Box 5.6. Thermohaline Circulation: Past Changes and Future Surprises?

Stefan Rahmstorf · Thomas F. Stocker

Ocean currents driven by surface fluxes of heat and freshwater and subsequent interior mixing of heat and salt are referred to as thermohaline circulation (Webb and Suginohara 2001; Bryden and Imawaki 2001; Rahmstorf 2003). Thermohaline circulation is complex, but can be summarised as a global-scale deep overturning of water masses, with sinking motions occurring in the northern Atlantic and around Antarctica and a transport of relatively warm surface waters towards these sinking regions (Schmitz 1995). A heat transport of up to 10^{15} W is associated with this circulation in the Atlantic (Ganachaud and Wunsch 2000), rivalling that of the atmosphere.

The opposing effects of cooling and freshening on density and associated feedbacks, together with the threshold behaviour of oceanic convection, make the thermohaline circulation a fragile system that can respond in a highly non-linear fashion to changes in surface climate. There is strong evidence that this has repeatedly occurred in the past, and reason for concern that it might happen again in the future (Broecker 1987, 1997; Alley et al. 2003).

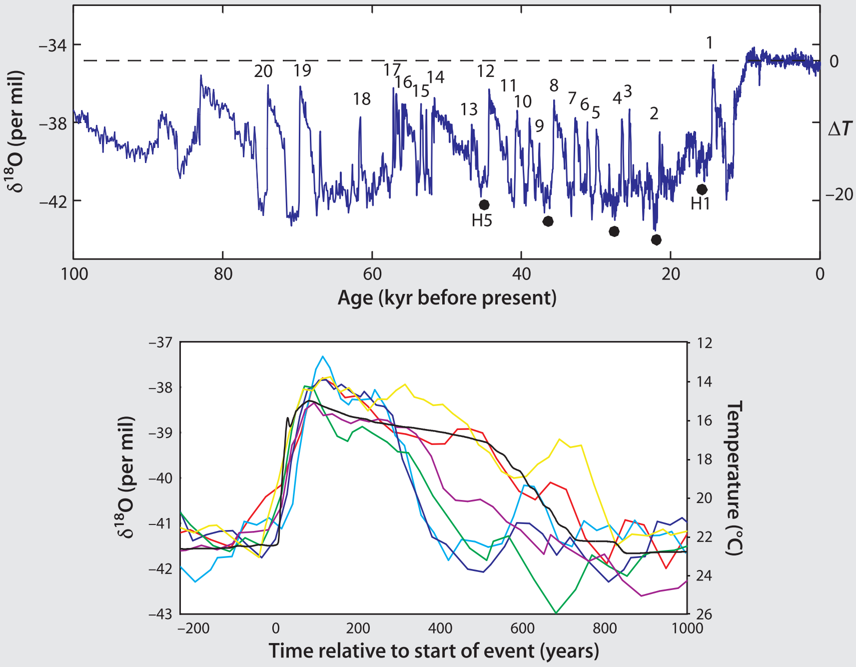
The best evidence for major past thermohaline circulation changes comes from the last glacial (120 000–10 000 years BP (see Clark et al. 2002; Rahmstorf 2002 for reviews). Two main types of abrupt and large climate shifts have occurred during that period, Dansgaard-Oeschger events and Heinrich events. Sediment records show that both of these were associated with major circulation changes in the North Atlantic.

Dansgaard-Oeschger events typically start with an abrupt warming (by up to 10 °C in Greenland) within a few decades or less, followed by gradual cooling over several hundred or thousand years (Fig. 5.36). The cooling phase often ends with an abrupt final temperature drop back to cold (*stadial*) conditions. Twenty-four such events occurred during the last glacial, and they have been documented at many sites around the world. The amplitude is largest around the northern Atlantic, while the South Atlantic responds with the opposite sign and a different temporal characteristic. Slow cooling starts when the north is abruptly warming, a behaviour that has been likened to a *bipolar seesaw* (Broecker 1998; Stocker 1998). Many of the observed features of these events can be explained by considering them as switches between different modes of the Atlantic thermohaline circulation, characterised by different locations of deep water formation (Broecker et al. 1985; Ganopolski and Rahmstorf 2001). The sudden warming is, according to this theory, caused by a northward push of warm Atlantic waters into the Nordic Seas. What triggers these mode switches is still unclear, but one hypothesis that is being debated proposes a mechanism associated with stochastic resonance (Alley et al. 2001).

Heinrich events are massive surges of the Laurentide Ice Sheet through Hudson Strait (Hemming 2003). They have a variable spacing of several thousand years. The icebergs released to the North Atlantic during Heinrich events leave tell-tale drop-stones in the ocean sediments when they melt. Sediment data suggest that Heinrich events completely shut down or at least drastically reduced the formation of North Atlantic Deep Water (NADW), and thus a major component of the thermohaline circulation. Consequently, Heinrich events led to cooling in the North Atlantic region. Models show that the amount of freshwater input due to the melting continental ice – on the order of 0.1 Sv, as suggested by the palaeo-climatic records (Clark et al. 2001) – is indeed sufficient to stop NADW formation. Palaeoclimatic data again suggest an Atlantic see-saw effect, consistent with the idea that the temperature changes are mainly caused by a reduction in interhemispheric heat transport in the Atlantic Ocean.

Palaeo-climate records provide no indication that the Atlantic thermohaline circulation (THC) has undergone large and rapid changes during the last 8 000 years, most likely because the continental ice sheets have become too small to produce instabilities and catastrophic freshwater discharges into the Atlantic Ocean, and because the circulation is more stable in a warm climate (Ganopolski and Rahmstorf 2001). However, global warming involves a number of new possibilities to alter substantially the freshwater balance of the Atlantic

Fig. 5.36.
Record of δ^{18}O (per mil, *scale on left*) from the Greenland Ice Sheet Project (GRIP) ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range, in °C relative to Holocene average, is given on the *right*), showing the relatively stable Holocene climate in Greenland during the past 10 000 years and Dansgaard-Oeschger (D/O) warm events (numbered) during the preceding colder glacial climate. The *lower panel* shows a close-up of several of the more recent events superimposed (*coloured lines*). The *black line* shows a model-simulated D/O event (Ganopolski and Rahmstorf 2001)



◀

in the future and thereby trigger THC variability or even collapses.

When air temperature rises, surface waters also tend to warm up, an effect which is enhanced particularly in the high latitudes via the snow/ice albedo feedback. In addition, the hydrological cycle may be accelerated in a warmer atmosphere because of increased evaporation, larger atmospheric moisture capacity and stronger meridional moisture transport (Dixon et al. 1999). The observed increase in river runoff in the high latitudes may be due to this effect (Peterson et al. 2002).

These effects tend to reduce the THC because heating and freshening both decrease surface water density. Indeed, the majority of coupled climate models indicates a reduction of the THC from 10% to 80% in response to increasing CO_2 concentrations in the atmosphere for the next 100 years (IPCC 2001a) (see figure). Knowledge, however, is still incomplete and significant uncertainties persist. This is illustrated by the large spread of simulated THC changes. Some models exhibit strong enough feedback mechanisms which stabilise the THC, at least for some decades. These are associated with changing modes of climate variability in a warmer world (Latif et al. 2000; Delworth and Dixon 2000).

Long-term simulations with different climate models suggest that the maximum projected CO_2 concentration may constitute a threshold for the Atlantic THC beyond which the circulation stops (Manabe and Stouffer 1993; Stocker and Schmittner 1997) (Fig. 5.37). In these early simulations a threshold was found between 2× and 4× pre-industrial CO_2 concentration. Although the existence of the threshold and its location critically depend on the climate sensitivity of the coupled models, the details of the hydrological cycle and other parameterisations (Rahmstorf and Ganopolski 1999), such a potentially irreversible change in circulation patterns cannot be excluded to occur in the future (Alley et al. 2003). A reduction or complete collapse would decrease the meridional heat transport in the Atlantic, and hence a regional cooling is superimposed on the global warming. Because of the uncertainty where this threshold lies, it is not known whether the combined effect leads to a net warming or net cooling in the regions most affected by the meridional heat transport of the Atlantic THC.

Model simulations indicate that the threshold may be crossed if the forcing is strong enough and applied for long enough. The threshold may well lie within the range of warming that is expected under business-as-usual in the next 100 years or less. However, prediction of the location of this threshold is impossible at the moment because of fundamental limitations of the predictability of non-linear events such as a THC collapse (Knutti and Stocker 2002). Nevertheless, current models suggest that the risk of major ocean circulation changes becomes significant for the more pessimistic warming scenarios, but can be greatly reduced if global warming is limited to the lower end of the IPCC range. Because of the interplay between the forcing and the limited rate of heat uptake in the ocean, also the rate of increase in CO_2 matters: the ocean-atmosphere system appears less stable under faster perturbations (Stocker and Schmittner 1997). This indicates that humankind has a choice: early action significantly widens policy options regarding future fossil fuel emissions scenarios.

Based on present knowledge of the climate system, the following results appear not to depend on model type, resolution or parameterisations:

- the Atlantic THC can have multiple equilibria which implies thresholds;
- reorganisations of the THC can be triggered by changes in the surface heat and freshwater fluxes;
- most models indicate a weakening of the THC in the next 100 years. This implies an approach towards possible thresholds;
- crossing of thresholds and associated irreversible changes of ocean circulation *cannot be excluded* within the range of projected climate changes of the next century.

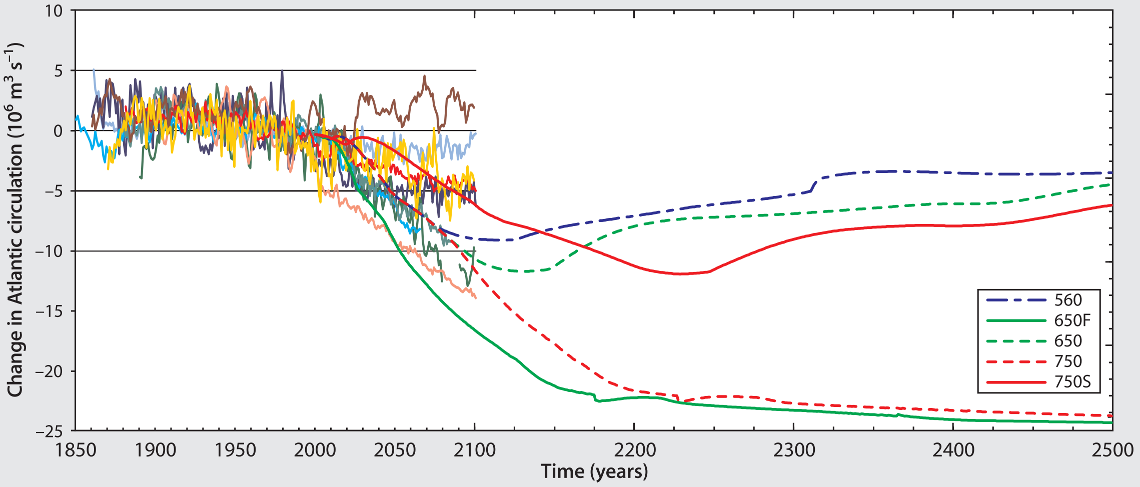


Fig. 5.37. Composite of changes in meridional overturning in the Atlantic Ocean simulated to 2100 by a set of comprehensive coupled climate models (*fine lines*) (Cubasch et al. 2001; IPCC 2001a). To illustrate the possible long-term behaviour of the thermohaline circulation, simulations using a coupled model of reduced complexity are overlaid (Stocker and Schmittner 1997). They use artificial CO_2 emissions scenarios that are identified in the inset. Carbon dioxide increases by rates of 0.5, 1 and 2% per year up to maximum concentrations of 560, 650 and 750 ppm, and constant thereafter. Depending on the rate of CO_2-increase and the maximum CO_2 concentration, and hence the warming, the THC crosses a threshold beyond which the circulation stops and remains collapsed