The Future of the Thermohaline Circulation – A Perspective

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Abstract

Evidence from paleoclimatic archives suggests that the ocean atmosphere system has undergone dramatic and abrupt changes with widespread consequences in the past. Climatic changes are most pronounced in the North Atlantic region where annual mean temperature can change by 10°C and more within a few decades. Climate models are capable of simulating some features of abrupt climate change. These same models also indicate that changes of this type may be triggered by global warming. Here we summarize what is known about such future changes and discuss the state of our knowledge about these potential threats to the stability of the Earth System.

1 Introduction

In the discussion of future climate change, a new issue has caught the attention of scientists and policymakers alike: the possibility of non-linear changes in the Earth System. Nonlinearity has many characteristics: non-linear changes are not easily extrapolated from ongoing observed changes, they may have large amplitudes and they may occur as surprises. Some of these changes may even be irreversible in the sense that they occur in response to perturbations and persist long after the perturbations have stopped to influence the climate system. Inherent to such changes is their reduced predictability. Among such non-linear changes are the collapse of large Antarctic ice masses and rapid sea level rise, the desertification of entire land regions, the thawing of permafrost and associated release of large amounts of radiatively active gases, and the collapse of the large-scale Atlantic thermohaline (i. e., the temperature and salinity driven) circulation (THC). The latter has clearly caught most of the attention and has spurred much research in the last decade. With the availability of high-resolution paleoclimatic records from the polar ice sheets and from marginal and deep basins in the ocean, a detailed picture of sequences of abrupt climate changes during the last glaciation and the glacial-interglacial transition emerges. The last of these dramatic coolings and warmings occurred about 8,200 years before present. Climate modelling has also produced important insights into the properties and role of the Atlantic THC, and model simulations indicate that such changes could lie ahead.

The purpose of this article is to summarize our current understanding of future changes of the Atlantic thermohaline circulation, and to give an assessment of the uncertainties which are associated with this phenomenon. This necessitates a discussion of stabilizing and destabilizing feedback mechanisms associated with the thermohaline circulation.

The paper presents a discussion of the representation of the THC in models in section 2, and a brief summary of past evidence for changes of the THC in section 3. Dynamical concepts responsible for the limited stability of the THC and associated feedbacks are presented in section 4. Section 5 discusses the implications of a breakdown of the Atlantic THC on air temperature and sea level. A catalog of feedback mechanisms is presented in section 6. The question of a possible "runaway greenhouse effect" due to a collapse of the THC is addressed in section 7; conclusions follow in section 8.

2 Thermohaline circulation and their representation in models

The thermohaline circulation of the world ocean is driven by differences in buoyancy caused by heat and freshwater fluxes at the surface of the ocean (Warren, 1981; Gordon, 1986). These fluxes lead to the formation of dense water masses preferentially in the Greenland-Iceland-Norwegian (GIN) Seas, in the Labrador Sea and around Antarctica (Killworth, 1983; Marshall and Schott, 1999). The dense waters from the Nordic seas flow in deep western boundary currents southward into the Southern Ocean from where they are distributed into the deep Indian and Pacific Oceans (Schmitz, 1995). The return flow takes various paths through the Indonesian Passage and around Africa into the Atlantic (de Ruijter et al., 1998), and through the Drake Passage. The popular view of this global circulation is a "conveyor belt" (Broecker, 1991), but this is somewhat misleading because the pathways are not continuous, and observations and inverse calculations indicate a much more complicated structure of boundary currents and recirculations (Macdonald and Wunsch, 1996).

The thermohaline circulation strongly influences the climate on regional-to-hemispheric scales. In the Atlantic Ocean, the meridional heat transport is mostly carried by the THC and is due to the surface and deep western boundary currents: warm waters flow northward in the Gulf Stream/Transatlantic Drift system and the cold deep waters flow southward. In combination this yields a northward meridional heat flux in the Atlantic at all latitudes with a maximum of about $10^{15}\,$W (Macdonald, 1998; Ganachaud and Wunsch, 2000). Associated with the presence of the warm waters at the western mid-latitudes in the North Atlantic is an intense storm system whose transient eddies also transport substantial heat northward. Changes in both the ocean THC and the atmospheric storm tracks would seriously affect the climate in northwestern Europe.

The large-scale dynamics of the thermohaline circulation can be characterized on the basis of the conservation of angular momentum (Stommel and Arons, 1960a; Stommel and Arons, 1960b). Stommel and Arons assumed that localized deep water formation is compensated by uniform deep upwelling. Water on the rotating Earth must flow poleward in the deep interior in order to conserve angular momentum. This mass flux is compensated by an opposite flow in deep western boundary currents which connect the three ocean basins (Stommel, 1958). In recent years, it became clear that water masses move preferentially along isopycnals (surfaces of constant density) and that uniform deep upwelling is inconsistent with tracer distributions (Toggweiler and Samuels, 1998). Upwelling appears much more localized and is likely associated with topographic features in the deep ocean (Ledwell et al., 2000). This will make the current structure in the deep ocean more complicated and fragmented than the present understanding suggests. Because deep currents are difficult to measure, emerging high-resolution ocean models will augment our knowledge significantly. However, the present generation of highest resolution models is not yet simulating deep ocean processes in a prognostic mode due to computational constraints (Smith et al., 2000).

Over the last few decades a hierarchy of models has been developed with which the variability of the thermohaline circulation was investigated (see review by Weaver et al., 1999). Most of these models use coarse resolution and require various degrees of parameterizations of convection, deep water formation and mixing. This still poses a limitation on the accuracy with which issues like the stability of the thermohaline circulation, or natural variability of the THC can be addressed. Furthermore, atmospheric processes associated with air-sea heat and freshwater fluxes are often crudely accounted for, especially in ocean-only models. In spite of these limitations, a number of important physical mechanisms have been identified and described.

The general structure of the thermohaline circulation is simulated in 3-dimensional ocean general circulation models of relatively coarse resolution. Deep western boundary currents can be identified in these models, and the water mass distribution that they produce is consistent with observations (Semtner and Chervin, 1992; Maier-Reimer, 1993; Drijfhout et al., 1996). However, many of these models still require rather unrealistic forcing in the high latitudes either by prescribing artificially high values of salinity (e. g., around Antarctica to promote deep water formation) or by restoring to observed values of temperatures and salinity at entire depth sections. Global models of the THC have still many deficiencies in simulating key processes thought to be important for the THC. There is hope that increasing resolution will alleviate these problems to a large extent; the most recent simulations at 1/10 degree resolution exhibit encouraging details of the surface flows along western boundaries, and the statistics of eddies (Smith et al., 2000).

Notwithstanding, the following processes will require continued attention in the simulation of the THC. Inter-basin exchanges such as the Agulhas current system (de Ruijter et al., 1998) or the Indonesian Passages, are poorly captured by coarse-resolution models. Of particular importance are water mass transformation processes in the marginal basins of the high latitudes. In the Atlantic, the GIN and Labrador Seas are known to influence strongly the water mass structure of the intermediate and deep waters from which global waters such as North Atlantic Deep Water (NADW) derive (Dickson et al., 1996; Dickson et al., 2000). The presence and formation of sea ice is known to dominate the fluxes of heat and freshwater in the high latitudes, but this component is often not included in current global ocean circulation models. A few potentially important feedback mechanisms associated with sea ice will be discussed below.

3 The paleo-thermohaline circulation and its changes

Without the paleoclimatic records, our knowledge about ocean changes would be limited to theoretical insight from models. Indeed, evidence from such records hinted at the importance of ocean circulation changes for climate change. Since the reconstruction of the rapid movement of the North Atlantic polar front during the last termination (Ruddiman and McIntyre, 1981) and the bold proposal by the late Hans Oeschger that carbonate isotope changes in Lake Gerzensee (Switzerland) and isotopic changes in Greenland ice have the same common origin (Oeschger et al., 1984), changes in ocean circulation have moved to center stage for the explanation of rapid climate change. Oeschger proposed that the ocean may be a "flip-flop" system, and Broecker et al. (1985) and Broecker and Denton (1989) have collected and synthesized evidence from the paleoclimatic records which point to the ocean as one of the key elements of abrupt change.

During the last decade an unprecedented growth of evidence for abrupt climate change during the last glaciation has occurred. This was enabled by a significant increase in temporal resolution of marine and polar ice core records, as well as new parameters and smaller analytical uncertainties in various proxy parameters. The most important manifestations of abrupt climate changes are the remarkable sequences of abrupt warmings and slower coolings registered in various ice cores from the Greenland ice sheet. They serve as model events although it should be noted that they are signals at a very remote and special location on the planet.

Dansgaard et al. (1993) counted 24 of these abrupt events that are now referred to as Dansgaard/Oeschger (D/O) events. Their evolution bears remarkable similarity among each other: the warming is always abrupt and measurements of stable isotopes of gases enclosed in the ice demonstrate that in Greenland the annual mean temperature warmed by about 16°C within a few decades (Lang et al., 1999; Severinghaus and Brook, 1999). The last of these warming events was the transition from the cold Younger Dryas (YD) to the warm Preboreal about 11,650 years ago and was accompanied by an abrupt increase in accumulation (Alley et al., 1993) and a sudden decrease of the dust load within less than 10 years (Taylor et al., 1993). The coolings, in general, are more gradual and evolve over a timescale of 1-3 thousand years, punctuated by some shorter cold events (e. g., during the Bølling/Allerød).

The wide spread nature of these abrupt climate changes has been confirmed in many paleoclimatic records from different archives and different locations provided that the temporal resolution of these archives is sufficient. This evidence is reviewed in several recent papers (Broecker, 1997; Stocker, 2000; Alley and Clark, 1999). High-resolution marine sediment records point at the central role of the ocean, in particular the North Atlantic. The first clear case of abrupt change of sea surface temperature (SST) that correlated surprisingly well with the Greenland ice core was presented by Lehman and Keigwin (1992) who showed that SST off the Norwegian shelf changed rapidly by more than 5°C within a few decades. The changes in SSTs during deglaciation correlate strongly with those inferred from the Greenland ice cores. A further important finding was that each D/O event was associated with a layer of ice rafted debris originating from icebergs from the circum-North Atlantic ice sheets (Bond et al., 1999). The thickest of these layers in the marine sediments are referred to as Heinrich events and they tend to occur close to some of the longest of the D/O events. This was an indication that the THC may have been disrupted by massive input of freshwater from melting icebergs. A still open problem, however, is the exact timing of the layers of ice rafted debris and the climate changes. Clearly, the meltwater input around the last major cold event, the YD, seems to occur about 1,000 years too early to be directly responsible for the break-down of the Atlantic THC (Bard et al., 1996; Clark et al., 1996). As this meltwater input is inferred from the rise in sea level, this does not exclude that there are smaller but crucial inputs of meltwater around the onset of YD. There are indeed indications of ice rafted debris at that time (Bond et al., 1999). The case is clearer for the 8,200-yr cold event (Alley et al., 1997) which apparently occurred in response to a huge outflow of proglacial lakes (Barber et al., 1999); the cooling in Greenland was estimated at about 7°C (Leuenberger et al., 1999) and most likely due to a slow-down of the Atlantic THC. It is clear that both a better synchronization of these meltwater records with the Greenland ice cores, as well as detailed investigation of the provenance of the ice rafted debris are necessary to solve this problem. The first is needed to compare the temporal evolution simulated by coupled models, the second will be the basis of more realistic freshwater perturbations used in coupled models.

Irrespective of possible mechanisms, an SST record from Bermuda traces all D/O events and indicate that these were climate phenomena of large, at least Atlantic, if not hemispheric extent. Sea surface temperatures varied in concert with Greenland by about 4°C for each D/O event (Sachs and Lehman, 1999). These climate signals are also recorded in remarkable detail in the tropical Atlantic (Cariaco Basin off Venezuela, Peterson et al., 2000), in the East Atlantic (off the coast of Portugal, Shackleton and Hall, 2000) and in the Santa Barbara Basin (eastern Pacific, Behl and Kennet, 1996). Moreover, Oppo and Lehman (1995) found that deep water mass properties co-vary with surface properties in the same core confirming that the Atlantic thermohaline circulation is indeed involved in these large climatic changes. Rapid deep water changes were also found by Adkins et al. (1998) who analyzed a coral that grew in deep water and registered an abrupt change from nutrient-rich to nutrient-low waters during the last deglaciation when the North Atlantic went through a series of dramatic climatic changes.

Indications of ocean changes also come increasingly from regions outside the North Atlantic, and probably these contribute now most to an understanding of the underlying mechanisms. Recent studies have found that in the South Atlantic large Heinrich events, which are cold events in the North Atlantic, appear as warmings (Vidal et al., 1999; Clark et al., 1999). This is consistent with what one would expect if the THC collapsed in the North Atlantic: as the Atlantic THC is associated with a cross-hemispheric heat transport, a THC collapse would result in excess heat in the South Atlantic. This is the bi-polar seesaw (Broecker, 1998; Stocker, 1998) suggested earlier by model simulations (Crowley, 1992; Stocker et al., 1992; Seidov et al., 2001).

Apart from paleoclimatic evidence directly from regions influenced by the Atlantic THC, there is now a growing body of circumstantial evidence that the THC plays a dominant role for abrupt climate change. The synchronization of climatic events identified in ice cores from Greenland and Antarctica during the last deglaciation (Blunier et al., 1997), as well as during the glacial (Blunier et al., 1998) is consistent with the concept of the bi-polar seesaw. It is remarkable that only the larger and longer of the D/O events have a counterpart in the Antarctic record, suggesting that only those are associated with a full collapse of the THC which would result in a strong inter-hemispheric coupling (Stocker and Marchal, 2000). A further indirect indicator for THC changes is the radiocarbon concentration (^{14}C)

in atmospheric CO_2, because a cessation of the THC would lead to an increase in ^{14}C. This was reconstructed from radiocarbon-dated varved sediments (Hughen et al., 2000) at the beginning of the YD cold event. Recent simulations suggest that the millennial changes of ^{14}C during deglaciation were a combination of changes in the production rate of ^{14}C and changes in the THC (Muscheler et al., 2000; Marchal et al., 2001).

In spite of this wealth of high-quality paleoclimatic information, there are major limitations that seriously hamper progress. The most important is a relatively poor data base outside the North Atlantic region. Especially the tropics are not well represented although it is clear that probably important processes for abrupt change may originate there. Practically nothing is known about the long-term variability in the tropics; it is not known whether the El Niño-Southern Oscillation (ENSO) cycle persisted in the glacial, or whether the tropics may have resided in a phase-locked state similar to La Niña. It would also be extremely important to know whether the statistics of the ENSO cycle is subject to long-term changes over millennia, as recent modelling suggests (Clement et al., 1999).

The Southern Ocean is severely undersampled and yet many records (e. g., the CO_2 during the glacial and during deglaciation) point to its importance in pacing climate change. Reliable proxies at high temporal resolution that inform us about water mass composition and origin would be extremely valuable and important progress in this respect was made (Yu et al., 1996; Marchal et al., 2000).

Polar ice cores have contributed significantly to progress in the last decade. However, it turned out that the interpretation of classical proxies such as the stable isotopes of ice had to be revised (Cuffey et al., 1995; Johnsen et al., 1995; Lang et al., 1999). Likewise, the regionality of the isotopic signal in Antarctica is practically unknown, but there are indications that it may be important in correctly interpreting the climate signals recorded in these cores (Steig et al., 1998; Mulvaney et al., 2000).

Even if the apparent gaps in coverage of paleoclimatic records will be closed in the future, the synchronization of records from various archives remains a top priority. New techniques have been established to synchronize polar ice cores based on methane (Blunier et al., 1998) and stable isotopes in oxygen of air (Sowers and Bender, 1995). However, changes in the enclosure processes and the gas age-ice age difference still limit the synchronization to a few centuries.

4 Thresholds in the ocean-atmosphere system

The freshwater balance in the North Atlantic is one of the major components that governs the strength of the THC. The THC is driven by atmosphere-ocean fluxes of heat and freshwater: in high latitudes surface waters are cooled and lose buoyancy. On the other hand, there is excess precipitation which increases buoyancy. The competition of these two effects, which activate very different feedback mechanisms in response to a change, gives rise to the possibility of large changes in the thermohaline circulation. Stommel (1961) showed that different removal times of sea surface temperature and salinity anomalies result in two very different circulation modes. This can be described as feedback mechanisms which influence the THC (Fig. 1). The two feedback mechanisms are due to the advection of surface waters from the low to the high latitudes via the wind-driven and thermohaline circulation (Bryan, 1986). A stronger

THC results in an increased meridional heat flux which tends to warm the surface waters in the high northern latitudes. This decreases density and therefore acts as a negative feedback mechanism for the THC. Negative feedback mechanisms may give rise to oscillations. Delworth et al. (1993) have shown that this feedback mechanism causes an interdecadal oscillation of the THC. Similarly, with increasing THC, more saline waters are transported northward which tends to increase density and speed up the THC – a positive feedback which may cause instability. The interplay between the temperature and the salinity feedbacks are the origin of multiple equilibria of the THC (Stommel, 1961).

Following the pioneering work of Bryan (1986), many ocean only models (Stocker and Wright, 1991; Mikolajewicz and Maier-Reimer, 1994; Rahmstorf, 1994; Seidov and Maslin, 1999) and coupled climate models (Manabe and Stouffer, 1988) have confirmed earlier hypotheses that the ocean-atmosphere system has more than one stable mode of operation (Broecker et al., 1985). The obvious statement is that, like many non-linear physical systems, the ocean-atmosphere system may exhibit hysteresis behavior (Stocker and Wright, 1991): for certain values of a control variable more than one stable state is permissible. Numerous modelling studies have demonstrated that the Atlantic surface freshwater balance is a key control variable for the THC which can assume different modes of operation.

For a simplified ocean-atmosphere model (Knutti and Stocker 2000), this hysteresis behaviour is illustrated in Fig. 2a. Starting in a present-day steady state of the ocean-atmosphere system with active overturning, an anomalous freshwater flux, ΔF, into the North Atlantic is slowly increased ($0.1\,\mathrm{Sv}/1{,}000\,\mathrm{yr}$; $1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$) until the North Atlantic becomes too fresh and deep water formation stops (transition from state 1 to state 2). The freshwater input is then decreased until the deep water formation restarts again. In this model experiment, two equilibrium states of the THC are possible for present day conditions (zero freshwater anomaly), one with active deep water formation in the North Atlantic (state 1) and one without (state 3). This classical picture can be extended by applying the freshwater flux

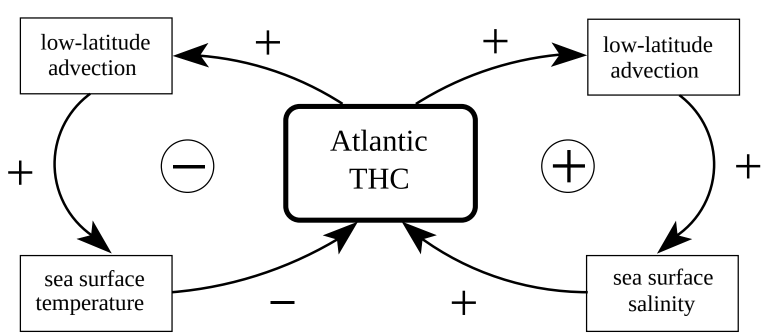

Figure 1: Principal advective feedback mechanisms influencing the Atlantic THC. The signs attached to the arrows indicate the correlation between changes in the quantity of the outgoing box with that of the ingoing box, e. g., warmer sea surface temperatures (SST) lead to weaker THC. Resulting correlations of a loop are circled and they indicate whether a process is self-reinforced (positive sign) or damped (negative sign). A stabilizing loop (left) is associated with changes in SST due to changes in the advection of heat. This loop may give rise to oscillations. The second loop (right) is due to the influence of advection of low-latitude salty waters into the areas of deep water formation. The resulting correlation is positive and the loop may therefore cause instabilities.

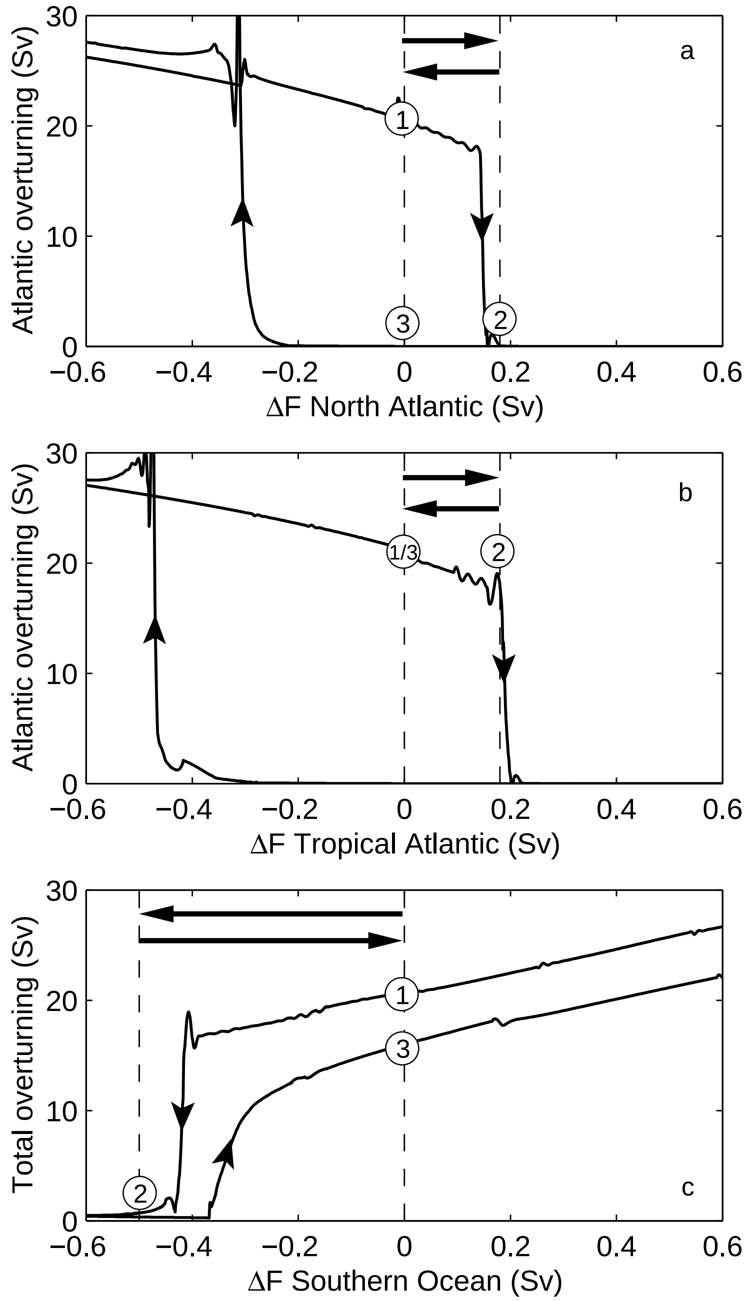

Figure 2: Hysteresis behaviour of the thermohaline circulation. The three panels show the dependence of the Atlantic overturning (total global overturning in panel c) on a slowly changing freshwater anomaly ΔF applied (a) in the North Atlantic, (b) in the tropical Atlantic or (c) in the Southern Ocean. Depending on the initial location of the state on the hysteresis curve (indicated by the circled numbers) and the amplitude of the perturbation (indicated by the horizontal arrows), three qualitatively different response types can occur: (a) non-linear/irreversible, (b) linear/reversible or (c) non-linear/reversible.

in the tropical Atlantic (Fig. 2b) or in the Southern Ocean (Fig. 2c) instead of the North Atlantic. When the freshwater input is applied in the tropical Atlantic, a very similar picture is observed, except that the hysteresis loop is stretched, because only part of the freshwater anomaly is transported to the regions of deep water formation in the North Atlantic. The perturbation must therefore be larger, or last longer, to induce a transition. When extracting freshwater from the Southern Ocean, southern sinking strengthens and the deep oceans are increasingly dominated by Antarctic Bottom Water, until a certain threshold is reached where deep water formation in the north stops. When the freshwater loss of the Southern Ocean is reduced again, the Antarctic Bottom Water retreats from the deep oceans and sinking in the northern hemisphere starts again. In this specific model experiment, intermediate water in the North Pacific evolves, but other model versions may also show Atlantic deep water formation. As the perturbation is applied in a zonally uniform way in the Southern Ocean, there is no direct control on the location where deep water formation in the north starts first. Fig. 2c indicates that changes in the THC of the northern hemisphere can also be remotely triggered from ocean changes around Antarctica.

The existence of hysteresis implies three fundamentally different responses to perturbations, which depend on the initial location in phase space and the amplitude of the perturbation. The response may be linear/reversible, non-linear/reversible, or non-linear/irreversible. Fig. 2 can be used to illustrate the three different response types. When a temporary freshwater flux of about 0.18 Sv is applied to the tropical Atlantic, the overturning is slightly reduced but recovers when the perturbation stops (Fig. 2b). The system shows a linear/reversible response. Applying the same perturbation in the North Atlantic, the threshold for a linear response is crossed and the system moves to a different circulation mode (Fig. 2a). The response is non-linear and irreversible. Considering the total amount of overturning in the northern hemisphere, a non-linear but almost reversible response is observed when a strong temporary perturbation is applied in the Southern Ocean (Fig. 2c).

Hysteresis behavior is well known in climate models and considered to be a robust feature, but its structure is highly model dependent. A critical question is: where are we now on the hysteresis, what is its structure and how close is the threshold?

As the freshwater supply to the North Atlantic is influencing the THC, any forcing modifying the freshwater fluxes directly or indirectly may move the THC beyond a threshold. Model simulations with different climate models suggest that the maximum concentration of CO_2 constitutes a threshold provided the THC has a second equilibrium state (Manabe and Stouffer, 1993). In these simulations the threshold lies between $2\times$ and $4\times CO_2$ concentration, but the existence of the threshold and its value strongly depend on the climate sensitivity of the coupled model, the details of the hydrological cycle and other parameterizations. Because of the interplay between the buoyancy uptake rate, which is limited by vertical mixing processes, and the warming of the atmosphere, also the rate of CO_2-increase is determining whether or not a threshold is crossed: the ocean-atmosphere system appears less stable under faster perturbations (Stocker and Schmittner, 1997).

The structure of the oceanic reorganization beyond the threshold, modelled in models of different complexity, is very similar: the Atlantic THC ceases and deep ocean ventilation stops. This leads to a reduction in the meridional heat transport in the Atlantic, and hence a regional cooling is superimposed on the global warming. It depends on the model's climate sensitivity 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.

5 Future changes could lie ahead

5.1 Short-term Evolution of the Atlantic THC

Given its relative stability over many millennia, one may wonder why the Atlantic THC is of any interest today. It turns out that anticipated global warming, caused by anthropogenic emissions of greenhouse gases, is another process that influences significantly the surface freshwater balance of the Atlantic ocean (Manabe and Stouffer, 1994). When air temperature rises, surface waters in the high latitudes also tend to warm up. This decreases surface density and reduces the THC; high-latitude amplification of the warming due to the snow-albedo feedback adds to this effect. In addition, the hydrological cycle may be enhanced in a warmer atmosphere because of increased evaporation, larger atmospheric moisture capacity and increased meridional transport of latent heat (Dixon et al., 1999). Both these effects tend to reduce the THC because they decrease surface water density. While the relative strength of these two mechanisms is debated (Dixon et al., 1999; Mikolajewicz and Voss, 2000), a general reduction of the Atlantic THC in response to global warming appears to be a robust result found by the entire hierarchy of current climate models: The majority of coupled climate models indicates a reduction of the THC from 10% to 50% under increasing CO_2 concentration in the atmosphere for the next 100 years (IPCC, 2001). This is illustrated in Fig. 3 which shows that the spread of the simulated reduction increases significantly after year 2000. This may partly result from the very large differences in maximum Atlantic overturning from which these models start. Values range from weak overturning of about 16 Sv to very strong overturning of over 25 Sv. It is known that the stability of the THC depends on the strength of the THC itself (Tziperman, 2000), and this may directly influence the amplitude of the transient response. In addition, each coupled model has a different climate sensitivity, i. e., warming and freshwater balance anomalies, that are realized over the 100 years of integration. A more quantitative assessment of these results requires more simulations and systematic comparisons in which these differences in control state and climate sensitivity are taken into account.

While all these models point towards a reduced THC under global warming, there are two exceptions. A stabilizing process for the THC has recently been suggested based on a coupled climate model (Latif et al., 2000). According to this model, and in agreement with reanalysis data (Schmittner et al., 2000), El Niños are associated with an increased atmospheric freshwater export from the tropical Atlantic which tends to make surface waters flowing northward in the Atlantic saltier and stabilize the Atlantic THC. Because the coupled model shows a tendency to more El Niño phases under global warming, the tropical Atlantic tends to become saltier and thus compensates, in this model, the gain of buoyancy in the northern high latitudes caused by warming and increased precipitation. Due to the high resolution of the isopycnal model in the tropics, the ENSO simulation in the model of Latif et al. (2000) is superior to that in the other models. Whether this model simulated the correct strength of the stabilizing feedback is doubtful, however, since the present-day ENSO has a too short recurrence time of about two years. The model is therefore biased towards El Niño. Furthermore, the area of deep water formation is simulated at a rather poor resolution due to the use of isopycnal coordinates, suggesting that the high-latitude processes influencing the THC are

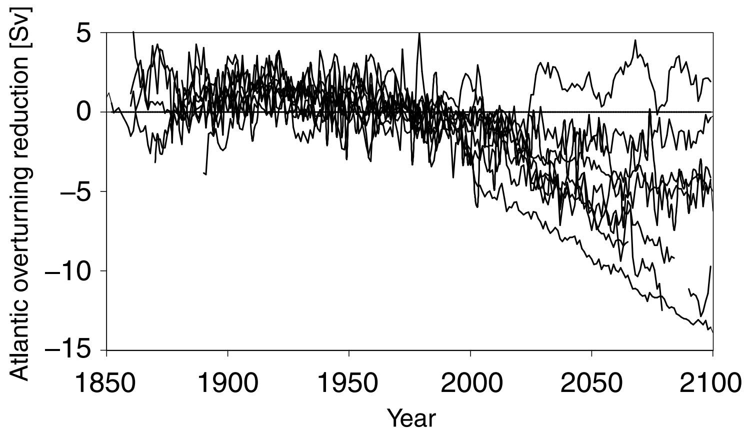

Figure 3: Anomaly of the maximum meridional overturning streamfunction in the Atlantic for a series of coupled model simulations up to year 2100 in Sv ($1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$). All models assume the same scenario of increasing CO_2 but each model has an individual response with respect to the changes in heat and freshwater fluxes. Nevertheless, most models indicate a reduction of the overturning of up to 50%. One model appears to be stable; this provides an indication of potentially important new feedback mechanisms. [Modified from IPCC, 2001]

probably not well captured. Nevertheless, this model points to a potentially important stabilizing feedback for the THC. This warrants focused investigation with other comprehensive climate models.

Gent (2001) presents a new simulation with a comprehensive coupled AOGCM in which the THC remains stable under global warming. In this model, the warming in the western Atlantic and stronger winds cause an increase in evaporation which is not compensated by local precipitation, i. e., there is net export of water vapor from the North Atlantic region. This helps to offset the buoyancy gain by warming and stabilizes the THC. However, it should be noted that the meridional overturning in the control simulation is unrealistically large which tends to stabilize the THC (Tziperman, 2000). Also, the coupled model does not yet dispose of a river routing scheme which would certainly influence the control state of the THC.

At this point it may be concluded that due to such stabilizing feedback mechanisms, a collapse of the THC may no longer be of concern. As discussed above, however, most 3-dimensional simulations indicate a reduction of the THC by the year 2100, but not a complete collapse (IPCC, 2001). A collapse appears therefore unlikely to occur by 2100 but it can not be ruled out for later. Recent simulations indicate that modes of natural variability and their future changes may also influence the strength and stability of the THC (Delworth and Dixon, 2000). Important in this context is to emphasize that a reduction of the THC moves the system closer to the threshold and the likelihood of a collapse may well increase (Tziperman, 2000). Concern for this potentially irreversible phenomenon may thus increase in the future. In any case, it should be a key priority to better understand the relative strength of different positive and negative feedback mechanisms with respect to the THC.

5.2 Long-term Evolution of the Atlantic THC

In the preceding section we discussed the fate of the THC under greenhouse warming for the next 100 years based on simulations with comprehensive 3-dimensional coupled general circulation models. A longer perspective and a careful investigation of parameter space is still difficult to achieve with such models. Here, simplified models of intermediate complexity fill an important void. Such models, which have been verified in various contexts, e. g., for tracer studies of paleoclimatic simulations, allow us to make progress regarding the question of robust results.

As ocean models indicate, an initial reduction of deep water formation in the northern North Atlantic due to a gain in buoyancy from a stronger meridional transport of moisture results in a freshening of the surface waters. A reduction of sea surface density is also caused by the increased surface air temperatures further reducing the thermohaline circulation. The question now is whether this reduction leads to a permanent shut-down, i. e., will certain thresholds be crossed in the process of a slow changing of the forcing? There is presently only one simulation using a comprehensive AOGM extending over many centuries (Manabe and Stouffer, 1993; Manabe and Stouffer, 1994). They showed that a complete shut-down can indeed occur in response to a sufficiently large perturbation. In those simulations the critical threshold lies between $2\times$ and $4\times CO_2$.

In order to investigate systematically on which quantities this threshold depends, only models of reduced complexity can be used, because they allow for a large number of long-term simulations. Stocker and Schmittner (1997) found that besides the stabilization level of greenhouse gases in the atmosphere, the rate of increase of greenhouse gas concentration also determines the threshold. This is illustrated in Fig. 4. The climate sensitivity is set at 3.7°C for a doubling of CO_2 in agreement with Manabe and Stouffer (1993). The standard rate of CO_2 increase is $1\%\,\mathrm{yr}^{-1}$ compounded; experiments with a fast rate of $2\%\,\mathrm{yr}^{-1}$ (denoted F) and a slow rate of $0.5\%\,\mathrm{yr}^{-1}$ (denoted S) are also performed. The maximum CO_2 values are 560 ppmv (exp. 560), 650 ppmv for experiments 650 and 650F, and 750 ppmv for experiments 750 and 750S. Once the maximum value is reached, CO_2 is held constant (Fig. 4a).

Simulated global mean surface air temperature changes do not depend on the emission history for a given maximum CO_2 concentration (Fig. 4b). However, there exists a bifurcation point for the maximum meridional overturning of the North Atlantic (Fig. 4c). In all cases, a reduction is obtained with an amplitude depending on the values of maximum atmospheric CO_2 and of the rate of CO_2 increase. The circulation collapses permanently for a maximum concentration of 750 ppmv with an increase at a rate of $1\%\,\mathrm{yr}^{-1}$ (exp. 750). It recovers, however, and settles to a reduced value if the increase is slower ($0.5\%\,\mathrm{yr}^{-1}$, exp. 750S) or if the final CO_2 level is reduced to 650 ppmv (exp. 650). Similarly, for a fast increase (exp. 650F) at a rate of $2\%\,\mathrm{yr}^{-1}$ the circulation collapses. All experiments have been integrated for 10,000 years and no further changes have been observed. In other words, once the THC collapses it settles to a new equilibrium and changes are hence irreversible. Even if CO_2 concentrations return to preindustrial levels many centuries after emissions are exhausted, the Atlantic THC may remain shut off (Rahmstorf and Ganopolski, 1999).

The few model simulations suggest that the critical level for THC collapse is somewhere between double and fourfold preindustrial CO_2 concentration. Extensive parameter studies

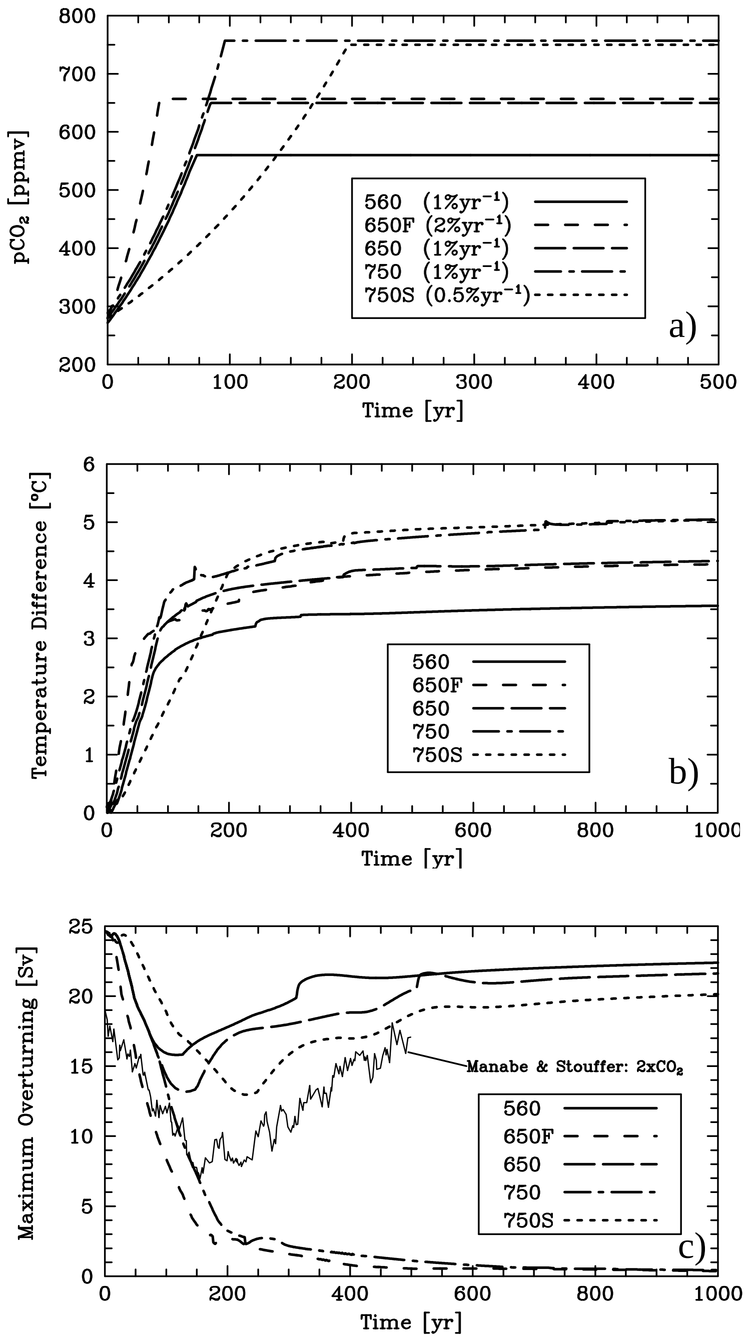

Figure 4: (a) Prescribed evolution of atmospheric CO_2 for five global warming experiments. (b) Simulated global mean surface air temperature changes. The climate sensitivity for a doubling of CO_2 was set at 3.7°C in agreement with the simulation of Manabe and Stouffer (1993). (c) Evolution of the maximum meridional overturning of the North Atlantic in Sverdrup ($1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$). Note the good agreement between the overturning simulated in the simplified model with that of the 3D AOGCM of Manabe and Stouffer (1993). [Modified from Stocker and Schmittner, 1997]

show that the position of thresholds depends critically on various model parameterizations (Schmittner and Stocker, 1999). A crucial process determining stability is the representation of vertical mixing in ocean models. Manabe and Stouffer (1999) argued that the vertical diffusivity in ocean models determines the number of equilibria of the THC: models with higher vertical diffusivity appear to be more stable and exhibit fewer equilibrium states. It is thus crucial to improve ocean mixing schemes and investigate their effect on the stability of the THC. A recent parameter study with a simplified ocean model indicates that the THC continues to have limited stability when modern mixing schemes are used, but that the values of thresholds depend quantitatively on the mixing (Knutti et al., 2000).

The Atlantic THC is an important transport mechanism from the surface to the deep ocean. The amount of heat mixed into the interior of the ocean therefore also depends on the strength of the THC. A stronger THC would represent a more efficient downward transport of heat. More than half of the projected sea level rise is due to the thermal expansion of the water column (IPCC, 1996). Because the vertical distribution of excess heat affects sea level, changes of the THC have the potential to influence the rate of sea level rise and its final value.

Simplified coupled models permit the construction of well-defined experiments. Knutti and Stocker (2000) placed their model on a bifurcation point of the Atlantic THC: just beyond the bifurcation point the THC collapses, otherwise it recovers. The point is that the equilibrium atmospheric global warming in these two simulations is nearly identical but the internal distribution of heat may differ substantially. This is shown in Fig. 5. Global mean warming is about 1.8°C with an equilibrium sea level rise of about 0.5 m if the THC remains active (solid lines, Fig. 5). However, if the circulation collapses, the equilibrium sea level rise is about 0.7 m larger, although the equilibrium atmospheric warming is identical (dashed lines, Fig. 5).

This result is counterintuitive at first sight because one might argue that a collapsed THC prevents heat from mixing into the interior and the warming now takes place only in the uppermost layers of the ocean. However, when the THC slows down, the surface waters in the North Atlantic tend to cool relative to a simulation in which the THC does not change. The increased air-sea temperature contrast enhances the heat uptake during the transient phase of a few centuries. This is sufficient to take up additional heat and more than double equilibrium sea level rise.

6 Stabilizing and destabilizing feedback mechanisms

The preceding sections have illustrated the importance of the THC for future climate change and indicated that there are still major uncertainties associated with the fate of the THC. This is due to a number of feedback mechanisms involving the THC whose relative strengths are poorly known. In this section we give an overview of different feedback mechanisms influencing the stability of the THC. Various feedback mechanisms influencing the THC were previously discussed by Marotzke (1996) and Rahmstorf et al. (1996).

The important question regarding the stability of the THC to perturbations or changes in the forcing can only be addressed if the most important feedback mechanisms are properly resolved in models and if their relative strength is simulated realistically. Even if we believe that a particular model succeeds in representing the important feedbacks, verification is

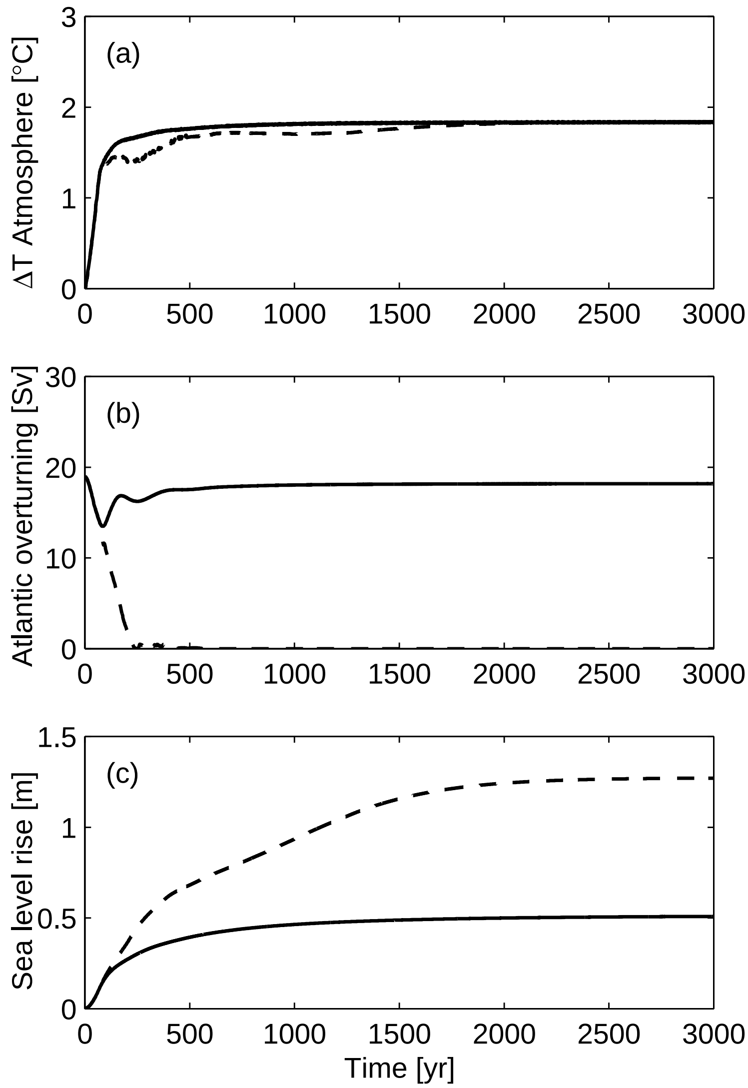

Figure 5: (a) Global mean atmospheric temperature increase, (b) Atlantic deep overturning, and (c) global mean sea level rise versus time in two almost identical global warming experiments using the model version with a Gent&McWilliams mixing scheme. If the Atlantic deep overturning collapses (dashed lines), sea level rise due to thermal expansion is much larger for the same atmospheric temperature increase than if the overturning recovers (solid lines). [From Knutti and Stocker, 2000]

extremely difficult. High-resolution paleoclimatic records in conjunction with model components that simulate directly observed proxies such as, e. g., stable isotopes, greenhouse gases, are currently the only means to assess the ability of these models to simulate THC changes reasonably.

Research in the past has probably too much focused on feedback mechanisms that lead to a collapse of the THC. Beyond the two principal feedback mechanisms already described in Fig. 1 above, a number of other stabilizing and destabilizing feedbacks have been described in model simulations. In the following figures the signs attached to the arrows indicate the correlation between changes in the quantity of the outgoing box with that of the ingoing box. Resulting correlations of a loop are circled and they indicate whether a process is self-reinforced (positive sign) or damped (negative sign).

An example of two mechanisms associated with the response of the atmospheric circulation to changes in the THC are given in Fig. 6. A stabilizing feedback is due to increased Ekman divergence in the area of deep water formation if the THC reduces. This brings up more saline waters from depth, thus helping maintain the THC (Fanning and Weaver, 1997). Conversely, Marotzke and Stone (1995) used a simple box model representing ocean-atmosphere interaction and suggested a destabilizing feedback mechanism due to the meridional transport of moisture. A weaker THC cools the high latitudes and thus increases meridional temperature gradients. This leads to a stronger meridional circulation in the atmosphere and stronger meridional moisture flux. The stronger import of moisture to the high latitudes decreases sea surface salinity and hence enhances the reduction of the THC.

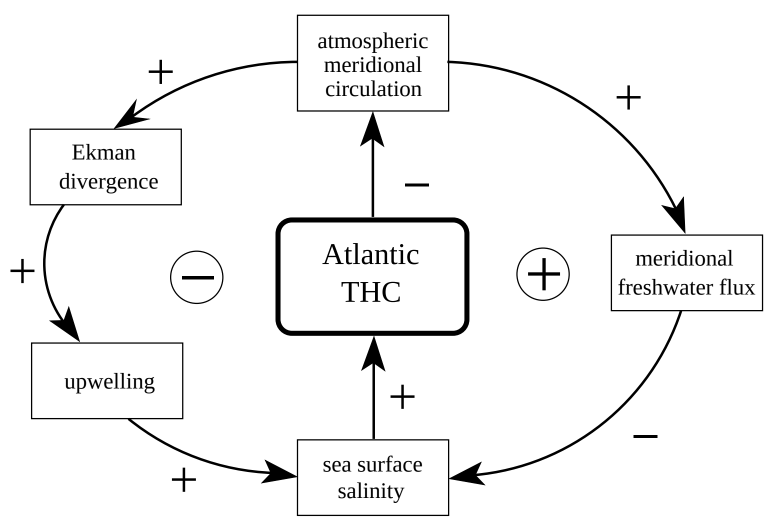

Figure 6: Schematics of two feedback mechanisms associated with changes in the atmospheric circulation in response to THC changes. The signs attached to the arrows indicate the correlation between changes in the quantity of the outgoing box with that of the ingoing box, e. g., increased sea surface salinity (SSS) leads to stronger THC. Resulting correlations of a loop are circled and they indicate whether a process is self-reinforced (positive sign) or damped (negative sign). A stabilising loop (left) is associated with changes in SSS due to wind stress changes. This loop may give rise to oscillations. The second loop (right) is due to the influence of the meridonal flux of freshwater whose resulting correlation is positive; the loop may therefore cause instabilities.

The influence of Arctic sea ice on the THC has hardly been studied because ocean models are often used without sea ice components. However, the influence of sea ice on the THC is potentially important because in the high latitudes, sea ice formation and sea ice export constitutes an important contribution to the freshwater balance (Dickson et al., 2000). Here we propose two feedback mechanisms associated with sea ice which have not yet been quantitatively studied with models (Fig. 7). A local effect arises through the process of brine rejection when sea ice forms. Increased sea ice formation thus tends to increase sea surface salinity (SSS) locally which promotes deep water formation. A weakening THC results in enhanced Arctic sea ice formation which tends to increase SSS and therefore the THC. On the other hand, sea ice is exported from the Arctic reducing SSS upon melting. This far-field effect in the form of a freshwater flux represents a destabilizing feedback mechanism for the THC. Beyond the feedback mechanisms associated with the salt balance, sea ice also influences the atmosphere-ocean heat transfer. Such feedback mechanisms have been discussed and simulated by Yang and Neelin (1993).

Finally, we speculate that there may also exist an interhemispheric feedback mechanism which involves deep water mass characteristics (Fig. 8). A stronger Atlantic THC extracts more heat from the Southern Ocean thereby cooling it (Crowley, 1992; Stocker, 1998). Cooling promotes sea ice formation and, via the process of brine rejection, enhances the formation of Antarctic Bottom Water (AABW). AABW is the densest large-scale water mass in the world ocean with an influence as far north as the North Atlantic. Ocean models suggest that if the density of southern component waters increases, NADW and with it the Atlantic THC tends to reduce (Stocker et al., 1992; England, 1992). This constitutes a negative feedback mechanism.

It is clear that the present "gallery" of feedback mechanisms is not complete and that further processes will be investigated as models increase their resolution and completeness. For example, the far-field effects of changes in the tropics and how these may influence the THC (Latif et al., 2000; Schmittner et al., 2000) are still poorly studied and only very few experiments with comprehensive models exist todate. It is, however, evident that we are not yet in the position to assess the overall stability of the THC to perturbations with sufficient confidence

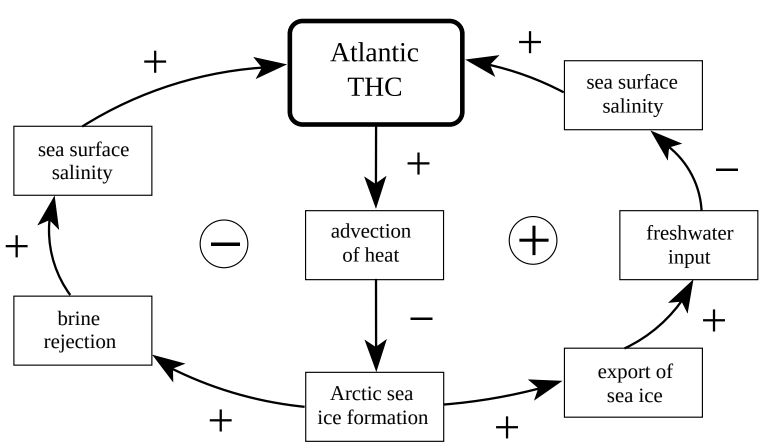

Figure 7: Schematics of a local (left loop) and a non-local (right loop) feedback mechansims associated with changes in Arctic sea ice in response to THC changes.

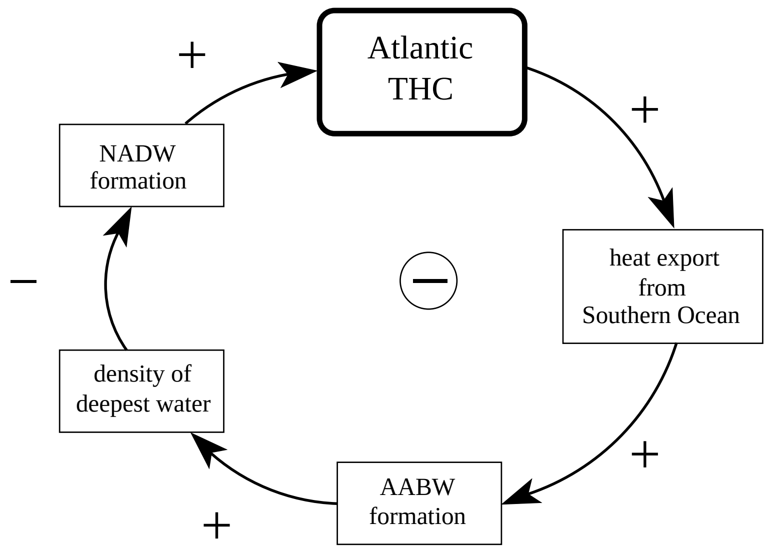

Figure 8: Schematics of a possible interhemispheric feedback mechanism.

because the strength of the individual feedback mechanisms is still poorly known. In particular, the strength of those feedback mechanisms that involve high-latitude processes such as sea ice, deep water formation and flow over sills, are fraught with the largest uncertainties. Progress in this area can only come from models which resolve the scales of these processes realistically.

7 A possible runaway greenhouse effect?

Given the insights about the workings of the climate system, we pose an important question: Do these massive ocean reorganisations have the potential to trigger a runaway greenhouse effect? The reasoning goes as follows (Fig. 9). A warming atmosphere clearly leads to increasing sea surface temperatures which, in turn, reduce the solubility of CO_2 in the surface waters. Warmer waters hold less dissolved carbon and warming thus causes an outgassing of this greenhouse gas. This constitutes a positive feedback loop (top in Fig. 9) enhancing the initial increase of atmospheric CO_2. A further positive feedback loop (left in Fig. 9) is associated with the effect of downward transport of carbon by the THC. If the THC collapses, much less carbon will be buried in the deep sea, again reinforcing accumulation of CO_2 in the atmosphere. There is a third feedback loop added in Fig. 9. This is associated with the reaction of the marine biosphere as described first by Siegenthaler and Wenk (1984). Its strength and even sign are very uncertain, but model simulations suggest that it may be a negative feedback which partly compensates the increase in atmospheric CO_2 caused by the left loop (Joos et al., 1999).

Model simulations using 3-dimensional ocean general circulation models with prescribed boundary conditions predicted a minor (Maier-Reimer et al., 1996) or a rather strong (Sarmiento and Le Quéré, 1996) feedback between the circulation changes and the uptake of anthropogenic CO_2 under global warming scenarios. However, the complete interplay of the relevant

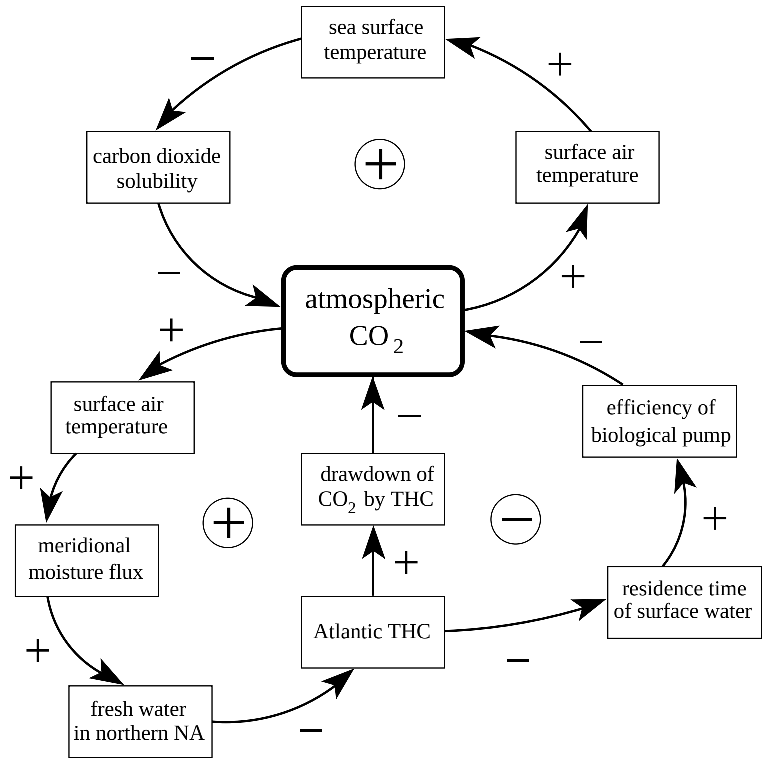

Figure 9: Possible feedback mechanisms that influence the atmospheric CO_2 concentration. In two cases, a positive feedback occurs with the potential of reinforcing the warming. NA denotes North Atlantic.

climate system and carbon cycle components was only recently taken into account using a physical-biogeochemical model of reduced complexity (Joos et al., 1999; Plattner et al., 2001).

With this model, different experiments with the ocean carbon pumps operating or suppressed can be performed. Such experiments are essential for a better understanding of the various processes influencing ocean uptake of CO_2 and hence atmospheric concentration (Fig. 10). By placing the model on a bifurcation point of the Atlantic THC, the impact of a breakdown of NADW formation on atmospheric CO_2 can be examined. Fig. 10a shows a set of simulations where the NADW formation weakens but recovers almost completely; the case of a complete collapse of the Atlantic THC is given in Fig. 10b. The CO_2 stabilization scenario is realized in a simulation with prescribed carbon emissions and a constant climate (long-dashed lines). The full simulation including all feedbacks (solubility, circulation and biota) shows a larger atmospheric CO_2 concentration for the same carbon emissions (the global warming at CO_2-doubling is 2.6°C). The additional increase in atmospheric CO_2 of about 11% in Fig. 10a is almost entirely associated with the effect of decreased solubility due to the warming. The breakdown of the THC in the Atlantic further reduces ocean CO_2 uptake significantly, resulting in an almost 20% increase in atmospheric CO_2 (Fig. 10b). In general, in this model the circulation and marine biota feedback nearly compensate each other, at least until year 2500, and the solubility effect remains the only significant global warming feedback (Joos et al., 1999). However, if the THC in the Atlantic collapses, the circulation feedback becomes dominant with minor contributions by the solubility effect and the marine biota feedback.

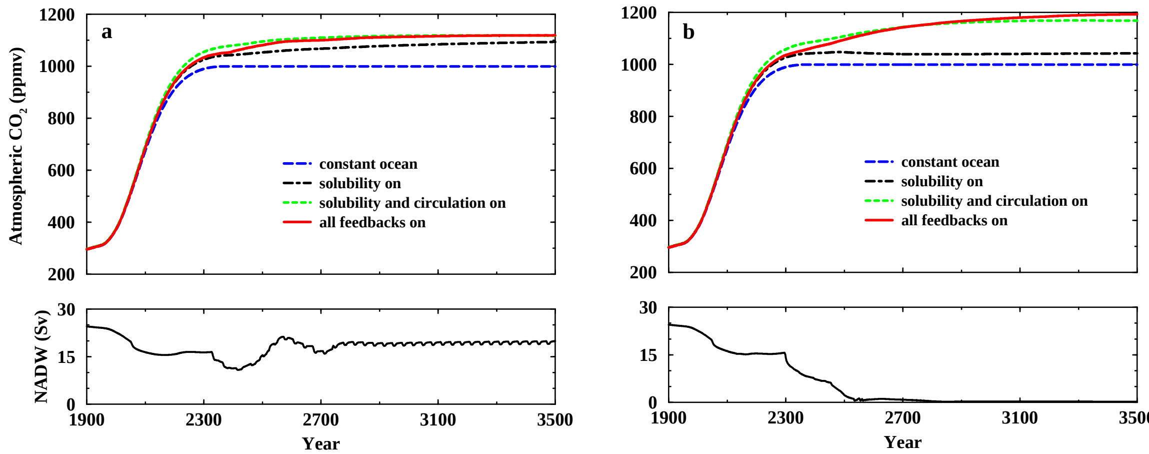

Figure 10: Evolution of atmospheric CO_2 and the formation rate of North Atlantic Deep Water (NADW, lower panels) in a model in which the emissions of carbon are prescribed based on a previous CO_2-stabilization simulation with a constant ocean. The stabilization target is 1,000 ppmv. The model was placed on a bifurcation point: (a) NADW formation weakens and recovers thereafter; (b) NADW formation breaks down completely. The global mean temperature increase for a doubling of CO_2 is about 2.6°C identical in both sets of simulations.

The reduction of strength of the ocean as a major carbon sink due to global warming appears to be a robust result, but the model also shows that dramatic feedback effects (such as a runaway greenhouse effect) are very unlikely. The maximum increase of atmospheric CO_2 in the case of a collapsed Atlantic THC is estimated at about 20%.

However, a recent study indicates that the terrestrial biosphere may constitute a more important feedback on the century time scale. In an integration using a coupled ocean-atmosphere-biosphere general circulation model, Cox et al. (2000) showed that by 2100 the terrestrial biosphere acts as a strong source of carbon due to increased soil respiration in a warmer and wetter world and the saturation of the fertilization effect at high CO_2. The effect on atmospheric CO_2 is estimated at more than 35%, significantly more than the oceanic effects in the year 2100. But as with the ocean simulations, one should emphasize that these results are still highly uncertain (Joos et al., 2001). Nevertheless, they indicate that significant, but not catastrophic positive feedback mechanisms are associated with the carbon cycle.

8 Conclusions

Since Broecker (1987) first drew attention to the possibility of large and abrupt changes associated with the THC, the joint effort of paleoclimatic reconstruction and climate modelling has provided tremendous detail to our understanding of the dynamics of non-linear THC changes in the Atlantic and its climatic impact. High-resolution records have told us that changes can be completed within a few years with amplitudes that are hard to imagine. In Greenland, mean annual temperature changed by up to 16°C within just a decade or so. Various records have indicated that these changes are wide spread and influence regions at least in the northern hemisphere. For some of the strongest events, changes are also seen as far south as Antarctica, but changes appear to be in opposite phase.

As the collection of findings of abrupt climate change in various records grows, paleoclimate modelling becomes increasingly important. This is for two reasons. First, only few paleoclimatic indices have a direct physical meaning; in most cases complex interactions in the ocean-atmosphere-biosphere system set the variations of variables that are measured. Models are needed to quantify the contribution of individual climate-relevant components to the observed signal. Second, models serve to quantitatively test hypotheses regarding the causes of abrupt change. Whereas in the early days of paleo-science, hypotheses were often formulated by educated guessing, nowadays we are able to put these hypotheses to a quantitative test. Clearly, the models do not replace further data but often they help us focus the data and embed them better into a large-scale context.

These same models send us a clear message: future changes of the THC in response to global warming are likely. Although the magnitude of the change is highly uncertain, the models agree that the THC in the Atlantic will reduce due to the gain of buoyancy associated with the warming and a stronger hydrological cycle. A few models, however, show a weak response and suggest that additional feedback mechanisms are at work. This apparent disagreement is the seed for new research. We need a better understanding of the individual feedback mechanisms, positive and negative, that are collectively influencing the THC. A few of these feedbacks are discussed in this article, others will be discovered with the next generation of climate models which will include better coupling to the atmospheric components, higher resolution and improved representation of deep water formation processes.

It is clear that future changes of the THC remain an important issue, even though there are few indications that an abrupt shut-down, a surprise, is a likely occurrence in the near future. It is also known that a slow-down of the THC moves the system closer to thresholds – and this should be of sufficient concern to warrant intensified research into this topic.

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