Predictability of the Atlantic Thermohaline Circulation under Global Warming

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1. The fate of the THC under global warming

In the recently published Third Assessment Report of the Intergovernmental Panel of Climate Change (IPCC, 2001) it was concluded that '*most models show a weakening of the ocean thermohaline circulation*' and that '*beyond 2100, the thermohaline circulation could completely, and possibly irreversibly shut down ...*'. The possiblity of such reorganisations represents additional and considerable uncertainty in climate projections of the future. CLIVAR is expected to contribute to a better understanding of these issues both through CLIVAR's 'Anthropogenic Climate Change' and its research on 'Atlantic Thermohaline Circulation'.

High-resolution paleoclimatic records (Broecker, 1997; Stocker, 2000), as well as numerous model simulations (an overview is given by Cubasch et al., 2001) suggest that global warming may reduce the merdional overturning circulation in the Atlantic (thermohaline circulation, THC). Some climate models even show a complete shut-down of the THC if some critical thresholds are crossed (Manabe and Stouffer, 1993; Stocker and Schmittner, 1997). However, the range of possible responses for the next 100 years is rather large: the THC in some models remains almost constant (Latif et al., 2000; Gent, 2001), while most models exhibit a substantial reduction of the meridional overturning. This uncertainty is likely due to model differences in climate sensitivity, in the response of the hydrological cycle, and in the representation of processes and feedbacks (e.g., NAO, ENSO). This indicates that the strength of stabilising and destabilising feedbacks influencing the THC is still largely unknown. Current research, therefore, must be concerned with a better understanding of the underlying processes.

However, there is an additional uncertainty which may severely limit the long-term predictability of the Atlantic THC. This uncertainty is associated with the fact that thresholds of instability in the THC may exist and that close to such thresholds prediction may be greatly reduced. The following is a brief summary of a paper in press (Knutti and Stocker, 2001).

2. Ensemble simulations below the instability threshold

We use a highly simplified coupled climate model which consists of a zonally averaged ocean model coupled to a moist energy balance model of the atmosphere, and includes the seasonal cycle (Schmittner and Stocker, 2001). Due to the absence of atmospheric dynamics and its associated variability, we employ a weak white-noise freshwater flux perturbation at the ocean surface to mimick the effect of 'weather' on the THC. Because the coupled model is efficient, Monte Carlo simulations can be performed. A ensemble consists of 100 simulations which differ only by the random sequence of freshwater flux perturbations. We assume a simple global warming scenario, in which the CO_2 is doubled within 140 years (0.5% increase per year) and held constant thereafter. Climate sensitivity is a parameter in this simplified climate model which is selected. Although internal variability is present in the model, the global mean temperature is tightly constrained (Fig. 1a). Global warming leads to a reduction in the strength of the Atlantic THC, and a new steady state is approached (Fig. 1b). The reduction is due to the combined effect of warmer

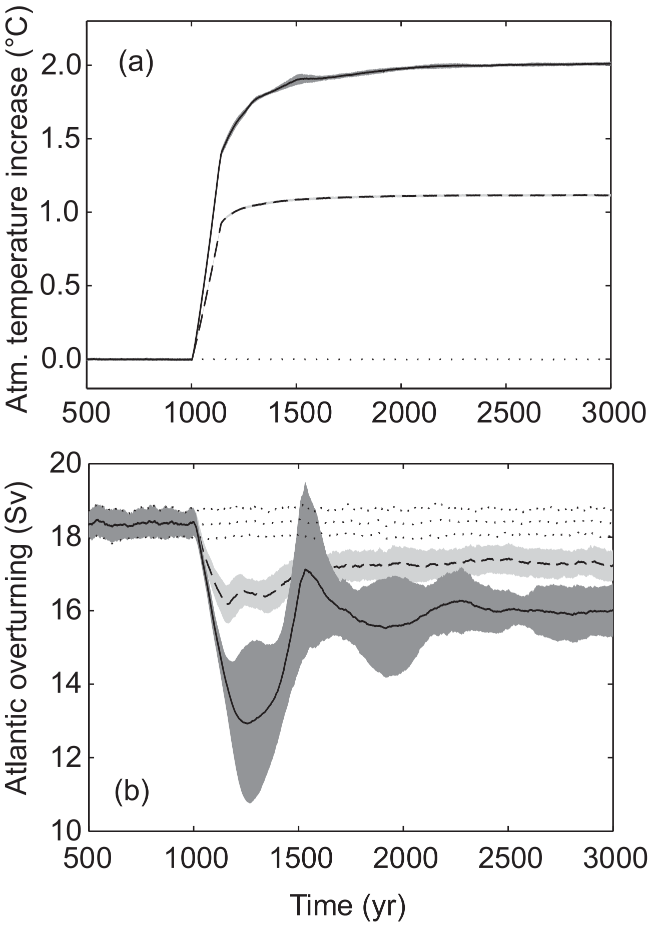

Figure 1: (a) Globally averaged surface temperature simulated by the coupled model of reduced complexity for two cases of prescribed climate sensitivity (1°C and 2°C for a doubling of CO_2 within 140 years). (b) Evolution of the overturning in the Atlantic (in Sv, 1 Sv = $10^6 m^3 s^{-1}$) for the weak (dashed) and the intermediate (solid) climate sensitivity, and a control simulation (dotted). The shaded bands denote the 1-σ range determined from 100 ensemble simulations with random sequences of freshwater anomalies (from Knutti and Stocker, 2001).

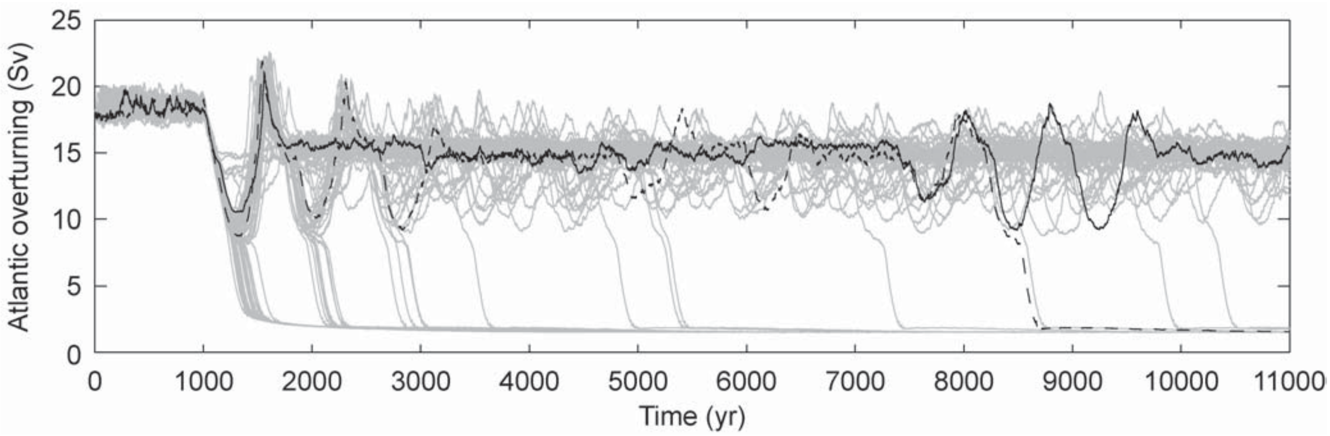

Figure 2: Multi-millennial evolution of the Atlantic overturning for 100 simulations (gray lines) using stochastic forcing close to an instability threshold of the thermohaline circulation. Complete shut-downs of the thermohaline circulation may occur even long after the radiative forcing has stabilised to a new mean value (by year 1140). Two simulations with qualitatively different behaviour are highlighted as black lines (from Knutti and Stocker, 2001).

sea surface temperatures and a stronger hydrological cycle consistent with comprehensive 3-dimensional climate models (Dixon et al., 1999; Mikolajewicz and Voss, 2000).

The present model posesses a second equilibrium circulation in which the Atlantic THC is shut down, i.e. there exists an instability threshold. When the Atlantic overturning reduces, the circulation approaches this instability threshold. The character of the transient phase is strongly dependent on how close the circulation comes towards the threshold (Fig. 1b). For the smaller climate sensitivity, the range of different evolutions within the ensemble (shaded band) remains approximately constant. Closer to the instability, the range grows significantly, even though the amplitude of the random forcing is unchanged. Even long after the perturbation, the ensemble range remains increased. It is also evident from Fig. 1b, that the predictability of the THC is particularly reduced during the transient phase.

3. Crossing the instability threshold

By increasing the climate sensitivity further, some of the ensemble members may now exhibit a full shut-down of the THC (Fig. 2). Most of the transitions occur at the time when the THC strength is most reduced, consistent with indications from 3-dimensional models (Tziperman, 1997). In realisations where the THC recovers, there is a tendency to multi-century oscillations of the Atlantic overturning. These oscillations seem to be damped on the time scale of a few thousand years, but there are also cases, where these oscillations re-appear much later (solid line) after a quiet period of many millennia. When the system is close to the instability, transitions can occur long after the perturbation. This implies a complete loss of predictability for the THC strength close to the threshold.

4. Conclusions

Investigating the long-term fate of the THC requires multi-century integrations of climate models. The currently available computing capacity still excludes thorough parameter studies with comprehensive 3-dimensional climate models. An assessment of uncertainty is therefore impossible. Models of reduced complexity can help overcome this difficulty and make valuable contributions to a better understanding of parameter space. These models are most useful as exploratory tools for hypothesis building. New concepts, or new research strategies can be readily assessed with these models. However, such models, which are intermediate within the climate model hierarchy, must be used wisely if they are to contriubute to scientific progress. In a continuous mode of scientific exchange, results from these models must be critically compared with those from comprehensive climate models in order to determine the robust findings.

It is herefore of particular importance in hierarchical climate modelling to test the new insights with specifically designed experiments using comprehensive models. Hopefully, multi-century ensemble simulations investigating the fate of the THC will soon become feasible.

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Can coupled models help to define an observing strategy for detection of climate change in the ocean?

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One of the priorities of the Global Climate Observing System is to make observations which allow the earliest possible detection of climate trends and climate change due to human activity. Until now detection of anthropogenic climate change has focused almost exclusively on surface temperature (for example, Barnett et al., 1999). In order to increase our confidence in these results it is desirable to apply this technique to other aspects of the climate system. Detection and attribution is also important in terms of model validation as it allows us to test the ability of models to reproduce historical changes. In the case of tropospheric temperature changes, discrepancies between observed and modelled changes have not yet been fully explained (IPCC, 2001).

We might expect the ocean to be less noisy than other parts of the climate system and for changes in surface fluxes (dynamic and thermodynamic) to change the ocean properties producing high signal-to-noise ratios. While decisions on where to make observations can often be made on a subjective basis we here attempt to make an objective assessment of which ocean variables will be useful for detection of anthropogenic climate change. Santer et al. (1995) looked at the signal-to-noise ratios of a number of different ocean indices in a coupled model and ocean-only models. We have extended this idea using HadCM3, one of the first coupled climate models to be run without artificial flux adjustments (Gordon et al., 2000). Clearly there are other requirements for ocean observations: forecasting, abrupt climate change, etc but our aim here is to show the potential usefulness of an objective assessment.

We make use of two experiments performed with HadCM3: CTL, the control experiment with fixed preindustrial greenhouse gases, and B2, an anthropogenic experiment forced with historical greenhouse gases, etc until present day and projected to 2100 with the IPCC SRES B2 scenario (IPCC, 2001). For a range of indices we have assumed that the index would be measured once and then for a second time fifty years later. We have calculated all the fifty year (overlapping) changes in each index from both CTL and B2 and compared the two distributions. It is clear when an index has a high signal-to-noise ratio because there is a clear separation of the two distributions.

Figure 1 shows the distributions from four indices; global mean SST, heat transport and the overturning streamfunction at 1500 m at 24°N in the Atlantic, and SubAntarctic Mode Water (SAMW) salinity. The distributions show that measures of the temperature and salinity of the ocean have high (and significant) signal-to-noise ratios on these timescales, the ratios of measures of the circulation (streamfunction) are marginally significant while for heat transports the two distributions are not distinguishable. This suggests that observations of heat transport are unlikely to be useful for the detection of climate change and we would need to measure the circulation over long periods. Ocean temperature and salinity on the other hand may have the potential for detection of change.

To examine this more closely, we have calculated signal-to-noise ratios in the temperature and salinity of each ocean basin. If we look on pressure surfaces we generally see fairly high signal-to-noise ratios in temperature but not salinity. To combine the two measurements we can look at salinity (or temperature) changes on isopycnal surfaces. Figure 2 shows where the signal-to-noise ratios are significant for the average fifty year signal from B2. These results show that there are large regions of the ocean where sig-