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Stability of the thermohaline circulation under millennial CO_2 forcing and two alternative controls on Atlantic salinity

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[1] A large ensemble of experiments with an efficient climate model is carried out to examine stability of the oceanic thermohaline circulation (THC) as a function of two key processes that maintain high Atlantic salinities: the "Atmospheric Bridge" by which moisture is exported from the Atlantic to the Pacific; and "Agulhas Leakage" of salty Indian Ocean waters into the Atlantic. We find that irreversible THC collapse during the next millennium is five times more likely if Agulhas Leakage dominates over the Atmospheric Bridge. This finding is consistent with freshwater import to the Atlantic sector associated with the overturning circulation, when the Atmospheric Bridge dominates. In contrast, slight freshwater export is associated with the overturning circulation under strong Agulhas Leakage, helping to maintain higher Atlantic salinity. Predictions of future climate change therefore critically depend on better understanding of the relative importance of the Atmospheric Bridge and Agulhas Leakage. **Citation:** Marsh, R., W. Hazeleger, A. Yool, and E. J. Rohling (2007), Stability of the thermohaline circulation under millennial CO_2 forcing and two alternative controls on Atlantic salinity, *Geophys. Res. Lett.*, *34*, L03605, doi:10.1029/2006GL027815.

1. Introduction

[2] The "conveyor mode" [*Broecker*, 1991] of the Atlantic thermohaline circulation (THC) is a key feature of the present-day climate [*Vellinga and Wood*, 2002]. This circulation state is dependent on relatively high surface salinity in the Atlantic [*Seidov and Haupt*, 2003], which is maintained by two processes: an "Atmospheric Bridge" (AB) by which moisture evaporated from the subtropical Atlantic is exported to the Pacific [*Broecker*, 1997] and "Agulhas Leakage" (AL) of salty Indian Ocean thermocline waters around South Africa into the South Atlantic [*Gordon*, 1986]. Both processes have varied substantially on similar time-scales as the THC [*Peeters et al.*, 2004; *Peterson et al.*, 2000], but causal relationships remain obscured by uncertainty about the relative importance of the two processes [*Zaucker and Broecker*, 1992; *de Ruijter et al.*, 1999]. This uncertainty hinders long-term predictions of the THC response to rising CO_2 as studies using idealised/efficient models suggest that the Atlantic THC stability is strongly dependent on both processes [*Wang and Birchfield*, 1992; *Weijer et al.*, 2001; *Marsh et al.*, 2004].

[3] Ocean models have been used to demonstrate: (a) the importance of AL for the conveyor [*Weijer et al.*, 1999]; (b) that the very presence of the conveyor maintains high salinity in the North Atlantic through net freshwater export from the basin by deep-sea transport [*Rahmstorf*, 1996]; and (c) that AL might be more efficient than AB in altering the THC [*Seidov and Haupt*, 2003]. The AL process supplies high salinity waters into the surface and thermocline of the South Atlantic, predominantly by means of eddies ("rings") that are intermittently shed at the Agulhas Current retroflection [*Richardson et al.*, 2003]. Observations show that 4–8 rings are shed per year [*De Ruijter et al.*, 1999], with a salt flux per ring of $0.15–6.3 \times 10^5$ kg s^{-1}. It has been found that AL was periodically shut off during glacial times [*Peeters et al.*, 2004], and the consequent reduction of AL salt flux into the Atlantic may have contributed to the weakening of glacial North Atlantic overturning inferred from proxy data [*McManus et al.*, 2004].

[4] Fully coupled ocean-atmosphere models, in contrast, do not resolve the AL and place more emphasis on the AB, with the hydrological cycle imposing a negative feedback on a collapsing THC through low-latitude atmospheric processes [*Lohmann*, 2003]. The AB process concerns a net atmospheric freshwater export from the Atlantic into the Pacific, driven by high rates of net evaporation from the Atlantic. For present day climate, humidity and wind observations suggest a net surface freshwater export from the Atlantic sector of 0.32 Sv (1 Sv = 10^6 m^3s^{-1}), partitioned equally between the tropics and northern extratropics [*Zaucker and Broecker*, 1992]. Conversely, inverse analysis of ocean hydrographic section data highlights a dominant role of South Atlantic evaporation in the net Atlantic freshwater loss [*Ganachaud and Wunsch*, 2002]. Using two different reanalysis datasets, differences of up to 0.1 Sv are obtained between monthly anomalies of net freshwater flux in the Atlantic zone 20°S to 20°N [*Schmittner et al.*, 2000]. Estimates of long-term mean net freshwater export based on short records [*Zaucker and Broecker*, 1992] may furthermore be compromised by natural variability associated with El Niño, which amounts to an estimated range of 0.3 Sv [*Schmittner et al.*, 2000]. Based on the evidence, and for the purposes of this study, we consider long-term mean freshwater export to be 0.15 ± 0.15 Sv. This range covers the majority of published estimates, so that in the experiments described below we account for the sensitivity of solutions to extreme AB cases.

[5] Here we investigate the relative importance of AB and AL for THC stability, with particular reference to the fate of the THC under rising atmospheric CO_2 concentrations. It has been proposed that the strength of the Atlantic Conveyor may decline over the next century [*Intergovernmental Panel on Climate Change*, 2001], due to a combi-

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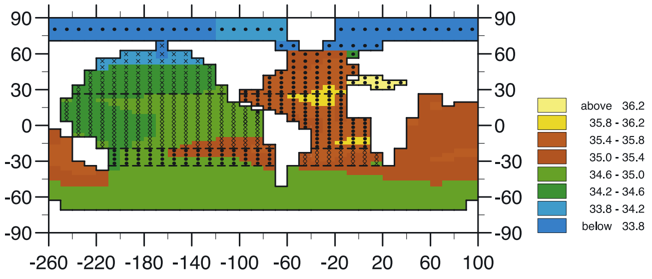
nation of warming and freshening at northern high latitudes. There is (even) greater uncertainty about the longer-term (post-2100) fate of the THC, due to our poor understanding of the Atlantic freshwater balance in addition to uncertainties in future projections of anthropogenic climate forcing. So far, only one study has addressed the THC response to the CO_2 transient on a millennial timescale, suggesting that irreversible collapse or recovery is contingent on changes in surface freshwater fluxes at mid-to-high latitudes of the North Atlantic [*Rahmstorf and Ganopolski*, 1999].

(a) AB flux maximum, AL flux zero



(b) AL flux maximum, AB flux zero

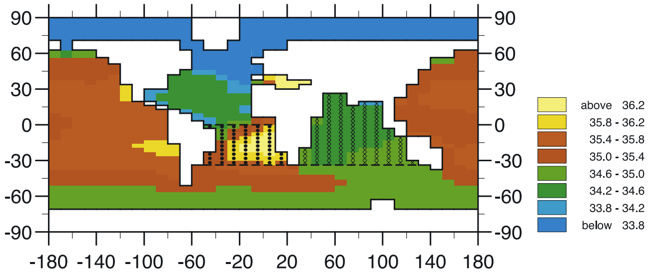


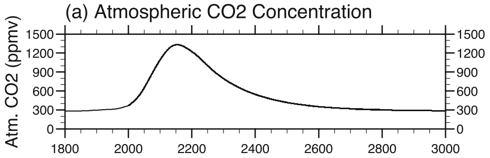
Figure 1. Fields of model surface salinity (psu) for AD 2000: (a) AB flux = 0.290, AL flux = 0 and (b) AB flux = 0, AL flux = 0.290. Zones of surface freshwater flux adjustment are delimited in the three Atlantic and Pacific zones (Figure 1a) and in the South Atlantic and Indian Ocean zones (Figure 1b; dots indicate net evaporation, crosses indicate net precipitation). In Figure 1a net evaporation in the Atlantic is sufficient to sustain a Conveyor mode THC and high salinity throughout the Atlantic, consistent with observations. In Figure 1b, the THC is in a collapsed state and high salinity is only maintained in the South Atlantic, incompatible with observations.

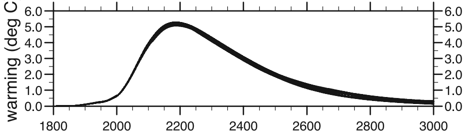
2. Model and Experimental Design

[6] To assess the importance of the sources of salinity to THC stability, a wide range of parameters must be considered in a coupled ocean-atmosphere context. We add a new perspective that considers THC changes over the next millennium in response to different combinations of AL and AB, using an intermediate complexity climate model that comprises a 3-D frictional geostrophic ocean component configured in realistic geometry, including bathymetry, coupled to an energy-moisture balance model of the atmosphere and a thermodynamic model of sea ice [*Edwards and Marsh*, 2005]. The model has a low resolution of 10° longitude by 36 equal increments in the sine of latitude (such that all grid cells are of equal area) by 8 depth levels. This, in conjunction with simplified physics, makes the model computationally efficient. Twelve key parameters in the model have been tuned to best simulate present-day atmosphere and ocean observations using the ensemble Kalman filter [*Hargreaves et al.*, 2004]. Our results comprise an ensemble of experiments across ranges of two model parameters, controlling the AL-equivalent (negative) freshwater flux and the AB process represented by an Atlantic-to-Pacific moisture flux. In each experiment, the model is spun up under pre-industrial atmospheric CO_2 concentration, which is then increased for 200 years as observed over AD 1800–2000 before undergoing a millennial transient according to an emissions scenario for AD 2000–3000 and a simple natural uptake scheme.

[7] AL and AB freshwater fluxes are applied as extra terms in the surface freshwater flux over selected regions, exactly compensating positive and negative terms to ensure no change in global net freshwater flux. The AL flux is applied over the South Atlantic and the Indian Ocean. The salt transport associated with Agulhas leakage has been diagnosed in an eddy-permitting ocean model at ~10 Sv psu [*Weijer et al.*, 2001], which is equivalent to a freshwater flux of −0.28 Sv. The AB flux is applied in three zones, as previously diagnosed from observations [*Zaucker and Broecker*, 1992]: south of 20°S; 20°S to 24°N; north of 24°N. The estimated net AB flux of 0.32 Sv is somewhat high compared with the equivalent flux in atmospheric models [*Zaucker and Broecker*, 1992]. As our model typically transports 0.03 Sv of moisture from the Atlantic to the Pacific through explicit advection and diffusion, we therefore specify a maximum prescribed AB flux of 0.29 Sv. Both AL and AB fluxes are varied by 10% increments in the range zero to 0.29 Sv, such that all possible combinations comprise a 121-member ensemble. Figure 1 shows model surface salinity in AD 2000 under two extreme combinations of AB (Figure 1a) and AL (Figure 1b). Superimposed on Figures 1a and 1b are the regions and zones over which we apply the surface freshwater flux adjustments. In Figure 1a, the salinity field compares reasonably well with observations, although the surface Atlantic is too fresh by about 1 psu (not shown). In Figure 1b, North Atlantic salinity cannot be maintained at a value sufficient for convective overturning, and the Atlantic THC is in a collapsed state. However, for a broad range of intermediate combinations of AL and AB, we get more realistic surface salinity fields (not shown) and a Conveyor mode THC. In fact, root mean square error for SST and SSS, relative to Levitus observations, is minimized and homogeneous across the corresponding region of AB-AL flux space.

[8] Each experiment begins with a spin-up phase of 4000 years during which atmospheric CO_2 concentration is set at a pre-industrial level (~280 ppmv) for 3800 years. Over the last 200 years of the spin-up, we specify historical CO_2 concentrations from ice cores (1800–1957) and Mauna Loa (1957–2000). After 2000, atmospheric CO_2 is determined by anthropogenic emissions and natural uptake that relaxes CO_2 back towards the pre-industrial level with an e-folding timescale of 150 years. The return towards a pre-industrial level of CO_2 at AD 3000 is specified to investigate whether the THC can operate in different stable states


(a) Atmospheric CO2 Concentration


(b) Global Warming (relative to 1800)

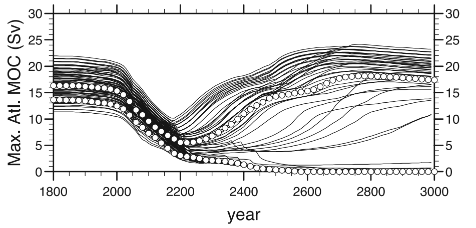

(c) Maximum Atlantic Overturning

Figure 2. Time series over AD 1800–3000 of simulated: (a) atmospheric CO_2 concentration, (b) global-mean air temperature anomaly (relative to 1800), and (c) maximum Atlantic THC strength (taken here as the maximum value of the meridional overturning streamfunction). The THC in ensemble members that are initially of similar strength, under the same net (combined) freshwater flux, can respond to CO_2 forcing in very different ways: the dotted curves identify two such ensemble members which are AB-dominated (THC fully recovered by AD 3000) and AL-dominated (THC irreversibly collapsed by AD 3000).

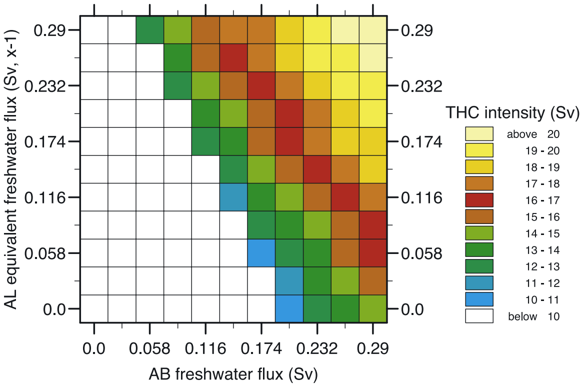
under near-identical CO_2 concentration (before and after a millennial-timescale transient). We specify the IPCC indicative scenario A1FI [*Intergovernmental Panel on Climate Change*, 2000] for CO_2 emissions up to 2100. After 2100, the emissions rate declines to zero at 2245. This extended emissions scenario is symmetric about 2100. As a consequence of this forcing, atmospheric CO_2 reaches a peak of 1322 ppmv in AD 2155 (see Figure 2a). After 2000, we include an extra freshwater flux due to melting of the Greenland Ice Sheet. This flux is parameterised as a function of the air temperature anomaly relative to 2000 using a sensitivity of 0.01 Sv per 1°C of global warming, which is comparable to prescribed levels of "hydrological sensitivity" used in similar experiments [*Rahmstorf and Ganopolski*, 1999]. Commencement of melting in 2000 is consistent with evidence that the Greenland mass balance has only recently started to change [*Rignot and Kanagaratnam*, 2006].

3. Results

[9] Figure 2 shows AD 1800–3000 time series of CO_2 concentrations, global warming and Atlantic overturning strength for 69 ensemble members with a conveyor mode THC (after spin-up). In the model, global warming peaks around 6°C by AD 2180, followed by a return to almost zero by AD 3000. The melting rate of the Greenland ice sheet rises to a peak of around 0.045 Sv at ~AD 2250, compared an estimated ice sheet mass deficit of 0.007 Sv in 2005 [*Rignot and Kanagaratnam*, 2006]. The Atlantic overturning displays an initial weakening of ~10% over AD 1800–2000, after which the accelerating warming and Greenland melting drive the THC towards collapse. Following the CO_2 peak, the THC continues to collapse in 29 ensemble members, while THC recovery occurs in the other 40. By AD 2300, clear bifurcation behaviour is apparent, and by AD 3000 the ensemble has separated into two distinct modes: one with a recovered THC, and the other with an irreversibly collapsed THC.

[10] Figure 3a shows the "present day" (AD 2000) maximum value of simulated Atlantic overturning as a function of AL and AB freshwater fluxes. Two stable states are evident, corresponding to conveyor and collapsed states of the THC. For a range of freshwater flux combinations, the THC is unrealistically collapsed at AD 2000. For combinations leading to a THC in conveyor mode, we obtain overturning strengths in the range 12–21 Sv, which

(a) AD 2000



(b) AD 3000 minus AD 2000

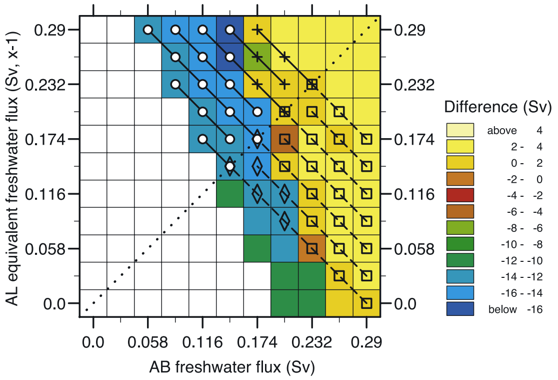


Figure 3. Atlantic THC strength (Sv) as a function of AB and AL freshwater transports in (a) AD 2000 and (b) AD 3000 minus AD 2000. In Figure 3b, we only indicate differences if the THC is in conveyor mode at AD 2000. The seven reverse diagonals correspond to seven levels of net freshwater flux, dominated by either AL (solid diagonals) or AB (dashed diagonals). Circles and diamonds indicate cases of a collapsed THC in AD 3000, while crosses and squares indicate cases of a recovered THC, both for AL and AB domination respectively. This interpretation of the results is used to infer the likelihood of irreversible collapse (Table 1).

Table 1. Likelihood of Irreversible THC Collapse Under Dominant AL or AB Fluxes, for Increasing Atlantic Freshwater Loss[a]

	Likelihood of Irreversible Collapse, %	
Net Freshwater Flux, Sv	AL Dominant	AB Dominant
−0.290	100	45
−0.319	100	40
−0.348	100	11
−0.377	**100**	**0**
−0.406	57	0
−0.435	33	0
−0.464	0	0
Average (−0.290 to −0.464)	70	14

[a] Net freshwater flux is the sum of AL and AB fluxes. "AL dominant" ("AB dominant") Likelihoods are obtained from "AD 3000 minus AD 2000" differences in THC strength, above (below) the dotted leading diagonal in Figure 3b: we divide the total number of pixels indicating AD 3000 collapse (circles and diamonds) along the solid (dashed) reverse diagonals by the total number of pixels. In the case that AB and AL fluxes are equal (i.e., lie along the leading diagonal), half-pixels are counted.

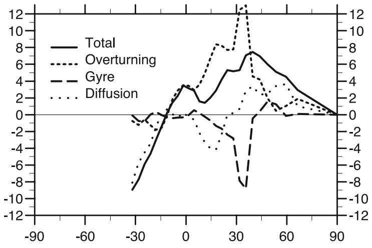
span recent estimates [*Bryden et al.*, 2005]. Furthermore, we find that Atlantic-mean errors in surface temperature and salinity (relative to present day observations) are minimised and locally invariant in this freshwater flux space, when the THC at AD 2000 is in the conveyor mode. The diagonal threshold between the two THC states indicates that either strong AL or AB freshwater fluxes (or both) can maintain the THC.

[11] Figure 3b shows "AD 3000 minus AD 2000" differences in Atlantic overturning strength, as a function of AL and AB freshwater fluxes, wherever the THC is in the conveyor mode at AD 2000. Large negative differences (circles and diamonds) indicate THC bistability, i.e., both conveyor and collapsed states of the THC are stable under the same combination of AL and AB freshwater fluxes, such that THC collapse is irreversible up to AD 3000. Differences elsewhere (crosses and squares) are mostly in the range 0–4 Sv, indicating recovery (and slight strengthening) of the THC by AD 3000. In this region of parameter space, we conclude that the THC is monostable in the conveyor state. Considering the 69 ensemble members with a Conveyor Belt THC at AD 2000 as equally probable, for a given net freshwater flux (equal along reverse diagonals in Figure 3b), the likelihood of irreversible THC collapse is greater if AL dominates the freshwater budget (Table 1). The extreme case is for net flux of −0.377 Sv (bold row in Table 1), in which case irreversible THC collapse is either 100% likely to happen under dominant AL, or 0% likely to happen under dominant AB. Averaged over a limited range of net freshwater flux, −0.290 to −0.464 Sv, irreversible THC collapse is five times more likely under AL dominance than under AB dominance.

[12] It has been argued that THC stability is linked to the strength and mode of oceanic freshwater transport at the Atlantic southern boundary [*de Vries and Weber*, 2005], which is in turn controlled by the combination of AB and AL. Figure 4 shows Atlantic salinity transports in AD 2000 for two ensemble members at the opposite ends of the reverse diagonal for which Atlantic net freshwater flux is −0.377 Sv (Figure 3b), corresponding to a THC that is bistable (Figure 4a) or monostable (Figure 4b). The different transient THC responses in these two ensemble members are indicated by the dotted curves in Figure 2c. Also shown in Figure 4 are the overturning, gyre and diffusion components of the total salinity transport. The gyre component is obtained as a difference between total advection and overturning components.

[13] Total salinity transport in Figure 4 equates reasonably well with freshwater transport estimates [*Ganachaud and Wunsch*, 2002]. At most latitudes in the Atlantic sector the overturning is transporting salinity northwards, equivalent to the southward freshwater transport established in other model studies [*Rahmstorf*, 1996; *de Vries and Weber*, 2005]. However, for the two ensemble members considered here, the overturning effectively imports fresh water at the southern boundary, although only marginally in the bistable case. This is in contrast to observational evidence that the overturning does indeed export fresh water from the Atlantic [*Weijer et al.*, 1999], although uncertainties in such estimates are rather large. However, the basin-net effect of overturning – taken as the difference between overturning salinity transports at 30°S and 60°N – is to freshen (slightly salinify) the Atlantic basin in the monostable (bistable) case, a relationship consistent with previous model results [*de Vries and Weber*, 2005]. Overturning transports are largely compensated by gyre transport in the subtropical North Atlantic, where there are strong zonal salinity gradients. Elsewhere, a rather limited wind-driven circulation supports only small gyre transports, and overturning transports are more dominant. There are, however, substantial diffusive transports in the model. While an artefact of low resolution, southward diffusive salinity transport at the southern boundary fulfils the role of the wind-driven gyre in the South Atlantic [*Weijer et al.*, 1999]. Diffusive salinity

(a) AL-dominated



(b) AB-dominated

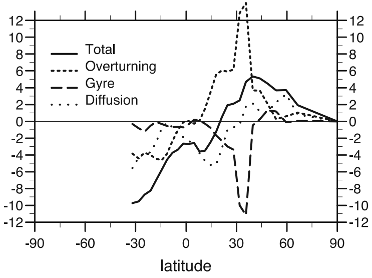


Figure 4. Atlantic salinity transports (Sv.psu) in AD 2000 for two ensemble members at the opposite ends of the "0.377 Sv diagonal" of Figure 3b: (a) AB flux = 0.087, AL flux = 0.290 Sv ("AL-dominated") and (b) AB flux = 0.290, AL flux = 0.087 Sv ("AB-dominated"). Total salinity transport is decomposed into overturning, gyre and diffusion components.

transports are stronger with a strong AL flux (Figure 4a) as this maintains a large meridional salinity gradient in the South Atlantic.

4. Summary and Discussion

[14] In summary, we find that the long-term fate of the THC is sensitive to two processes by which high surface salinity is maintained in the present-day Atlantic: Agulhas Leakage and the ‘‘Atmospheric Bridge’’. There is a corresponding influence on long-term climate change. In the experiments reported here, reduced northward heat transport in cases of irreversible THC collapse leads to the ‘‘bipolar seesaw’’ [*Stocker*, 1998] in air temperature remaining in a position with northern cooling of up to 7°C and southern warming of up to 2°C at AD 3000, within a climate that elsewhere is close to present day, while in cases of THC recovery, present-day climate is restored. In terms of the Atlantic freshwater budget, neither the combined effect of Agulhas Leakage and the Atmospheric Bridge, nor the balance between them, is well known for the present day. Indeed, the Atmospheric Bridge may be too strong in current state-of-the-art models, implying unrealistic northward freshwater transport and a monostable THC [*de Vries and Weber*, 2005]. Estimates of the actual probability of irreversible collapse must formally account for a range of uncertainties, including future CO_2 concentrations, and climate/hydrological sensitivity [*Challenor et al.*, 2006]. Here we stress the importance of reducing uncertainties in the two processes that control Atlantic salinity, particularly with respect to the balance between them, since the likelihood of irreversible THC collapse increases considerably when assuming a higher contribution of Agulhas Leakage. For credible long-term climate predictions, it is therefore essential that these different freshwater pathways are realistically simulated in state-of-the-art models.

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References

Broecker, W. S. (1991), The Great Ocean Conveyor, *Oceanography*, *4*, 79–89.

Broecker, W. S. (1997), Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588.

Bryden, H. L., H. R. Longworth, and S. A. Cunningham (2005), Slowing of the Atlantic meridional overturning circulation at 25°N, *Nature*, *438*, 655–657.

Challenor, P. G., R. K. S. Hankin, and R. Marsh (2006), Towards the probability of rapid climate change, in *Avoiding Dangerous Climate Change*, edited by H. J. Schellnhuber et al., pp. 55–63, Cambridge Univ. Press, New York.

de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. van Leeuwen, and W. Weijer (1999), Indian-Atlantic interocean exchange: Dynamics, estimation and impact, *J. Geophys. Res.*, *104*(C9), 20,885–20,910.

de Vries, P., and S. L. Weber (2005), The Atlantic freshwater budget as a diagnostic for the existence of a stable shut down of the meridional overturning circulation, *Geophys. Res. Lett.*, *32*, L09606, doi:10.1029/2004GL021450.

Edwards, N. R., and R. Marsh (2005), Uncertainties due to transport-parameter sensitivity in an efficient 3-D ocean-climate model, *Clim. Dyn.*, *24*, 415–433.

Ganachaud, A., and C. Wunsch (2002), Large-scale ocean heat and freshwater transports during the World Ocean Circulation Experiment, *J. Clim.*, *16*, 696–705.

Gordon, A. L. (1986), Interocean exchange of thermocline water, *J. Geophys. Res.*, *91*, 5037–5046.

Hargreaves, J. C., J. D. Annan, N. R. Edwards, and R. Marsh (2004), An efficient climate forecasting method using an intermediate complexity Earth system model and the ensemble Kalman filter, *Clim. Dyn.*, *23*, 745–760.

Intergovernmental Panel on Climate Change (2000), *Special Report on Emissions Scenarios*, edited by N. Nebojsa and R. Swart, 612 pp., Cambridge Univ. Press, New York.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., Cambridge Univ. Press, New York.

Lohmann, G. (2003), Atmospheric and oceanic freshwater transport during weak Atlantic overturning circulation, *Tellus, Ser. A*, *55*, 438–449.

Marsh, R., et al. (2004), Bistability of the thermohaline circulation identified through comprehensive 2-parameter sweeps of an efficient climate model, *Clim. Dyn.*, *23*, 761–777.

McManus, J. F., D. W. Oppo, and J. L. Cullen (2004), A 0.5-million-year record of millennial-scale climate variability in the North Atlantic, *Science*, *283*, 971–975.

Peeters, F. J. C., et al. (2004), Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods, *Nature*, *430*, 661–665.

Peterson, L. C., G. H. Haug, K. A. Hughen, and U. Rhöl (2000), Rapid changes in the hydrologic cycle of the tropical Atlantic during the Last Glacial, *Science*, *290*, 1947–1951.

Rahmstorf, S. (1996), On the freshwater forcing and transport of the Atlantic thermohaline circulation, *Clim. Dyn.*, *12*, 799–811.

Rahmstorf, S., and A. Ganopolski (1999), Long-term global warming scenarios computed with an efficient coupled climate model, *Clim. Change*, *43*, 353–367.

Richardson, P. L., J. R. E. Lutjeharms, and O. Boebel (2003), Introduction to the ‘‘Inter-ocean exchange around southern Africa,’’ *Deep Sea Res., Part II*, *50*, 1–12.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland ice sheet, *Science*, *311*, 986–990.

Schmittner, A., C. Appenzeller, and T. F. Stocker (2000), Enhanced Atlantic freshwater export during El Niño, *Geophys. Res. Lett.*, *27*, 1163–1166.

Seidov, D., and B. J. Haupt (2003), Freshwater teleconnections and ocean thermohaline circulation, *Geophys. Res. Lett.*, *30*(6), 1329, doi:10.1029/2002GL016564.

Stocker, T. F. (1998), The seesaw effect, *Science*, *282*, 61–62.

Vellinga, M., and R. A. Wood (2002), Global climate impacts of a collapse of the Atlantic thermohaline circulation, *Clim. Change*, *54*, 251–267.

Wang, H., and G. E. Birchfield (1992), An energy-salinity balance climate model: Water vapor transport as a cause of changes in the global thermohaline circulation, *J. Geophys. Res.*, *97*, 2335–2346.

Weijer, W., et al. (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284.

Weijer, W., W. P. M. de Ruijter, and H. A. Dijkstra (2001), Stability of the Atlantic overturning circulation: Competition between Bering Strait freshwater flux and Agulhas heat and salt sources, *J. Phys. Oceanogr.*, *31*, 2385–2402.

Zaucker, F., and W. S. Broecker (1992), The influence of atmospheric moisture transport on the fresh water balance of the Atlantic drainage basin: General circulation model simulations and observations, *J. Geophys. Res.*, *97*, 2765–2773.

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