Thermohaline circulation hysteresis: A model intercomparison

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[1] We present results from an intercomparison of 11 different climate models of intermediate complexity, in which the North Atlantic Ocean was subjected to slowly varying changes in freshwater input. All models show a characteristic hysteresis response of the thermohaline circulation to the freshwater forcing; which can be explained by Stommel's salt advection feedback. The width of the hysteresis curves varies between 0.2 and 0.5 Sv in the models. Major differences are found in the location of present-day climate on the hysteresis diagram. In seven of the models, present-day climate for standard parameter choices is found in the bi-stable regime, in four models this climate is in the mono-stable regime. The proximity of the present-day climate to the Stommel bifurcation point, beyond which North Atlantic Deep Water formation cannot be sustained, varies from less than 0.1 Sv to over 0.5 Sv. **Citation:** Rahmstorf, S., et al. (2005), Thermohaline circulation hysteresis: A model intercomparison, *Geophys. Res. Lett.*, *32*, L23605, doi:10.1029/2005GL023655.

1. Introduction

[2] The Atlantic thermohaline circulation [*Rahmstorf*, 2003] is an important feature of the climate system, since it is responsible for most of the northward heat transport in the North Atlantic (up to 10^{15} W) [*Ganachaud and Wunsch*, 2000]. Model experiments and paleoclimatic data suggest that changes in thermohaline circulation can have a major impact on climate, particularly around the northern Atlantic [see, e.g., *Rahmstorf*, 2002]. Models, ranging from Stommel's classic conceptual ocean model [*Stommel*, 1961] through to an idealized one-basin ocean GCM [*Bryan*, 1986], to coupled global general circulation models (GCMs [*Manabe and Stouffer*, 1988]), further suggest that the thermohaline circulation is a highly non-linear system with multiple equilibrium states. The key control parameter is the freshwater budget of the Atlantic; the response of the circulation to changing freshwater input takes the form of a hysteresis curve [*Rahmstorf*, 1995].

[3] The Stommel-type conceptual ocean model describes a basin-scale positive feedback: enhanced thermohaline circulation transports more salt northward, enhancing high-latitude salinity and density and thereby the circulation. Another, more localized positive feedback is captured in Welander's "flip-flop" model of convective mixing [*Welander*, 1986]. Once thermally driven convection stops, freshwater can accumulate near the surface (in regions of net freshwater input, as is typical in high latitudes), which inhibits any further convection. This can lead to multiple equilibria with different convection patterns [*Lenderink and Haarsma*, 1994; *Rahmstorf*, 1994].

[4] In addition, negative feedbacks (e.g. the temperature feedback [*Rahmstorf and Willebrand*, 1995]) act which have a stabilizing influence on the circulation. As they depend on the coupling of the ocean and atmosphere, coupled climate models are required to simulate a realistic response of the thermohaline circulation to perturbations. This paper compares a range of such coupled models.

[5] The response of the circulation to freshwater forcing can be summed up in a schematic stability diagram (Figure 1), which will be useful in the interpretation of the model results described below. We will describe results of a standardized freshwater perturbation experiment conducted with eleven different models at nine scientific institutions in seven countries, as a part of the international network of Earth system models of intermediate complexity (EMICs [*Claussen et al.*, 2002]). Focusing on the quasi-equilibrium response, this work complements other recent intercomparisons of the transient response of the thermohaline circulation [*Gregory et al.*, 2005; *Stouffer et al.*, 2005].

2. Experimental Design

[6] We aim to compare the quasi-equilibrium states of the Atlantic thermohaline circulation as function of freshwater entering the North Atlantic. The freshwater input (except in the Bremen model in form of a virtual salt flux) was continually increased or decreased as a function of time, at a rate so slow that the circulation can adjust to this change while remaining close to equilibrium [see *Rahmstorf*, 1995]. Understanding the equilibrium states existing in a model is the basis for understanding the response to transient perturbations.

[7] The experimental design adopted is identical to that described in [*Rahmstorf*, 1995, 1996]. Each model started from an equilibrium state for present-day climate, using the

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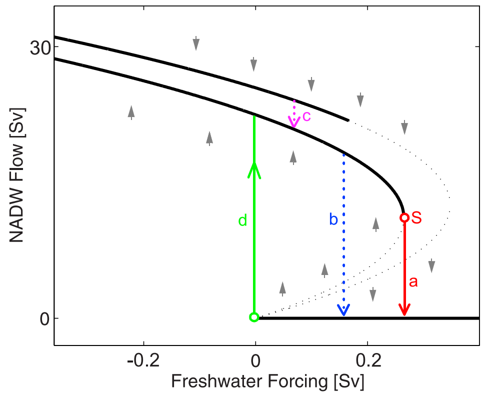

Figure 1. Schematic of hysteresis, with solid black lines indicating stable equilibrium climate states and dotted black lines unstable states. Different types of transition are indicated by colored arrows: (a) an advective spindown related to Stommel's salt transport feedback, (b) a convective shutdown related to Welander's "flip-flop" feedback, (c) a transition between different convection patterns, and (d) the restart of convection. A full hysteresis loop cycles between the "on" and "off" states of the Atlantic thermohaline circulation via transitions (a) and (d). Small arrows show the movement in phase space of non-equilibrium states. "S" marks the Stommel bifurcation beyond which no NADW formation can be sustained. Figure adapted from *Rahmstorf* [2000].

parameter choices that each group had adopted for their standard present climate simulation. Additional freshwater was then added uniformly to the latitude band 20–50°N across the Atlantic. This changes the large-scale freshwater balance of the North Atlantic, without forcing the high-latitude convection regions directly. To keep the experiment simple, the freshwater input was not compensated for elsewhere in the ocean. Previous experiments found that compensating for this freshwater input in the Pacific makes little difference [*Rahmstorf and Ganopolski*, 1999]. The rate of change of the freshwater input was 0.05 Sv per 1,000 model years. A typical experiment (i.e., up to freshwater perturbations of plus 0.25 Sv and minus 0.25 Sv) takes 20,000 model years to complete. In some of the more costly models faster rates of change were employed; this will result in the model deviating more from the true equilibrium curve, particularly near bifurcation points [*Rahmstorf*, 1995].

3. Participating Models

[8] The computational cost of calculating a quasi-equilibrium thermohaline hysteresis curve puts this experiment squarely in the domain of intermediate complexity models (EMICS) [*Claussen et al.*, 2002]. The participating EMICS fall into three groups: (1) EMICS in which the ocean and atmosphere are both of intermediate complexity; (2) ocean GCMs coupled with simple atmosphere models; and (3) a "stripped-down" coarse-resolution coupled GCM. The models used here are of very different types; they differ far more from each other than a sampling of different GCMs would. One aspect of the model variety is dimensionality: some models are (partly) zonally averaged, others are not; some models do have a vertical dimension to the atmosphere, while others employ a one-layer surface energy balance. Also, other components (e.g., sea ice) differ between the models. The large variety in model construction adds credence to those results that are robust across all models. An overview over the participating models is given in Table 1.

4. Hysteresis Curves

[9] Results of the hysteresis computation are shown in Figure 2. Shown here is the maximum of the meridional volume transport stream function in the North Atlantic (excluding the near-surface wind-driven Ekman transport) as an integral measure of the rate of North Atlantic Deep Water (NADW) circulation.

[10] It is remarkable that all models, despite their large differences in construction, show a clear hysteresis response. The *shape* of the hysteresis curves in most models, rounded to the right, is consistent with an underlying parabolic equilibrium curve that results from Stommel's model. This suggests that the salt advection feedback, which causes this type of solution in Stommel's conceptual model, is a dominant feature in all these models. (The "spike" in some of the curves near zero freshwater input is a transient feature not relevant to the equilibrium response.)

[11] Several models show some deviations from this basic shape, particularly vertical "steps" in the curve. It was previously shown that these can arise due to a shift in convection location in a model [*Rahmstorf*, 1995]. In some

Table 1. Models Participating in This Study[a]

Model Name	Ocean Component	Atmosphere Component	Reference for Model Details
Bern 2.5D	zonally averaged, 3 basins	zonally averaged energy moisture	[*Stocker et al.*, 1992]
Bremen	large-scale geostrophic	energy balance	[*Prange et al.*, 2003]
Climber-2	zonally averaged, 3 basins	statistical-dynamical	[*Petoukhov et al.*, 2000]
ECBilt-CLIO	3D primitive equations	quasi-geostrophic	[*Goosse et al.*, 2001]
C-GOLDSTEIN	3D simplified	energy-moisture balance	[*Edwards and Marsh*, 2005]
MIT_UWash	3D prim. equations, square basins	zonally averaged	[*Kamenkovich et al.*, 2002]
MoBiDic	zonally averaged, 3 basins	zonally averaged	[*Crucifix et al.*, 2002]
MOM-hor	3D primitive equations (MOM)	simple energy balance	[*Rahmstorf and Willebrand*, 1995]
MOM-iso	as above, with isopycnal mixing	simple energy balance	
MPM	zonally averaged, 3 basins	energy-moisture balance	[*Wang and Mysak*, 2000]
UVic	3D primitive equations (MOM)	energy-moisture balance	[*Weaver et al.*, 2001]

[a]All of the ocean models use z-coordinates.

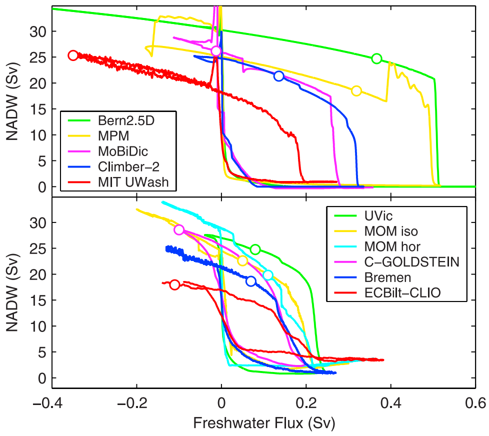

Figure 2. Hysteresis curves found in the model intercomparison. The bottom panel shows coupled models with 3-D global ocean models, the top panel those with simplified ocean models (zonally averaged or, in case of the MIT_UWash model, rectangular basins). Curves were slightly smoothed to remove the effect of short-term variability. Circles show the present-day climate state of each model.

cases the circulation is switched off altogether in such a sudden step; this is likely the result of a complete shutdown of convection and is known as "convective instability", as opposed to the more gradual "advective shutdown" associated with Stommel's salt advection feedback [*Rahmstorf et al.*, 1996]. Thus, the qualitative features of the hysteresis curves can be understood in terms of the two basic positive feedbacks described in the introduction.

[12] The *width* of the hysteresis curves, i.e. the difference in freshwater forcing between the two bifurcation points where the circulation turns on and off, can be computed for Stommel's conceptual model as

$$F_{crit} = \frac{\alpha}{4\beta c_p \rho S_0} Q$$

where Q is the heat transport, α is the thermal expansion coefficient, β is the haline expansion coefficient, c_p is the heat capacity and ρ the density of sea water, and S_0 is a reference salinity (taken as 35 psu).

[13] For a meridional heat transport of 1 PW, a typical value for the Atlantic thermohaline circulation [*Roemmich and Wunsch*, 1985], the resulting hysteresis width is 0.24 Sv. Indeed, most of the hysteresis curves in our intercomparison are clustered around this value (range 0.15–0.5 Sv). We further note that the improved version of the MPM produces a hysteresis width of 0.32 Sv [*Wang*, 2005].

[14] The *height* of the hysteresis curves, i.e. the value of the volume transport at the point designated as zero freshwater input (see discussion below), is a tunable value in Stommel's box model: there is a linear relation between density difference and flow rate in this model, the proportionality constant being a free model parameter. A similar (though of course more complex) parameterized relation between the density field and the flow field is assumed in zonally averaged ocean models, which applies to many of the models in this intercomparison (see Table 1). In these models, the volume transport and thus the height of the hysteresis curves can be scaled up by changing a parameter. When volume transport increases this will also increase heat transport (if temperatures remain unchanged to first order), so that the hysteresis curve could be scaled up in both dimensions in this manner.

[15] In contrast, in three-dimensional ocean models the link between density and flow field arises from the basic hydrodynamic equations, so that the magnitude of the hysteresis loop is not directly tunable. However, it can be indirectly affected to some extent by choices in oceanic diffusion [*Prange et al.*, 2003; *Schmittner and Weaver*, 2001].

5. Position of Present-Day Climate

[16] An important aspect is the position of the present-day climate on the hysteresis curves, which is marked by a circle in Figure 2. This determines whether present-day climate is *mono-stable* or *bi-stable* in a model (i.e., whether the thermohaline circulation will recover after it was switched off by a long but temporary perturbation), and how close the present-day climate is to the Stommel bifurcation point (see Figure 1).

[17] All model simulations were started from a present-day climate state, i.e., zero freshwater anomaly equals present-day climate. In Figure 2 the hysteresis curves are not plotted directly as function of the added freshwater anomaly, but shifted in order to align them on their left sides. This point is designated zero freshwater flux, since this is what it is in Stommel's conceptual model: bi-stable solutions in this model can only arise for positive freshwater input. This point is the only physically meaningful point for aligning the models, since otherwise there is no unique definition for an absolute value of the freshwater flux. In a geographically explicit model there is no unique value of the freshwater flux since it is a spatially varying quantity, and it is ill defined what catchment area should be considered when calculating an integral (see [*Rahmstorf*, 1996]). To the right of the origin the present-day climate is in a bi-stable regime, to the left it is in a mono-stable regime.

[18] It is clear that the models differ greatly in where the position of the present-day climate is located on the hysteresis curve. This is an important difference as it determines the model sensitivity to perturbations, with models further on the left being less sensitive. Such a difference can be brought about by differences in the surface fluxes to the ocean, which are treated very differently by different models; they result from a mix of observed fluxes, computed fluxes (with greatly differing sophistication of the physics) and flux adjustments.

[19] The reason for these model differences requires further study. So does the question of where the real Atlantic Ocean is likely to reside, although some evidence suggests it may be in the bi-stable regime [*Rahmstorf*, 1996; *Weijer et al.*, 1999]. We found (not shown) that there is a tendency for models with greater evaporation to be further on the left in the hysteresis diagram (i.e., with a more stable thermohaline circulation) but the connection is not clear-cut. The freshwater budget of the Atlantic

deserves further attention in future modeling and observational studies.

6. Discussion and Conclusions

[20] Our main finding is that 11 different climate models of intermediate complexity show a qualitatively similar hysteresis behavior when quasi-equilibrium changes in freshwater forcing are applied to the northern Atlantic. This result supports the validity of Stommel's classic feedback [*Stommel*, 1961].

[21] The ocean components used include zonally averaged ocean models, simplified 3-D models and 3-D ocean GCMs. The atmosphere components and the feedbacks they allow also differ widely, ranging from a very simple energy balance with no wind or moisture feedback to a simplified atmospheric GCM which includes synoptic variability, wind, and evaporation feedback. Some include a vertical structure, some do not. We do not find that the hysteresis response and hence Stommel's feedback are fundamentally affected by these model differences.

[22] We therefore consider it highly likely that a similar hysteresis response would also be found in currently used coupled climate GCMs. This has so far not been tested due to the computational expense. Some authors have argued that coupled GCMs do not show non-linear hysteresis behavior but rather a linear response [e.g., *Rind et al.*, 2001]. However, this was based on transient experiments, which must not be confused with the equilibrium response. At least some of the EMICs used here give a similar linear response when the same transient experiments are performed. For example, EMICS [*Petoukhov et al.*, 2005] and GCMs [*Gregory et al.*, 2005] exhibit quantitatively similar THC responses to increasing GHG concentrations, and a recent intercomparison of identical transient freshwater perturbation experiments [*Stouffer et al.*, 2005] has found no systematic differences between EMICs and coupled GCMs. Note also that a recovery of the circulation after a major freshwater pulse does not argue against hysteresis behavior; it may only argue for a model being in the monostable regime (and for a brief freshwater perturbation, a recovery from a very weak circulation is still possible even in the bi-stable regime).

[23] Important differences between the models tested here were found in the dimensions of the hystereses, the position of the present-day climate on the hysteresis diagrams, and thus the proximity to the Stommel bifurcation, which is the critical threshold beyond which no deep water formation in the North Atlantic can be sustained. The additional amount of freshwater that can be added to the northern Atlantic before this threshold is reached varies from less than 0.1 Sv to over 0.5 Sv in the models. Further experiments with individual models suggest this depends on ocean mixing parameters, on the freshwater budget of the Atlantic and on atmospheric feedbacks [*Edwards and Marsh*, 2005; *Lohmann*, 2003; *Schmittner and Weaver*, 2001]. This dependence of the equilibrium threshold is likely to be relevant also for transient climate changes, where meltwater runoff from Greenland due to future global warming would average $\sim$0.1 Sv if the ice sheet were to disappear over $\sim$1,000 years [*Hansen*, 2005]. This needs to be investigated further and physically understood, in order to narrow down how far the present climate may be from a critical threshold.

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