $F$  below  $F_{crit}$ , the overturning would return along the lower (weak) branch (iv).

It is tempting to use this simple model to speculate on the fate of the THC under a change of climate forcing such as anthropogenic global warming. A robust feature of climate model projections of climate change in response to increasing greenhouse gases is a strengthening of the atmosphere’s hydrological cycle, due to the increased saturation vapour pressure of water in warmer air (Cubasch *et al.* 2001). In the simple model this would correspond to an increase in  $F$ . Assuming the meridional temperature contrast to be unchanged, this would result in a gradual weakening of the equilibrium strength of the overturning. However, if the forcing increased to the point where  $F > F_{crit}$ , the upper-branch solution would become untenable and the THC would switch to the lower branch. Such a change would be quasi-irreversible, in that a subsequent gradual reduction in  $F$  would be expected to bring the THC back along the lower branch, even if  $F$  were brought back below its critical value. Given sufficient natural variability in the system (not included in this model), it is also conceivable that a spontaneous ‘flip’ from the upper to the lower branch (or vice versa) could occur. Such transitions were seen by Monahan (2002) in a version of the Stommel model with added stochastic noise. However, that study also showed that for physically plausible parameter values the presence of noise can result in low probability that the solution will reside on the lower branch.

This simple model must be treated with caution. The role of the fresh-water budget of the Atlantic is still uncertain. Rahmstorf (1996) emphasizes the importance of the water budget of the whole Atlantic, whereas Gregory *et al.* (2003) show evi-

dence that the internal distribution of fresh-water flux within the Atlantic may also be important. A number of studies have suggested that temperature and salinity gradients between the North and South Atlantic (rather than the North and tropical Atlantic) are the dominant control on the equilibrium overturning strength (e.g. Hughes & Weaver 1994; Klinger & Marotzke 1999; Thorpe *et al.* 2001). The inter-hemispheric viewpoint implies that smaller density anomalies might be needed to induce a state transition than would be thought from the low–high latitude formulation of Stommel’s model. It could be argued that the assumption of unchanging SSTs applied in the Stommel model implies an unrealistically large or infinite atmospheric heat capacity: a puzzling limit given the apparent importance of the THC for air temperature. However, Marotzke & Stone (1995) show that a similar bifurcation structure exists for the THC in the opposite (and more physically justifiable) limit of zero atmospheric heat capacity. The key point in Stommel’s simple ocean model, which sets the overall solution structure, is that the adjustment time-scale of the ocean temperature to temperature anomalies is shorter than that of the salinity to salinity anomalies. The model only gives information about the equilibrium state of the THC; transient changes around or between equilibria will be controlled by dynamical processes not included in the model. The discussion above also assumes implicitly that the changes in forcing take place on a slower time-scale than the equilibration time-scale of the THC, an assumption which may not be realistic. Despite these caveats, the ideas of a gradual weakening of the equilibrium THC in response to increased fresh-water forcing, and the possibility of threshold or hysteresis effects, give a useful framework in which to assess the results of more comprehensive climate models. These two aspects of the THC response are considered in more detail in §§ 4 and 5.

#### 4. Response of the THC to global warming

While many uncertainties remain in model projections of the climate response to increasing greenhouse gases, two features are common to all projections and are considered to be fairly robust, namely a general warming of surface climate and a strengthening of the atmospheric hydrological cycle (Cubasch *et al.* 2001). Both these features would be expected to increase the vertical stability of the water column in the subpolar North Atlantic and Nordic seas by warming and freshening the surface, resulting in a reduction in formation rate and/or density of deep water and a weakening of the THC/MOC system. Most coupled climate models do show such a weakening over the next century in response to plausible forcing scenarios defined by IPCC. Over the Northern Hemisphere, such a weakening would be expected to provide a cooling effect (see § 2) which would offset somewhat the warming due to increasing greenhouse gases.

There is little agreement between different models over how much the MOC will weaken. Given the same greenhouse-gas forcing scenario, a range of models used by IPCC produces changes in the Atlantic overturning of between 0 and  $-14$  Sv by 2100 (no model shows a strengthening; Cubasch *et al.* 2001). Even models which show a fairly similar weakening do so for different reasons; for example in the GFDL\_R15\_a model (Dixon *et al.* 1999) changes in fresh-water fluxes are shown to dominate changes in heat fluxes in driving the THC response, whereas in the ECHAM3/LSG model (Mikolajewicz & Voss 2000) the opposite is the case.

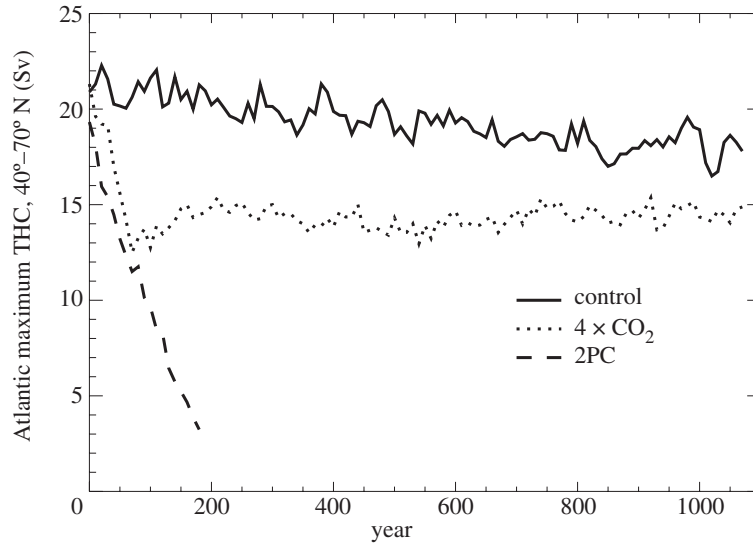


Figure 4. Time-series of MOC from three runs of HadCM3 (Atlantic THC response): a control run with fixed pre-industrial greenhouse gases (solid), a ‘ $4 \times \text{CO}_2$  stabilization’ run, in which  $\text{CO}_2$  is increased at 2% per annum up to four times pre-industrial (70 years) and then kept fixed (dotted), and an extreme ‘2%’ run, in which  $\text{CO}_2$  is increased continuously at 2% per annum up to about 32 times pre-industrial (dashed).

The quantitative response of the MOC is most likely the result of a number of processes, some acting as positive and some as negative feedbacks. For example, in the ECHAM4/OPYC model the THC/MOC is stabilized by the following process. Global warming increases the strength of the hydrological cycle, and thus results in an increase in fresh-water transport by the trade winds from the Atlantic to the Pacific. This process is enhanced by the El Niño-like pattern of the SST response. The consequent salinification of the North Atlantic provides a negative feedback which keeps the THC going, and the net result in this model is no MOC change (Latif *et al.* 2000). A similar process has been shown to operate in the HadCM3 model (Thorpe *et al.* 2001), but in this case the MOC weakens by *ca.* 20–25%.

It is also of interest to understand the longer-term behaviour of the THC/MOC, following a possible future stabilization of greenhouse-gas concentrations. Again, there is little consensus among models. Manabe & Stouffer (1999a) show results from runs of the GFDL climate model in which atmospheric  $\text{CO}_2$  is gradually increased, and then stabilized at twice or four times pre-industrial values. In the  $2 \times \text{CO}_2$  run, the overturning weakens, but starts to recover *ca.* 70 years after stabilization, and returns to its original value by 400 years after stabilization. In the  $4 \times \text{CO}_2$  case, the overturning becomes very weak, and remains weak for over 1000 years after stabilization. Then, there is a fairly rapid recovery to pre-industrial values over 100–200 years. This behaviour is probably due to gradual heat storage in the deep ocean during the weak overturning phase, which eventually causes static instability and a resumption of deep convection. We have repeated the  $4 \times \text{CO}_2$  experiment using the HadCM3 model. In this case the overturning weakens as the  $\text{CO}_2$  is increased, but stabilizes at a value *ca.* 20–25% weaker than the control run soon after  $\text{CO}_2$  stabilization. The run has been continued for 1000 years so far with no indication of



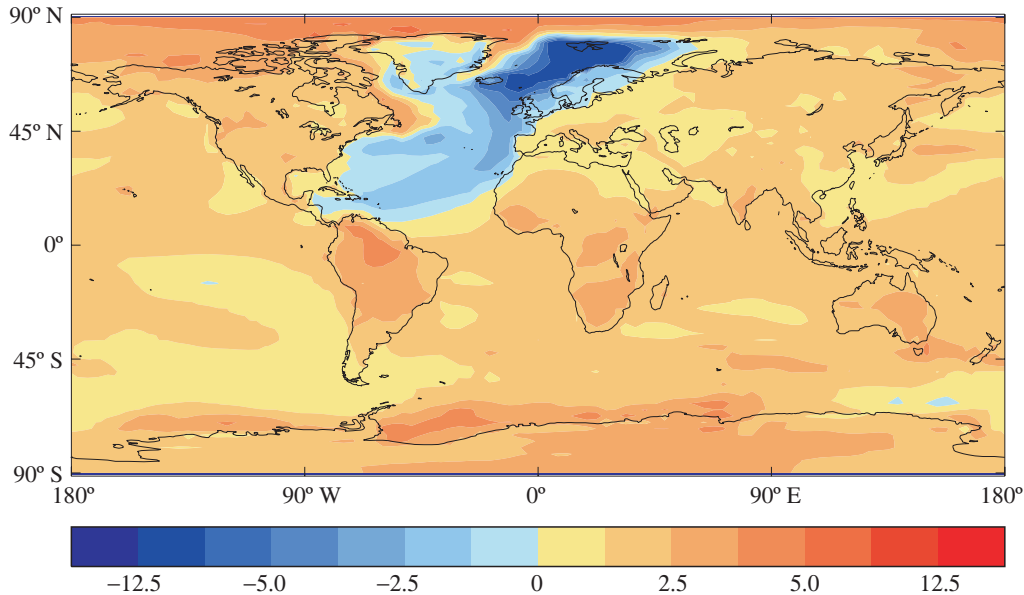


Figure 5. Surface temperature change ( $^{\circ}\text{C}$ ) due to a hypothetical THC shutdown in 2049. The HadCM3 model has been run to 2049 under the IPCC IS92a greenhouse-gas-forcing scenario. At this point, fresh water was added to the North Atlantic to induce a THC shutdown. Anomalies shown are the mean for the first decade after fresh-water addition, relative to the pre-industrial climate. See text for interpretation.

a recovery (figure 4). In the HadCM3 model, some degree of meridional overturning continues even when the model is forced with up to 32 times pre-industrial  $\text{CO}_2$  (figure 4).

It appears that a reliable prediction of the MOC response to global warming will require quantitatively accurate modelling of a range of key processes. We are still at the stage of using modelling studies to identify what those key processes are likely to be. Some of them (such as those described above) involve large-scale atmospheric and oceanic transports of heat and moisture. Others may involve detailed local circulation features (e.g. Wood *et al.* 1999; Gent 2001). Observationally based studies focusing on these key processes will be important if we are to reduce the current large modelling uncertainty (e.g. Schmittner *et al.* 2000).

### 5. Will the THC cross a threshold in future?

The discussion of § 4 shows that there are many processes controlling the THC which are not included in the simple conceptual model of Stommel, described in § 3. However, that model does at least suggest a weakening of the THC in response to a strengthening atmospheric hydrological cycle—a feature which is reproduced to some extent in most GCMs. To what extent are the other qualitative features of the Stommel model (alternative, ‘THC-off’ state with present-day forcing, and a threshold beyond which only the ‘off’ state is viable) seen in more complete climate models? Surprisingly, there is evidence that these features are quite robust.

A stable ‘THC-off’ state with pre-industrial climate forcing has been found in two atmosphere–ocean GCMs (Manabe & Stouffer 1988, 1999b; Rind *et al.* 2001).

However, Manabe & Stouffer (1999b) were unable to produce a stable ‘off’ state in an alternative version of their model, with increased vertical diffusion in the ocean. Vertical mixing is a critical process in the ocean circulation, and is still not fully understood, but recent advances during the World Ocean Circulation Experiment (WOCE) and other programmes give hope that it can be more accurately represented in climate models in future (Toole & McDougall 2001).

In most coupled GCMs, no transition from the present-day to ‘THC-off’ states has been reported. A THC shutdown is usually induced artificially in the models by discharging a large amount of fresh water into the North Atlantic, but in many cases (e.g. Manabe & Stouffer 1999a; Schiller *et al.* 1997; Vellinga & Wood 2002) the THC recovers following an initial weakening. The time-scale of the recovery, and hence presumably the processes responsible, varies in these experiments between *ca.* 100 years (Schiller *et al.* 1997; Vellinga & Wood 2002) and more than 1000 years (Manabe & Stouffer 1999b), and in some cases the recovery is punctuated by large, rapid oscillations of the MOC (e.g. Manabe & Stouffer 1997). In the HadCM3 experiment described above, the recovery is driven by the changes in tropical fresh-water fluxes shown in figure 2. A strong salting of the tropical North Atlantic is transported by the wind-driven circulation to higher latitudes, where it gradually intensifies the THC (Vellinga *et al.* 2002). The fact that a stable ‘off’ state has not been found in some GCMs does not imply that such a state does not exist in those models. Computational expense means that only a few experiments can be run with these models, and it may be that these experiments have simply not moved the model onto the attractor of the ‘off’ state. On the other hand, the apparent difficulty of achieving such a transition does suggest that the pre-industrial (Holocene) climate does not favour a spontaneous ‘flip’, a conclusion supported by the theoretical work of Monahan (2002).

A more likely way in which the THC could shut down would be by passing a critical threshold, as discussed in § 3. Such behaviour has been seen in several climate models of intermediate complexity. For example, Rahmstorf & Ganopolski (1999) run the CLIMBER model through a scenario of increasing greenhouse-gas concentrations up to about 2150, followed by a gradual decrease. In one version of their model the MOC weakens until 2150 and then recovers but, in a slightly different version of the model (with the same forcing), a threshold is crossed. The MOC shuts down and does not recover even as greenhouse-gas concentrations are reduced. Such scenarios are clearly relevant to policy decisions on ‘safe’ levels of greenhouse gases. Stocker & Schmittner (1997) show that it is not just the stabilized greenhouse-gas concentration that determines the fate of the THC, but also the stabilization pathway; in their model a rapid rise to a given concentration is more likely to result in a THC shutdown than a more gradual rise. Further predictive uncertainty arises because near the threshold the intrinsic predictability of the system (‘when will the THC turn off?’) may be very low in the presence of stochastic climate ‘noise’ (Wang *et al.* 1999; Knutti & Stocker 2002).

Such studies using computationally cheap climate models are invaluable in developing our understanding of the system by exploring its phase and parameter spaces. However, the fact that two slightly different versions of Rahmstorf & Ganopolski’s (1999) model resulted in very different outcomes (THC recovered in one version but not in the other) illustrates the level of modelling uncertainty which surrounds this area. In their case the difference between the two model versions was in the amount

of strengthening of the hydrological cycle per unit of surface warming, a parameter which is not easily constrained by observations.

A permanent shutdown of the THC has not been seen to date in any run of a comprehensive coupled GCM, forced by a plausible scenario of greenhouse-gas increase. The most extreme response seen to date was the near-cessation of overturning for 1000 years seen in the  $4 \times \text{CO}_2$  stabilization study of Manabe & Stouffer (1999a), described in § 4.

Based on the evidence above there are reasonable grounds to speculate that a rapid or irreversible shutdown of the THC over the next century is a rather low probability event. Nonetheless, given the evidence from models that there are probably thresholds in the system, and the fact that we are clearly not yet at a stage where the that a spontaneous ‘flip’ is unlikely in models are good enough to make confident, quantitative statements about THC changes, the possibility needs to be taken seriously. The impact of such an event could locally swamp the effects of global warming. Figure 5 shows the effect in HadCM3 of a hypothetical rapid THC shutdown in 2049. It must be stressed that the model does not predict such a shutdown, but it has here been artificially induced to illustrate what might happen if the model were making an accurate prediction of large-scale global warming but had overestimated the stability of the THC. Following several decades of global warming, such a shutdown would return northwestern Europe in particular to a climate that was substantially colder than pre-industrial (Central England temperature would be *ca.* 2 °C colder in the first decade: see § 2), and the potential rapidity and unpredictability of such a change could make adaptation particularly difficult (Hulme 2003).

## 6. Conclusions and prospects

The consensus among current model projections is that the THC will weaken or remain unchanged over the next century in response to increasing greenhouse gases. A weakening would have a cooling effect which would partly offset the effects of global warming over much of the Northern Hemisphere. This effect is included in the projections currently made by GCMs, but such projections still suggest surface warming almost everywhere over the next century in response to IPCC forcing scenarios.

The possibility of more rapid and dramatic THC changes during the next century, due to a sudden ‘flip’ (internal variability) or the passing of a threshold due to greenhouse-gas forcing, cannot be ruled out but is considered a low-probability, high-impact event. Such events have not been seen in comprehensive GCMs under IPCC forcing scenarios. However, such events have been produced in EMICs under plausible greenhouse-gas forcing and there is some reason to suppose that global warming may bring the THC closer to a threshold.

Both the above paragraphs should be read in the context of the very high level of modelling uncertainty that still exists in this area. One approach to reduce this uncertainty is (i) to identify the key processes controlling the strength and stability of the THC using a range of models, then (ii) to subject these modelled processes to observationally based tests. At present we are still at stage (i). A current project under the auspices of the international Coupled Model Intercomparison Project aims to compare processes in a number of GCMs and EMICs, under standard forcing scenarios (see <http://www-pcmdi.llnl.gov/cmip>). It is worth emphasizing that the

studies already done (some of which are reported in earlier sections of this paper) suggest that both atmospheric and oceanic processes are important.

There are grounds for optimism that a number of recent and planned observational advances will give us worthwhile constraints on some of the key processes for THC stability (for example, aspects of the hydrological cycle (see Dickson *et al.* 2003)), and so allow the uncertainty in projections to be reduced as stage (ii) of the above strategy. However, lack of useful observationally based constraints for some important processes may ultimately limit the accuracy of THC projections. To work round this, a more probabilistic approach is called for, in which ensembles of model runs are used to explore the range of feasible model parameters. Whichever approach proves ultimately most fruitful, a close interaction between models of varying levels of complexity and well-targeted observations will almost certainly be the key to progress.

This work was supported under DEFRA contract number PECD 7/12/37. We thank Brian Hoskins and Jochem Marotzke for valuable reviews and editorial suggestions. This work is published with the permission of the Met Office on behalf of the Controller of Her Britannic Majesty's Stationery Office.

## References

- Alley, R. B. 2003 Palaeoclimatic insights into future climate challenges. *Phil. Trans. R. Soc. Lond. A* **361**, 1831–1849.
- Bryden, H. L. & Imawaki, S. 2001 Ocean heat transport. In *Ocean circulation and climate* (ed. G. Siedler, J. Church & J. Gould). Academic.
- Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A., Raper, S. & Yap, K. S. 2001 Projections of future climate change. In *Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the International Panel on Climate Change*. (ed. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson). Cambridge University Press.
- Dickson, R. R., Curry, R. & Yashayaev, I. 2003 Recent changes in the North Atlantic. *Phil. Trans. R. Soc. Lond. A* **361**, 1917–1934.
- Dixon, K. W., Delworth, T. L., Spelman, M. J. & Stouffer, R. J. 1999 The influence of transient surface fluxes on North Atlantic overturning in a coupled GCM climate change experiment. *Geophys. Res. Lett.* **26**, 2749–2752.
- Ganachaud, A. & Wunsch, C. 2000 Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature* **408**, 453–457.
- Gent, P. R. 2001 Will the North Atlantic Ocean thermohaline circulation weaken during the 21st century? *Geophys. Res. Lett.* **28**, 1023–1026.
- Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B. & Wood, R. A. 2000 The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynam.* **16**, 147–168.
- Gregory, J. M., Saenko, O. A. & Weaver, A. J. 2003 The role of the Atlantic freshwater balance in the hysteresis of the meridional overturning circulation. (Submitted.)
- Hughes, T. C. M. & Weaver, A. J. 1994 Multiple equilibria of an asymmetric two-basin ocean model. *J. Phys. Oceanogr.* **24**, 619–637.
- Hulme, M. 2003 Abrupt climate change: can society cope? *Phil. Trans. R. Soc. Lond. A* **361**, 2001–2021.

- Klinger, B. A. & Marotzke, J. 1999 Behavior of double-hemisphere thermohaline flows in a single basin. *J. Phys. Oceanogr.* **29**, 382–399.
- Knutti, R. & Stocker, T. F. 2002 Limited predictability of the future thermohaline circulation close to an instability threshold. *J. Clim.* **15**, 179–186.
- Latif, M., Roeckner, E., Mikolajewicz, U. & Voss, R. 2000 Tropical stabilisation of the thermohaline circulation in a greenhouse warming simulation. *J. Clim.* **13**, 1809–1813.
- Manabe, S. & Stouffer, R. J. 1988 Two stable equilibria of a coupled ocean–atmosphere model. *J. Clim.* **1**, 841–866.
- Manabe, S. & Stouffer, R. J. 1997 Coupled ocean–atmosphere model response to freshwater input: comparison to Younger Dryas event. *Paleoceanography* **12**, 321–336.
- Manabe, S. & Stouffer, R. J. 1999a The role of the thermohaline circulation in climate. *Tellus A* **51**, 91–109.
- Manabe, S. & Stouffer, R. J. 1999b Are two modes of thermohaline circulation stable? *Tellus A* **51**, 400–411.
- Marotzke, J. & Stone, P. H. 1995 Atmospheric transports, the thermohaline circulation and flux adjustments in a simple coupled model. *J. Phys. Oceanogr.* **25**, 1350–1364.
- Mikolajewicz, U. & Voss, R. 2000 The role of individual air–sea flux components in CO<sub>2</sub>-induced changes of the ocean’s circulation and climate. *Climate Dynam.* **16**, 627–642.
- Monahan, A. H. 2002 Stabilisation of climate regimes by noise in a simple model of the thermohaline circulation. *J. Phys. Oceanogr.* **32**, 2072–2085.
- Parker, D. E., Legg, T. P. & Folland, C. K. 1992 A new daily Central England temperature series. *Int. J. Climatol.* **12**, 317–342.
- Rahmstorf, S. 1996 On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Climate Dynam.* **12**, 799–811.
- Rahmstorf, S. & Ganopolski, A. 1999 Long-term global warming scenarios computed with an efficient coupled climate model. *Climatic Change* **43**, 353–367.
- Rind, D., deMenocal, P., Russell, G., Sheth, S., Collins, D., Schmidt, G. & Teller, J. 2001 Effects of glacial meltwater in the GISS coupled atmosphere–ocean model. 1. North Atlantic Deep Water response. *J. Geophys. Res.* **106**, 27 335–27 353.
- Schiller, A., Mikolajewicz, U. & Voss, R. 1997 The stability of the thermohaline circulation in a coupled ocean–atmosphere general circulation model. *Climate Dynam.* **13**, 325–347.
- Schmittner, A., Appenzeller, C. & Stocker, T. F. 2000 Enhanced Atlantic freshwater export during El Niño. *Geophys. Res. Lett.* **27**, 1163–1166.
- Seager, R., Battisti, D. S., Yin, J., Gordon, N., Naik, N., Clement, A. C. & Cane, M. A. 2002 Is the Gulf Stream responsible for Europe’s mild winters? *Q. J. R. Meteorol. Soc.* **128**, 2563–2586.
- Stocker, T. F. & Schmittner, A. 1997 Influence of CO<sub>2</sub> emission rates on the stability of the thermohaline circulation. *Nature* **388**, 862–865.
- Stommel, H. 1961 Thermohaline convection with two stable regimes of flow. *Tellus* **13**, 224–230.
- Thorpe, R. B., Gregory, J. M., Johns, T. C., Wood, R. A. & Mitchell, J. F. B. 2001 Mechanisms determining the Atlantic thermohaline circulation response to greenhouse gas forcing in a non-flux-adjusted coupled climate model. *J. Clim.* **14**, 3102–3116.
- Toole, J. M. & McDougall, T. J. 2001 Mixing and stirring in the ocean interior. In *Ocean circulation and climate* (ed. G. Siedler, J. Church & J. Gould). Academic.
- Trenberth, K. & Solomon, A. 1994 The global heat balance: heat transports in the atmosphere and ocean. *Climate Dynam.* **10**, 107–134.
- Vellinga, M. & Wood, R. A. 2002 Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change* **54**, 251–267.
- Vellinga, M., Wood, R. A. & Gregory, J. M. 2002 Processes governing the recovery of a perturbed thermohaline circulation in HadCM3. *J. Clim.* **15**, 764–780.

- Wang, X., Stone, P. H. & Marotzke, J. 1999 Global thermohaline circulation. I. Sensitivity to atmospheric moisture transport. *J. Clim.* **12**, 71–82.
- Wood, R. A., Keen, A. B., Mitchell, J. F. B. & Gregory, J. M. 1999 Changing spatial structure of the thermohaline circulation in response to atmospheric CO<sub>2</sub> forcing in a climate model. *Nature* **399**, 572–575.
- Wunsch, C. 2002 What is the thermohaline circulation? *Science* **298**, 1179–1180.

### Discussion

A. B. MCDONALD (*Wimborne, Dorset, UK*). You say that shutting down the THC changes West European temperature by 2 °C. This is a lot less than the change during the Younger Dryas. Should we not be investigating where this difference comes from?

R. A. WOOD. In principle yes, though this requires lengthy model integrations and it is not clear how to specify either the forcing or the initial conditions for such runs. A number of such model runs are likely to be attempted over the next few years.

A. B. MCDONALD. Sea ice seems to be very important in amplifying the effect of the halting of the NADW. Do we know how far south it extended?

R. A. WOOD. The second question may contain the answer to the first. The different states of land and sea ice at the time of the Younger Dryas would probably result in a stronger albedo feedback and hence a stronger cooling in response to a THC shutdown (if indeed there was a THC shutdown associated with the YD). There are reconstructions that suggest that at the last glacial maximum the sea ice extended well south—maybe down to 45° N on the western side of the Atlantic.

J. L. BAMBER (*School of Geographical Sciences, University of Bristol, UK*). What impact will including realistic aspects of the cryosphere have on the THC?

J. SLINGO (*Department of Meteorology, University of Reading, UK*). You emphasized the importance of the tropical Atlantic as a potential stabilizer of the THC via increased moisture transport to the Pacific. We know that there are major errors and uncertainties in the simulations of the tropical Pacific. How important is it to consider the global context of THC variability?

R. A. WOOD. To answer Professor Slingo's last point first, it is clear that the influence of, and influences on, the THC extend well beyond the North Atlantic Ocean.

To answer both Dr Bamber and Professor Slingo, both tropical circulation and cryospheric processes are included in global GCMs at some level (along with many other processes). The questions single out two processes from many which potentially have a strong influence on the response of the THC. Some such processes are rather large scale in nature, whereas others rely on quite localized, small-scale features of the climate system. Until we can establish the importance of these processes in the real world through observationally based constraints, this will present a challenge to models, since we are always limited by human and computer time and judgements must be made on what level of complexity to use in modelling each component of the system. The best that can be done is to base such judgements on the best available estimates (from observations or detailed process models) of the relative contribution of each process. Just as it would be a mistake to rely totally on a particular (imperfect) model, it would also be a mistake to assume that because a

particular feature of the system is not simulated perfectly, a model cannot give useful information.

M. W. HO (*Institute of Science in Society, London, UK*). Can you test your model by post-diction against data already collected?

R. A. WOOD. This is a current topic of research. The models reproduce many of the observed changes, given historical forcings, although the attribution of the changes (e.g. to internal variability, natural or anthropogenic forcing) is not always unambiguous.

