Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes

Thomas F. Stocker* & Daniel G. Wright†

Centre for Climate and Global Change Research, McGill University, Montreal, Quebec, Canada H3A 2K6
* Now at: Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964, USA
† Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada B2Y 4A2

DEEP water in the world's oceans flows predominantly from the northern North Atlantic into the Pacific[1], slowly upwells on the way to become part of the upper warm-water circulation, and returns to the North Atlantic. The stability of this thermohaline conveyor belt has recently been questioned on the basis of palaeoclimatic data from deep-sea sediment and ice cores[2,3]. Different modes of deep circulation have been confirmed in numerical ocean models[4–6], and the present-day circulation has been shown to be sensitive to changes in the surface-water budget[7]. Here we use an idealized model[4,5] to examine the hypothesis that small changes in the atmospheric flux of fresh water from the Atlantic to the Pacific could force the thermohaline circulation to switch between two stable modes. Our results indicate that a decrease of this flux can reverse the Atlantic circulation, although the Pacific thermohaline circulation does not change direction. This is consistent with reconstructions of conditions in the Atlantic Ocean during the last glacial obtained from deep-sea cores[8]. To re-establish the conveyor belt, the fresh-water flux need be increased only slightly beyond its present value.

Quaternary ice ages have been related to interactions between ice cover, lithosphere and atmosphere responding to astronomically forced variations in seasonality of insolation[9]. Isotope measurements in deep-sea cores indicate that at the last glacial maximum, 18,000 BP (before present), the deep ocean had properties different from today[8,10]: deep-ocean temperatures were cooler[11], North Atlantic deep-water production was reduced[8] and considerably more bottom water was flowing from the Southern Ocean into the Atlantic[10]. Several authors[2,3] conclude that the ocean may have been in a different circulation mode than the present one. Broecker and Denton[2] suggested that changes in the hydrological cycle could induce mode changes in the ocean circulation with consequent rapid climate changes.

Recent results of two- and three-dimensional numerical ocean models[5,6] are consistent with the original idea[12] that different modes of operation of the global thermohaline circulation may exist. It was also shown that the present-day meridional circulation is sensitive to anomalous fresh-water fluxes applied locally to the surface of the Atlantic[7], and to changes in the net Atlantic-to-Pacific fresh-water flux, F, through the atmosphere[5]. The present estimate for F lies in the range of +0.1 to +0.45 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m\ s^{-1}}$)[2,13]. Model simulations of atmospheric conditions at the last glacial maximum corroborate the possibility of glacial-to-interglacial changes in the hydrological cycle and suggest that F was greatly reduced or even negative[14].

To investigate the implications of such changes in the thermohaline circulation, we used an idealized ocean model consisting of two coupled, zonally averaged basins representing the Atlantic and Pacific[4,5]. The model is purely buoyancy-driven by surface fluxes of heat and salt, and it yields results consistent with more complex three-dimensional general circulation models for the oceans[6,15]. After initial integration to steady state by relaxing surface temperature and salinity to prescribed profiles, we apply mixed boundary conditions, whereby the sea surface temperature is still relaxed and the surface salt flux is kept fixed.

The steady state obtained under present-day surface forcing (mode A) shows a conveyor-belt circulation[1,5]: deep water is formed in the North Atlantic and flows into the Pacific where broad upwelling occurs (Fig. 1*a*). Temperature and salinity fields in both Pacific and Atlantic compare favourably with observed zonal averages (Fig. 1*b* and *c*)[16]. Associated with this conveyor belt is a net Atlantic-to-Pacific fresh-water flux through the atmosphere, F, of 0.3 Sv, which is close to the estimate of 0.45 Sv obtained by Baumgartner and Reichel[13]. The circulation is not sensitive to changes in F unless it is reduced to ~0.03 Sv, at which point the system changes to a second equilibrium (mode B). In this state the conveyor belt is shut off, and the Atlantic circulation resembles that of the Pacific (Fig. 2*a*); deep water is now only formed in the Southern Ocean. As a consequence, the temperature and particularly the salinity distribution in the two ocean basins have changed (Fig. 2*b* and *c*). Just as mode A compares well with today's circulation pattern, mode B is consistent with the reconstruction by Duplessy *et al.*[10] of ocean conditions during the last glacial maximum.

Once in mode B, the Atlantic-to-Pacific fresh-water flux can be increased to its initial value without significant change of the thermohaline circulation, confirming the existence of two stable modes under identical boundary conditions[12]. But if a threshold of ~0.36 Sv (1.2 times the original value) is exceeded, the conveyor belt is re-established. This behaviour is qualitatively consistent with the observation that the climate system remains stable for many millennia, then relatively quickly undergoes a transition to a new state where it again remains for many millennia[2]. Figure 3 shows the meridional heat transport carried northward by the Atlantic as a function of *F*, exhibiting the hysteresis behaviour described above. Mode A on the upper branch of the hysteresis curve is associated with a maximum northward heat flux of $\sim 0.6 \times 10^{15}$ W, whereas a similar heat flux is directed southward in mode B (lower branch). Shutting off the ocean heat flux carried by the Atlantic could cause a climatic event similar to the Younger Dryas[3]: reversing this heat flux would certainly have a considerable global impact.

Decreasing the atmospheric Atlantic-to-Pacific fresh-water flux thus alters the global circulation from the conveyor belt to a flow with little exchange between the two ocean basins. Equally important, an increase in the Atlantic-to-Pacific fresh-water flux is a plausible and consistent mechanism by which the present-day temperature and salinity distributions in the Pacific and Atlantic ocean could be re-established and the conveyor-belt circulation resumed. Several experiments with varying resolution, vertical diffusivities and relaxation temperatures show that the locations of the transition points on the hysteresis curve are sensitive to these modifications, but the circulation, temperature and salinity patterns of the stable modes, as well as the existence of hysteresis, are robust features.

a

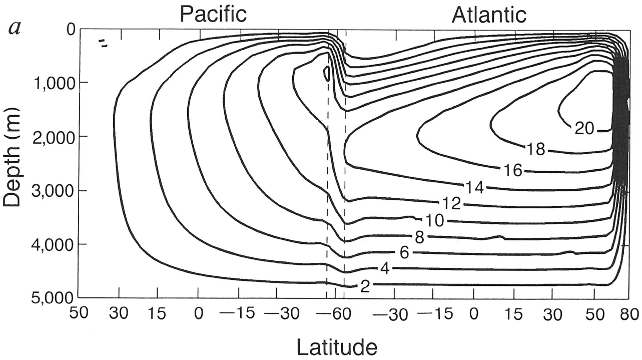
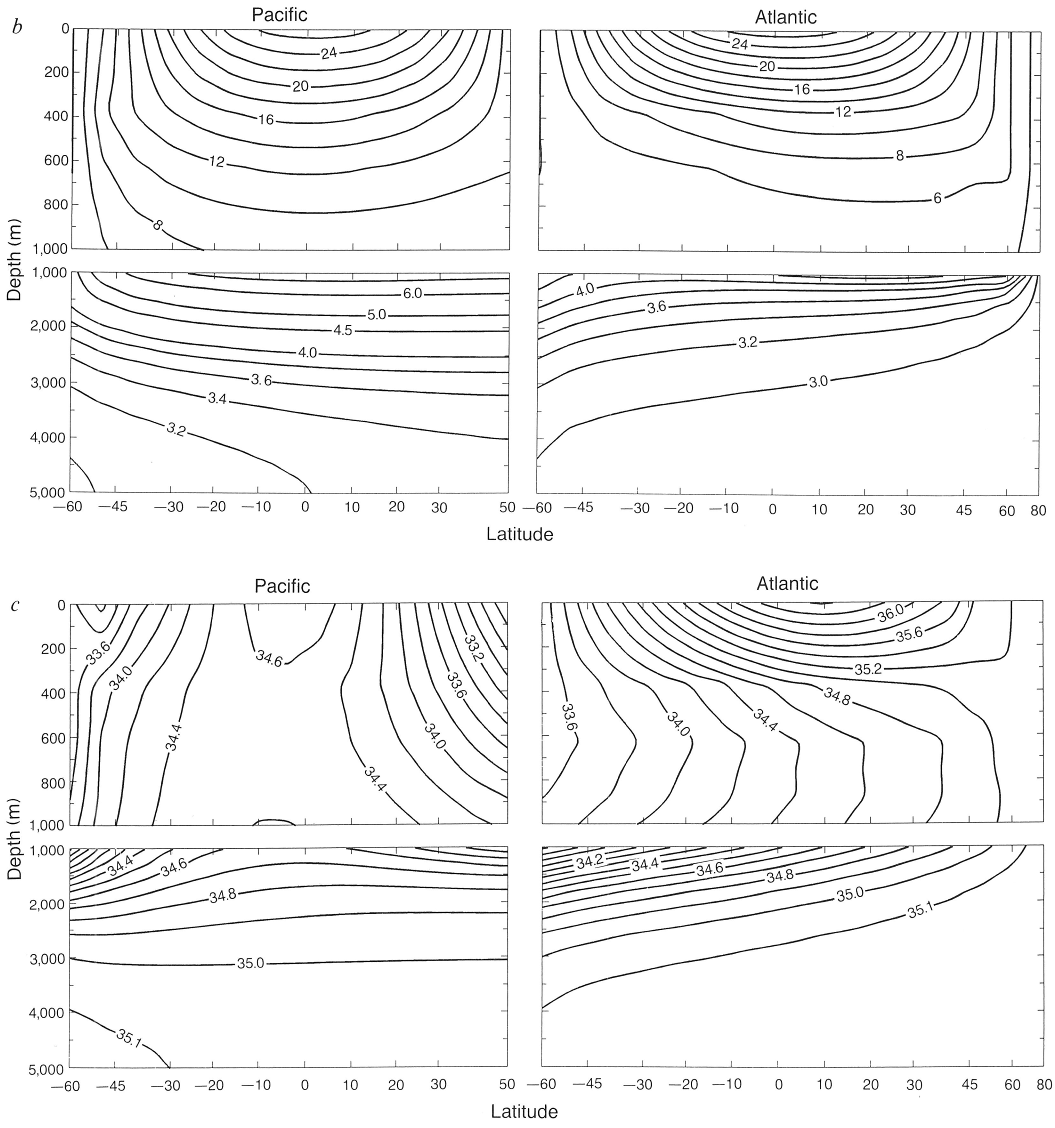


FIG. 1 *a*, Contours of the overturning streamfunction in Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m^3\ s^{-1}}$) for the steady-state thermohaline circulation in the Pacific–Atlantic basin system under mixed boundary conditions. Mode A is the conveyor belt operating in today's ocean with deep water formation in the North Atlantic and broad upwelling in the Pacific. *b*, Temperature and *c*, salinity fields in both ocean basins compare favourably with observations[16].

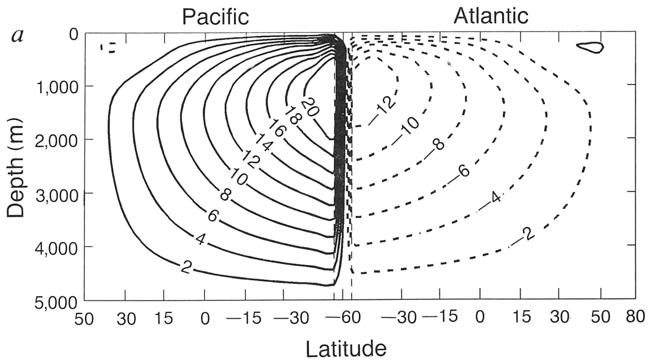
b

c



The cessation of the conveyor belt and its subsequent resumption are illustrated in Fig. 4, where time series of the mean sea-surface salinity for Atlantic and Pacific are given. Both transitions are triggered by modifying *F*. The experiment starts from mode A with *F* abruptly reduced to 0 Sv. During the first few hundred years, reduced Atlantic evaporation causes a steady increase of deep-water formation in the South Atlantic and a reduction of the Atlantic surface salinity to the Pacific level. The subsequent transition to mode B is apparent in the rapid drop of Atlantic surface salinity, leading to a reversed surface salinity contrast between Atlantic and Pacific. At $t = 5{,}000$ yr, *F* is increased from 0 Sv to 0.6 Sv, triggering the resumption of the conveyor belt. Enhanced fresh-water loss leads to maximum surface salinity in the Atlantic. Comparison of Figs 1*c* and 2*c* shows that mode changes involve considerable rearrangement of the salinity distribution in both ocean basins.

Several features of Quaternary climate evolution, such as the rapid termination and resumption of the present-day conveyor belt under steady forcing, cessation of North-Atlantic deep-water formation and advection of Southern Ocean deep water into the Atlantic during the glacial, are reproduced by this idealized model. This suggests the importance of the inter-ocean transport of fresh water and indicates that the present-day contrast between surface salinity of the Atlantic and Pacific was



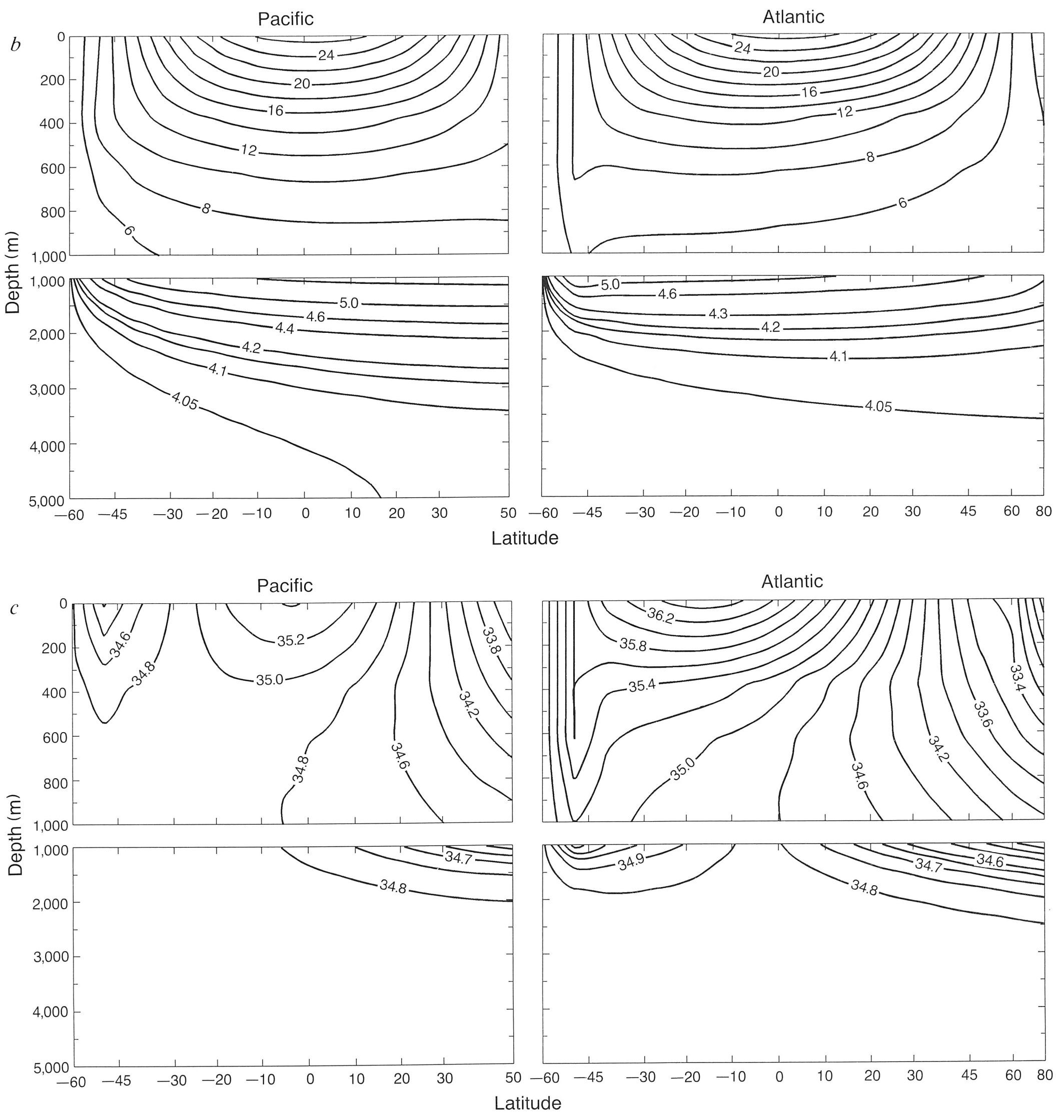


FIG. 2 *a*, Contours of the overturning streamfunction for the second steady state under the same mixed boundary conditions. In mode B the Atlantic flow is reversed and deep water is formed only in the Southern Ocean, whereas the thermohaline circulation in the Pacific remains unchanged. This mode could have operated during much of the glacial. Although the temperature field, *b*, is only slightly altered, the salinity distribution in both basins, *c*, is substantially different from mode A.

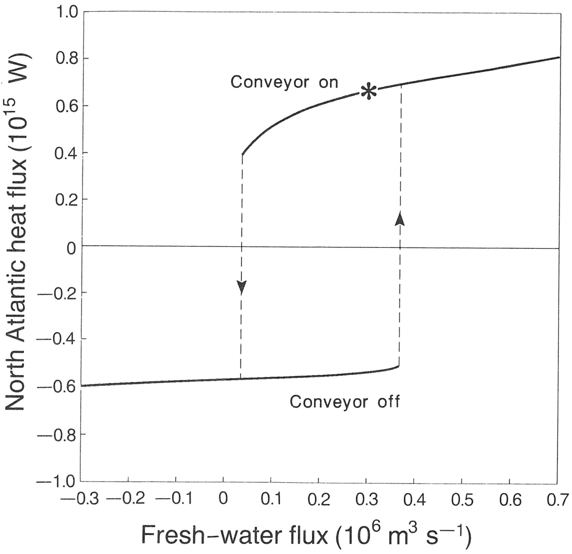


FIG. 3 Hysteresis characteristic of the two stable equilibria for changes of the atmospheric Atlantic-to-Pacific fresh-water transport. The star on the upper branch (mode A) indicates the present-day state according to our model; its location on the curve depends on the model parameters. Results from a three-dimensional model[7] indicate that the present-day climate may be much closer to the transition point and hence more sensitive to anomalies in the fresh-water flux. Mode A becomes unstable if the Atlantic evaporation excess is reduced to less than 0.03 Sv, and a rapid transition to mode B on the lower branch occurs. Mode B is unstable for an Atlantic evaporation excess larger than 0.36 Sv, and the system returns to mode A. Variation of the atmospheric Atlantic-to-Pacific fresh-water transport is a plausible mechanism by which the global conveyor belt could be shut down as well as re-established.

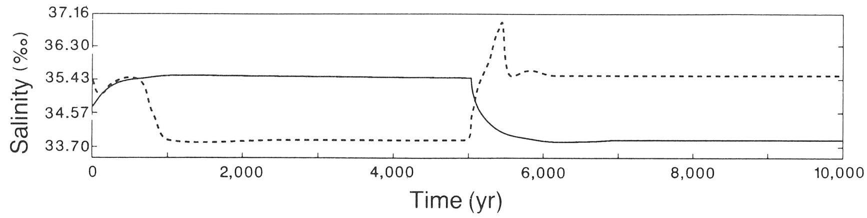


FIG. 4 Evolution during mode changes of the mean surface salinity (parts per 10^3) in the Pacific (solid) and Atlantic (dashed). The transition to mode B is initiated at $t=0$ yr by reducing the net Atlantic-to-Pacific fresh-water transport to zero. The transition back to the conveyor belt, mode A, is triggered at $t=5{,}000$ yr by an increase in fresh-water transport to 0.6 Sv. The transfer of fresh water re-establishes maximum surface salinity in the Atlantic. The transition to mode B is a relatively smooth process with a steady decrease of North Atlantic deep water production, but the resumption of the conveyor belt involves strong convective overturning in the North Atlantic in the early stages.

probably absent or even reversed in the glacial ocean. Small and realistic changes of the atmospheric water balance provide a plausible mechanism by which fundamental mode changes of the global thermohaline circulation (both shut-down and resumption of the conveyor belt) can be induced. This supports the earlier hypothesis, based on the reconstruction of various palaeoclimatic records[2,3], that the world ocean has more than one stable mode of operation. But rather than the inverse conveyor belt[3], whereby the circulation reverses in both ocean basins, the model indicates that changes of the thermohaline flow should involve primarily the Atlantic Ocean, while the deep circulation in the Pacific changes little.

Changes to the surface-water budget in the Atlantic and Pacific oceans may thus cause reversals of the Atlantic thermohaline flow. Because of the hysteresis, possible mode transitions depend critically on the initial state and the direction of the change in the hydrological cycle. Determining the present state and predicting future changes in the hydrological cycle are therefore central issues for climate research. Recent results suggest that F may increase in a climate with twice the present carbon dioxide concentration[17]. From the findings presented here, it seems unlikely that this will result in fundamental changes in ocean mode of the type described above. □

Received 21 December 1990; accepted 16 May 1991.

1. Gordon, A. L. *J. geophys. Res.* **91,** 5037–5046 (1986).
2. Broecker, W. S. & Denton, G. H. *Geochim. cosmochim. Acta* **53,** 2465–2501 (1989).
3. Broecker, W. S., Peteet, D. M. & Rind, D. *Nature* **315,** 21–26 (1985).
4. Wright, D. G. & Stocker, T. F. *J. phys. Oceanogr.* (in the press).
5. Stocker, T. F. & Wright, D. G. *J. phys. Oceanogr.* (in the press).
6. Marotzke, J. & Willebrand, J. *J. phys. Oceanogr.* (in the press).
7. Maier-Reimer, E. & Mikolajewicz, U. in *Oceanography* (eds Ayala-Castañares, A. *et al.*) 87–100 (UNAM Press, Mexico, 1989).
8. Boyle, E. A. & Keigwin, L. *Nature* **330,** 35–40 (1987).
9. Berger, A. *Rev. Geophys.* **26,** 624–657 (1988).
10. Duplessy, J. C. *et al. Paleoceanography* **3,** 343–360 (1988).
11. Labeyrie, L. D., Duplessy, J. C. & Blanc, P. L. *Nature* **327,** 477–482 (1987).
12. Stommel, H. *Tellus* **13,** 224–230 (1961).
13. Baumgartner, A. & Reichel, E. *The World Water Balance* (Elsevier, Amsterdam, 1975).
14. Miller, J. R., Russell, G. L. *Paleoceanography* **5,** 397–407 (1990).
15. Marotzke, J., in *Ocean Circulation Models: Combining Data and Dynamics* (eds Anderson, D. L. T. & Willebrand, J.) 501–511 (Kluwer, Dordrecht, 1988).
16. Levitus, S. *Climatological Atlas of the World Ocean* (NOAA Prof. Pap. 13, 1982).
17. Zaucker, F. & Broecker, W. S. *J. geophys. Res.* (in the press).

ACKNOWLEDGEMENTS. We are grateful for comments by J. Lazier, J. Loder and B. Petrie. This work was supported by the Swiss NSF and NSERC Canada.