Mechanisms Determining the Atlantic Thermohaline Circulation Response to Greenhouse Gas Forcing in a Non-Flux-Adjusted Coupled Climate Model


Met Office, Hadley Centre for Climate Prediction and Research, Bracknell, Berkshire, United Kingdom

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ABSTRACT

Models of the North Atlantic thermohaline circulation (THC) show a range of responses to the high-latitude warming and freshening characteristic of global warming scenarios. Most simulate a weakening of the THC, with some suggesting possible interruption of the circulation, but others exhibit little change. The mechanisms of the THC response to climate change using the HadCM3 coupled ocean–atmosphere general circulation model, which gives a good simulation of the present-day THC and does not require flux adjustment, were studied. In a range of climate change simulations, the strength of the THC in HadCM3 is proportional to the meridional gradient of steric height (equivalent to column-integrated density) between 30°S and 60°N. During an integration in which CO₂ increases at 2% per year for 70 yr, the THC weakens by about 20%, and it stabilizes at this level if the CO₂ is subsequently held constant. Changes in surface heat and water fluxes are the cause of the reduction in the steric height gradient that derives the THC weakening, 60% being due to temperature change (greater warming at high latitudes) and 40% to salinity change (decreasing at high latitude, increasing at low latitude). The level at which the THC stabilizes is determined by advective feedbacks. As the circulation slows down, less heat is advected northward, which counteracts the in situ warming. At the same time, northward salinity advection increases because of a strong increase in salinity in the subtropical Atlantic, due to a greater atmospheric export of freshwater from the Atlantic to the Pacific. This change in interbasin transport means that salinity effects stabilize the circulation, in contrast to a single basin model of the THC, where salinity effects are destabilizing. These results suggest that the response of the Atlantic THC to anthropogenic forcing may be partly determined by events occurring outside the Atlantic basin.

1. Introduction

The thermohaline circulation (THC) in the North Atlantic is an important component of the climate system (Broecker 1991), which today is responsible for transporting large amounts of heat northward to high latitudes in the Atlantic sector. As a result of this heat transport, the North Atlantic and western Europe are significantly warmer than they would otherwise be, especially in winter. For example, Bergen, Norway (60°N, 5°E, 44 m above sea level) has a mean January temperature of 1°C, and a mean July temperature of 15°C, while Juneau, Alaska (58°N, 134°W, 8 m above sea level) has corresponding temperatures of around −3°C for January, and 14°C for July.

The temperate climate of the North Atlantic sector depends upon the heat supplied by the THC. We have known since the pioneering work of Stommel (1961) that thermohaline flows have the potential to display multiple equilibria, manifested in an hierarchy of models, ranging from simple box models to coupled ocean–atmosphere general circulation models (Stommel 1961; Manabe and Stouffer 1988; Marotzke and Willebrand 1991; Hughes and Weaver 1994; Mikolajewicz and Maier-Reimer 1994; Schiller et al. 1997; Scott et al. 1999). Furthermore, evidence from various paleoclimate indicators suggests that rapid climate changes have occurred in the geologically recent past (Broecker et al. 1985; Severinghaus and Brook 1999). Indeed the relative stability of the Holocene climate seems to have been atypical in the context of the much longer period covered by ice core records (Petit et al. 1999). The apparent concentration of past rapid climate changes within the North Atlantic region (Jouzel et al. 1995), and their coincidence in time with changes in the mode of formation of North Atlantic Deep Water (NADW), implicates the THC as a probable cause of past abrupt climate change (Duplessy et al. 1992), and raises the possibility that it may again trigger a rapid climate shift in the future if it should respond suddenly to increased anthropogenic forcing.

Past disruptions of the THC are generally thought to have been triggered by massive freshwater discharge from continental-scale ice sheets that fringed the North Atlantic (Broecker et al. 1985, 1988; Barber et al. 1999).
Although this mechanism is now less relevant because the volume of high-latitude Northern Hemisphere ice has shrunk dramatically, it is possible that the enhanced hydrological cycle associated with a warmer world (Kattenberg et al. 1996) may operate in an analogous way and deliver enough freshwater to the North Atlantic to interrupt the conveyor-belt overturning due to the THC. The extent to which this might happen remains an open question. Some climate modeling studies have hinted that the circulation in the North Atlantic may be close to a “bifurcation point” (e.g., Rahmstorf 1996), implying that a relatively modest freshening of the high-latitude ocean might be enough to result in a cessation of deep convection and a shutdown of the THC. If this were indeed the case, a rapid nonlinear response of the THC, with a concomitant climatic impact in western Europe would be a possible consequence of human-induced climatic warming (Ganopolski et al. 1998). The modeling studies of Manabe and Stouffer (1994) and Manabe and Stouffer (1999), are suggestive of a THC that is both sensitive to greenhouse gas forcing, and not far from a bifurcation point. In their model, increasing atmospheric CO$_2$ at a rate of 1% compound yr$^{-1}$ (doubling time 70 yr) leads to a significant weakening of the THC. By the time of CO$_2$ doubling, the THC is about 80% weaker than in the control. If atmospheric CO$_2$ is then held fixed at this level, the THC gradually recovers its original strength on a century timescale. But if, on the other hand, atmospheric CO$_2$ is allowed to increase for a further 70 yr at 1% compound yr$^{-1}$, until it reaches four times the present-day levels, the circulation collapses completely, and remains in this collapsed state for around 1000 yr. In contrast, other transient climate simulations (Murphy and Mitchell 1995; Gordon and O’Farrell 1997; Wood et al. 1999; Boer et al. 2000) do not display a bifurcational response and suggest relatively modest reductions in thermohaline overturning, while Latif et al. (2000) find no significant reduction in the strength of the THC in response to enhanced levels of atmospheric CO$_2$.

In the light of the uncertainty surrounding the response of the THC to anthropogenic forcing, with predictions for the transient weakening of the THC at the time of CO$_2$ doubling ranging from 0% to 80% (Kattenberg et al. 1996), and the significant climatic effects associated with this uncertainty, it is important that we understand why the THC behaves differently in the various models, elucidate the mechanisms that are responsible for the modeled behavior, and assess the credibility of these mechanisms.

Wood et al. (1999) used HadCM3, a coupled ocean–atmosphere general circulation model (AOGCM) recently developed at the Hadley Centre, to evaluate the change in the THC in response to increasing greenhouse gas concentrations. In this paper we investigate the mechanisms that are responsible for the changes observed by Wood et al.

2. The HadCM3 coupled climate model

The atmospheric component of HadCM3 (Pope et al. 2000), has a regular latitude–longitude grid with a horizontal resolution of 2.5° × 3.75°, and 19 hybrid coordinate levels in the vertical. The ocean component is a Cox-type (1984) ocean model on a 1.25° × 1.25° latitude–longitude grid (Gordon et al. 2000). It incorporates the tracer mixing scheme of Gent and McWilliams (1990) using the Visbeck et al. (1997) method of determining thickness diffusion coefficients locally. Convective adjustment in the region of the Denmark Strait and Iceland–Scotland Ridge is modeled so as to represent the downslope mixing of the overflow water, allowing it to find its level of neutral buoyancy (Roether et al. 1994) instead of convectively mixing it through the water column.

Past coupled climate model studies of the THC response to increased greenhouse gases have been subject to two major criticisms. First, it has been necessary either to use unphysical surface flux adjustments, or else accept a control state with an unrealistically strong or weak Atlantic meridional overturning (Gates et al. 1996). Because the flux adjustment procedure contains implicit feedbacks on the strength of coupled phenomena such as the THC, a requirement for flux adjustment may distort the stability of the modeled THC in an unrealistic way (Marotzke and Stone 1995; Dijkstra and Neelin 1999), while starting from an unrealistic state is equally unsatisfactory. Second, deep water formation generally occurs south of the Greenland–Iceland–Scotland (GIS) Ridge in models (Rahmstorf 1995), while in reality such regions are observed both north and south of the GIS Ridge, a separation of sources facilitated by the existence of a number of narrow channels in the ridge (Dickson and Brown 1994).

Use of HadCM3 helps us to avoid both of these problems (Wood et al. 1999). The simulation of surface heat fluxes and poleward heat transport has improved to such an extent that the need for heat flux adjustment has been obviated (Gordon et al. 2000). The higher resolution has also allowed an improved representation of the various channels in the GIS, which while still not fully realistic, has enabled HadCM3 to capture the observed separation of deep water sources (Wood et al. 1999; Gordon et al. 2000).

3. Climate change experiments

In addition to a control run of the model that simulates a constant preindustrial climate, our analysis is mostly based upon a run in which CO$_2$ was increased at 2% compound yr$^{-1}$ until it reached four times the control simulation values after about 70 yr, and was then held fixed at this level. We call this run “2PC” following Wood et al. (1999). The run begins in the year 1859, but this date is purely nominal. 2PC should not be considered as a prediction of the likely future climate since
the forcing trajectory of this scenario is not realistic (greenhouse gas concentrations are currently rising at around 0.7% yr\(^{-1}\) (Schimel et al. 1996)), but is here used to help evaluate the sensitivity of the THC to “rapid change.” The motivation for this sensitivity test is given by two previous studies. Stocker and Schmittner (1997) argued that the response of the THC depends upon the rate as well as the magnitude of the climate change forcing, while Manabe and Stouffer (1994) showed that the THC can be semipermanently shutdown in their model by a \(\text{CO}_2\) level of four times present day, occurring over the course of 140 yr (i.e., with a rate of increase of 1% compound yr\(^{-1}\) or half of that in our 2PC scenario).

Wood et al. (1999) also studied a run they termed “GHG” in which greenhouse gases concentrations followed the historical record from 1859 to 1990, and projections of the Intergovernmental Panel on Climate Change’s (IPCC) IS92a emissions scenario (Leggett et al. 1992; Alcamo et al. 1995) from 1990 onward. It should be noted that while the IPCC IS92 scenarios have been subject to some criticism on economic grounds (Alcamo et al. 1995; Hoffert et al. 1998), and modeling studies have suggested that sulphate aerosol forcing can have important climatic effects (Mitchell and Johns 1997), the behavior of the THC in our model is not particularly sensitive to these factors. The THC response in HadCM3 experiments using the more recent IPCC SRES scenarios (available online at (http://sres.ciesin.org); Nakićenović et al. 2000) is in all material respects identical to GHG, so we do not discuss them further.

4. Time dependence of \(\text{CO}_2\) forcing and THC response

The time evolution of radiative forcing at the tropopause for the two climate change scenarios is shown in Fig. 1. The 2PC scenario results in much the stronger initial forcing, but by 2100 the two are roughly comparable.

Figure 2 shows the predicted change in the maximum of the North Atlantic overturning streamfunction for the two climate change scenarios and for a sensitivity test in which atmospheric \(\text{CO}_2\) was instantaneously increased to four times the preindustrial levels (\(4 \times \text{CO}_2\)).

4.1. Time dependence of \(\text{CO}_2\) forcing and THC response

The time evolution of radiative forcing at the tropopause for the two climate change scenarios is shown in Fig. 1. The 2PC scenario results in much the stronger
much larger than the magnitude of decadal variability) in the weakening in 2PC at the time when the forcing stabilizes. This was confirmed in a sensitivity experiment (4 × CO₂) in which atmospheric CO₂ was instantaneously increased to four times preindustrial concentration without inducing a transient response any larger than that seen in 2PC (Fig. 2). In contrast, Stocker and Schmittner (1997) found a strong rate dependence of the threshold beyond which the THC would collapse on advective timescales, with rapidly increasing forcing being much more effective at triggering a collapse than a more slowly varying forcing of comparable magnitude. Manabe and Stouffer (1999) likewise showed a dependence of the final THC strength on forcing in a range of scenarios where CO₂ increased at different rates up to the same final value.

5. Mechanisms governing the behavior of the thermohaline circulation in HadCM3

a. Dependence of THC strength on the meridional gradient of steric height

Assuming geostrophy and a linear relation between the zonal and meridional pressure gradients implies that there ought to be a linear relationship between the meridional pressure gradient and the strength of the overturning (Park 1999), as found by Hughes and Weaver (1994), and as frequently prescribed in Stommel-type models (Stommel 1961; Scott et al. 1999). On the other hand, scaling analysis based upon geostrophy and advective–diffusive buoyancy balance in the thermocline (Bryan and Cox 1967; Welander 1971) would suggest a one-third power dependence upon the meridional pressure gradient (Park 1999). A relationship of this form is supported both by numerical experiments (Winton 1996; Park and Bryan 2000), and laboratory measurements (Park and Whitehead 1999).

The Stommel model relates the THC to the density contrast between equatorial and polar latitudes in one hemisphere, but Rooth (1982) argued that the contrast between Northern and Southern Hemispheres was the driving force. More recently, Scott et al. (1999) and Klinger and Marotzke (1999) have also argued in favor of this interhemispheric picture. The linear relationship between thermohaline overturning and depth-integrated density differences reported by Hughes and Weaver (1994) for equilibrium simulations using their ocean general circulation model spans the latitudinal extent of the Atlantic basin as far south as the tip of Africa, while the equilibrium response studies of Rahmstorf (1996) also report an overturning circulation cross hemispheric in extent.

Using decadal-mean data from a large range of HadCM3 experiments (not only 2PC and GHG), we have found empirically that the THC strength correlates most strongly with the meridional gradient between 60°N and 30°S (i.e., the whole Atlantic) of the density integrated between the surface and 3000 m (i.e., within the layer of NADW). The gradient is found by least squares fit against latitude. The correlation is not very sensitive to the choice of level of integration, so long as the level chosen lies within the body of southward-flowing NADW. Correlations are weakened by reducing the latitude range at either end.

The depth-integrated density anomaly is equivalent to steric height anomaly defined as

$$-\int_0^h \delta \rho \rho_0 \, dz,$$

where $\rho_0$ is a reference density, and $z$ is the vertical coordinate, ranging from $0$ (the surface) to $H$, the reference depth, which is here taken as 3000 m. The Atlantic THC is associated with a positive meridional pressure gradient (depth-integrated density decreasing southward), and hence a negative steric height gradient in the north–south sense. In the discussion that follows, we define steric height gradient in the south–north sense, hence increasing positive gradient is associated with a strengthening THC and vice versa. The assumption of a linear relation between the meridional gradient of steric height and THC strength is evidently good in HadCM3 (Fig. 3). In particular, the relationship continues to hold in runs in which the 2% compound increase in CO₂ is sustained beyond 1929, eventually reaching more than 20 times its initial level. In these runs the THC declines by 80% to only 5 Sverdrup (Sv = 10⁶ m³ s⁻¹), but does not collapse completely.

b. Dependence of steric height on temperature and salinity

The relative importance of temperature and salinity effects in driving changes in the THC is highly model dependent, with the weakening being predominantly...
thermally driven in Mikolajewicz and Voss (2000), and mainly influenced by changes in salinity in Dixon et al. (1999). Figure 4 shows the changes in steric height gradient induced by changes in temperature ($x$ axis) and salinity ($y$ axis) in 2PC. In general terms, the changes in temperature are acting to weaken the THC, and changes in salinity to strengthen it, with the former being slightly larger than the latter, resulting in the weaker circulation seen in 2PC. The overall behavior is therefore more reminiscent of Mikolajewicz and Voss (2000) than Dixon et al. (1999), although it should be noted that our experimental setup differs from these other studies in their partition into “heat” and “freshwater” fluxes was done using parallel experiments with separate forcings, ours is done by reference to the influence of temperature and salinity upon steric height gradient within a single experiment. The experiments of Mikolajewicz and Voss (2000), and Dixon et al. (1999) therefore constitute a direct test of the role of the surface fluxes, while our experiments infer the role of surface forcing from the impact that this forcing has on the steric gradient that drives the circulation in HadCM3. As such the other results in the literature are not exactly comparable in the strictest sense. Whether estimates of the relative importance of heat and freshwater forcing are in fact sensitive to this difference in scenario construction will depend upon the way in which the effects of the surface fluxes are communicated downward through the ocean, a matter that is currently under investigation. However, the relative linearity of the transient response to the surface fluxes when they are separated in Mikolajewicz and Voss (2000), and Dixon et al. (1999), leads one to suspect that the relative balance of heat and freshwater forcing may not be sensitive to this difference in methodology. The initial weakening during the first 70 yr when greenhouse gas forcing is increasing is essentially driven by changes in temperature, with salinity changes having little impact. For a few decades after the forcing has stabilized, changes in temperature favor a further weakening of the THC, but these are now more than counterbalanced by changes in salinity, leading to the partial recovery of the circulation seen between 1930 and 2030 before the system appears to settle down with a THC some 25% weaker than in the control.

c. Effect of surface fluxes upon steric height gradient

Having demonstrated a relationship between THC strength and steric height gradient, and shown the dependence of the latter on temperature and salinity, we now proceed to consider the physical processes that determine the temperature and salinity changes. Our explanation of the THC changes will thus be made in terms of these processes. In HadCM3, we have diagnosed rates of change of temperature and salinity in each grid box separately due to surface fluxes, advection (i.e., convergence due to the model 3D velocity field), Gent–McWilliams advection [due to the additional eddy velocity field implied by the scheme of Gent and McWilliams (1990)], sea ice processes, diffusion, and vertical mixing due to mixed layer processes and convection. For each decadal mean, we calculate the contribution due to rate of change of density from each of these terms, integrate down to 3000 m, and regress against latitude. The slope gives the contribution of the term at that time to the rate of change of the steric height gradient (and hence the rate of change of THC). We also present the results integrated in time, giving the contributions of each term to the change in THC since the start of the experiment. Because of the regression against latitude, changes at either the northern or southern ends of the Atlantic have greater weight than changes at intermediate latitudes in determining the contribution of the term. Changes at opposite ends have opposite effects; a term tending to increase the density at 60°N increases the THC driving force, while the same term at 30°S reduces the driving force, with a smooth variation in between.

Figure 5a shows the rate at which the various terms alter the meridional steric height gradient as they change the density of the upper 3000 m in the Atlantic basin during the course of the 2PC experiment. The corresponding integral picture (net contribution to the steric height gradient, and hence THC overturning strength) is presented in Fig. 6a. Both pictures show clearly that the critical terms are the surface forcing terms and the advective terms. Other terms such as diffusion, Gent–McWilliams mixing, and sea ice process are much less important, and have here been lumped together for clarity of presentation, while the depth-integrated picture implies contributions from convection and mixed layer processes that are essentially zero.
The surface terms stem from the impact of the greenhouse forcing on climate, which changes the surface fluxes of heat and freshwater. The warming leads to a large reduction in the amount of heat being lost from ocean to atmosphere in the North Atlantic, and therefore tends to make the water less dense. Although heating of the ocean occurs across the latitudinal extent of the THC (and hence there is an element of cancellation in its impact on the density gradient), stronger net heating in the North Atlantic relative to the region between the equator and 30°S (see Fig. 7), and more rapid downward propagation of the resulting warming through the water column as a consequence of a reduction in convective mixing in the sinking regions (Fig. 8) together imply a reduction in the meridional density gradient, and hence tend to weaken the THC.

Patterns of precipitation, runoff, and evaporation also change in response to an increasingly vigorous hydrological cycle in a warmer world (Kattenberg et al. 1996). Greater net precipitation at latitudes poleward of about 45° leads to a freshening of the surface waters of the North Atlantic (Fig. 9), while an increase of evaporation at low latitudes leads to an increased density at the southern end of the Atlantic basin. Both of these changes tend to weaken the THC.

It is apparent from Figs. 5 and 6 that both heat and freshwater fluxes are important in driving the initial weakening of the THC in HadCM3. Even though the cross-hemispheric nature of the THC results in partial cancellation of the effects of surface heating, while providing reinforcement of high-latitude freshening through a corresponding salinification of low-latitude waters, the overall effect of the surface heat fluxes is generally around 50% greater than the surface fresh-
Fig. 7. The difference in the average atmosphere to ocean heat flux during years 60–80 of the 2PC experiment relative to the control. It can be seen that the North Atlantic surface waters are absorbing much more additional heat than the rest of the Atlantic.
water fluxes. This contrasts both with the study of Mikolajewicz and Voss (2000) where the heat fluxes were estimated to be more important by a factor of 3, and Manabe and Stouffer (1999) and Dixon et al. (1999), where freshwater forcing is significantly more important than heat flux forcing. These differences are likely to be primarily a function of the model-dependent patterns of heat and freshwater fluxes induced by a given greenhouse forcing, but differences in the temperature and salinity properties of the Atlantic control state in the various models could also be a factor via nonlinearities in the equation of state. The North Atlantic is too warm and saline in HadCM3 (Table 1), and this may lead to the model THC response being too heat dominated, though it should be noted that when we repeated 2PC for a much later period in the control, we found that the THC response to anthropogenic forcing was insensitive to the multicentury drifts of temperature and salinity in the control.

d. Effect of advection upon steric height gradient

We showed earlier (section 5b, Fig. 4) that salinity changes have little effect on the steric height gradient (and hence the THC strength) in the initial phase of 2PC. This appears to contradict our observation (section 5c, Fig. 5) that freshwater fluxes have a significant, though not dominant, influence. This apparent conflict can be reconciled by noting that the temperature and salinity terms in Fig. 4 represent the combined effect on the density field of surface fluxes and advection, which have opposing influences. In the case of salinity, advection cancels out the effect of the surface fluxes, but in the case of temperature it does not. Hence salinity has much less overall effect that temperature on THC strength during this early phase of the run, even though the surface-forced weakening is comparable from freshwater and heat.

The advective effects are feedbacks that come into play as soon as the THC begins to weaken. Advection of heat leads to a stabilizing feedback on the THC (positive in Fig. 5). This is as expected from box models; the reduced advection of heat tends to cool the northern latitudes and warm the south, thus increasing the driving force. Changes in advection of salinity in 2PC also tend to strengthen the driving force, that is, they tend to increase salinity in the north relative to the south. This is at variance with box models, in which salinity advection is a destabilizing feedback, because the weakening of the circulation reduces the advection of relatively saline water northward. This difference is explained in section 6.
Fig. 9. Change in the freshwater budget (precipitation + runoff − evaporation) for the eighth decade of the 2PC experiment relative to the corresponding period in the control. High-latitude freshening and low-latitude increases in salinity both act to weaken the THC.
The role played by salinity advection in stabilizing the THC was investigated further through a parallel experiment ("2PCF") starting from the point at which atmospheric CO₂ reached four times the preindustrial levels (after 70 yr, nominally 1929), with additional freshwater (equivalent to 0.49 Sv) to adjust the net surface freshwater flux from 1929 in the Atlantic between 30°N and 30°S back to its long-term mean value in the control simulation, and compensating evaporation in the Pacific so that salinity was conserved globally. The effect of northward salinity advection is much weaker in 2PCF because salinity does not build up further after year 1929 as it does in 2PC.

Figures 5b and 6b show the analysis of the steric height gradient for 2PCF. Comparison with Figs. 5a and 6a shows that the effect of imposing the flux correction field from 1929 is twofold. The additional freshwater eliminates salinity advection as a stabilizing tendency beyond 1929 (dotted blue line in Fig. 5), and appreciably reduces its contribution to THC overturning strength (Fig. 6). If this were the only change occurring, the 0.4-m reduction in the steric height gradient might well be enough to collapse the THC. In fact, however, it only weakens from 15 to 12 Sv, because of a compensating change affecting steric gradient through the direct impact of the additional surface freshwater forcing, which tends to reduce the density of low-latitude waters, strengthening the steric height gradient and hence the THC. This can be seen in the substantial reduction in the tendency of freshwater forcing to weaken the THC from 1929 onward (solid blue line in Fig. 5), and in the significant reduction of the surface freshwater forcing contribution to the overall weakening of the THC (Fig. 6), a change that largely offsets the reduced salinity advection.

To summarize: in 2PC the local effect of the increased high-latitude freshwater flux is to weaken the THC, and this effect is opposed by advection of saline water from low latitudes. In 2PCF, the latter effect is cancelled, but its removal is largely offset by the local effect of the additional low-latitude freshwater flux, which tends to strengthen the THC.

6. Understanding the role of salinity advection in stabilizing the thermohaline circulation

Broadly speaking, there are two reasons why salinity advection may be increasing in 2PC even though the meridional overturning is reducing in strength. First, some other process may be compensating for reduced advection by the meridional overturning. The Stommel-type box models assume that advection by the meridional overturning is the only method by which the salt can be transported northward, whereas in reality transport by the oceanic gyre circulation does also occur. Such transport would continue, even if the THC were to shut down, and this process may be operating more effectively in the 4 × CO₂ climate than it does in the control. Secondly, it may be the case that changes in precipitation, evaporation, and runoff in 2PC enhance the salinity gradient so much that even though the meridional circulation slows it advects more salt. Because the Stommel model applies to a single basin, it fails to take account of any changes in the interbasin flux of freshwater, changes that will redistribute density between the Atlantic and Pacific.

We determined which of these explanations is more valid by considering the time-dependent behavior of the northward salinity advection. Figure 10 shows the change in northward salinity advection at 33°N, broken down into the component due to the advection of the

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**Table 1.** Temperature, salinity, and density in the Atlantic. The table illustrates drifts that occur in the first 100 yr of the control. The North Atlantic warms significantly and becomes too saline, while there is little change in the South Atlantic. Though the errors in the North Atlantic are largely density compensating, there is a slight increase in the density of waters in this region, and a more significant increase in the Atlantic meridional steric gradient as the THC adjusts during the first century of the control. Drifts in temperature and salinity continue to occur in the control after this first century, but at a much slower rate.

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**Fig. 10.** Northward salinity advection across 33°N, showing the contributions made by the reduction in the strength of the meridional overturning (dotted line), and the enhanced Atlantic salinity gradient (dashed line).
mean salinity gradient by the anomalous flow (the reduction due to the weakening of the THC), and the component due to the advection of the anomalous salinity by the mean THC (the enhancement due to the strengthened equator–Pole salinity gradient). The results clearly show that the increased salinity gradient in 2PC drives stronger salinity advection, even though the meridional overturning has weakened. Therefore, there is no need to postulate more efficient gyre transport to account for the observed enhancement of northward salinity advection.

The development of a high-salinity anomaly in the subtropical Atlantic, and the subsequent enhanced northward advection associated with this anomaly is illustrated in Fig. 11. The initial development of the salinity signal occurs around 20°N. The signal then propagates northward to the North Atlantic sinking regions on timescales of 20–100 yr (see also Fig. 5). This is significantly slower than a simple advection based upon the mean northward flow speed at 200-m depth (order 1 cm s⁻¹), and the 12–15-yr timescale for the advection of surface anomalies reported by Sutton and Allen (1997).

7. Mechanisms responsible for the buildup of salinity in the subtropical Atlantic

The initial development of the salinity anomaly is a consequence of a change in the efficiency of Atlantic to Pacific freshwater exchange in the anthropogenically warmed climate. Figure 12 shows changes in (a) precipitation + runoff, (b) evaporation, and (c) net surface freshwater budget for the Atlantic and Pacific basins. Both precipitation and evaporation generally tend to increase with temperature, the exception being the anomalous decrease in precipitation in the central Atlantic that directly reflects an enhanced export of water vapor from Atlantic to Pacific. Changes in atmospheric pressure patterns that develop during 2PC lead to an increasingly strong trade wind regime in the western subtropical Atlantic and Caribbean. Also associated with the warmer climate is a general increase in specific humidity of maritime air caused by a more vigorous hydrological cycle and the increased carrying capacity of warmer air. These factors together lead to a large increase in the water vapor export from Atlantic to Pacific of the order of 0.4–0.5 Sv. One consequence of the change in circulation and precipitation patterns is the sharp decrease in rainfall over the Amazon basin that drives a dieback of the Amazonian rain forest when used to force vegetation models (P. Cox 2000, personal communication).

The general picture of increasing salinity in the subtropical Atlantic leading to enhanced northward advection of salt, densification of the high-latitude North Atlantic, and a stabilization of the THC is reminiscent of Latif et al. (2000), though in their model the stabilization
The large increase in surface salinity in the central Atlantic is due primarily to a reduction of precipitation in the subtropical Atlantic. This effect is so strong as to prevent any significant weakening of the thermohaline circulation. They invoke a change in the character of the El Niño–Southern Oscillation (ENSO; Timmermann et al. 1999) as being the ultimate cause of the changes in the freshwater budget that stabilize the THC in their model. It should be noted that Latif et al. (2000) do not discuss the stability of the circulation in terms of steric control, and hence it is not possible to say whether the shallowing of steric gradient caused by the increase in subtropical Atlantic salinity is acting to partially offset the stabilizing influence of northward salinity advection in their model. Nevertheless, it is instructive to consider the extent to which the changes in the freshwater budget in the low-latitude Atlantic that lead to a buildup of saline water over time bear some similarity to the effect of ENSO in the control climate of HadCM3. Figure 13 shows changes in the freshwater budget relative to the control long-term mean for (a) years in which there is a strong El Niño, (b) years in which there is a strong La Niña, and (c) the freshwater budget for the 2PC experiment. The pattern of change in the equatorial Atlantic for the 2PC case is strikingly similar to that for strong El Niño years in the control, and opposite to that typical of La Niña years. However, the patterns of change in the Pacific region do not show a similarity between El Niño–La Niña, and 2PC, and indeed we do not find that ENSO is significantly responsive to greenhouse forcing in HadCM3 (M. Collins 2000, personal communication). The freshwater budget changes seen in HadCM3 cannot therefore be explained in terms of a change in ENSO, in contrast to the situation in Latif et al. (2000), although the results do support Latif’s suggestion of a potential link between the pattern of SST change in the Pacific and the buildup of salinity and hence the robustness of the thermohaline circulation in the Atlantic.

8. Summary and conclusions

The sensitivity of the North Atlantic thermohaline circulation (THC) to anthropogenic climate forcing is still an open question. Many models simulate a modest weakening of the THC in response to surface warming and freshening at high latitudes (Kattenberg et al. 1996), and some suggest a complete breakdown of the THC under sufficiently strong forcing (Manabe and Stouffer 1999), while at least one previous model study suggests no significant transient weakening at all (Latif et al. 2000).

In this paper we have presented results from the HadCM3 AOGCM that indicate a modest 25% weakening of the THC by 2100 in response to IS92a greenhouse gas forcing or to stabilization of CO₂ at a level four times that of the control simulation. In contrast to previous modeling studies that emphasized the importance of either heating (Mikolajewicz and Voss 2000) or freshwater (Manabe and Stouffer 1999; Dixon et al. 1999), we find a more complex picture. In terms of the overall impact of temperature and salinity effects, temperature changes are responsible for driving the initial weakening observed in the climate change simulations, while in the longer term, a balance between temperature and salinity effects is responsible for stabilizing the THC at a 25% weaker level. In terms of surface forcing, warming and freshwater changes are both important,
We find no evidence that the century-scale behavior of the THC is particularly sensitive to the rate of change of the climate forcing, or to specific details of the forcing scenario, at least within the range of experiments considered here. Results for a wide range of time-dependent HadCM3 experiments show that there is a good linear relationship between the THC strength and the meridional gradient of steric height in the Atlantic. This relationship continues to hold as CO₂ increases to very high levels (>20 × control), when the THC has weakened by up to 80%, but does not collapse.

Two major mechanisms operating on advective time-scales were found to limit the weakening of the THC. First, the heat transport of the circulation itself is a stabilizing influence. As the THC weakens, less heat is transported northward, and consequently water in the high-latitude sinking regions is colder (and denser), and the steric height gradient driving the THC stronger than it would otherwise be. Second, enhancement of the meridional salinity gradient means that northward salinity advection increases even though the THC weakens, again leading to denser high-latitude waters and a strengthening of the steric height gradient driving the THC.

The enhancement of northward salinity advection was found to be qualitatively similar (though weaker) to that reported by Latif et al. (2000), involving an increase in atmospheric water vapor export from the Atlantic to Pacific basins of the order of 0.4–0.5 Sv, and a large increase in near-surface salinities in the subtropical Atlantic. This mechanism needs to be considered in the light of a control climatology that is already too evaporative and saline in the subtropical Atlantic (A. Paradaens 2000, personal communication), nevertheless, the fact that a mechanism of qualitatively similar type is also present in ECHAM4 may provide some reassurance as to its robustness. As previously found by Latif et al. (2000), the changes in the low-latitude Atlantic freshwater budget are similar to those occurring within the control climate in El Niño years, but in HadCM3 the Pacific changes do not resemble El Niño. Nonetheless, the results suggest that SST patterns in the Pacific can influence the behavior of the thermohaline circulation in the Atlantic through their impact on the freshwater budget of the latter. It is therefore desirable to improve our understanding of the processes that determine SST patterns and freshwater transports in the Tropics, and their representation within models, if we are to increase confidence in our prediction of future changes in the behavior of the thermohaline circulation, and by implication the climate of western Europe.

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