Effect of the Greenland Ice-Sheet Melting on the Response and Stability of the AMOC in the Next Centuries

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The Atlantic Meridional Overturning Circulation (AMOC) transports large amounts of heat in the North Atlantic, being thus a major component of the climate system. This ocean circulation is very sensitive to buoyancy perturbations in the North Atlantic convection sites and is expected to decrease during the next centuries due to global warming. General Circulation Models (GCM) participating in the Intergovernmental Panel on Climate Change (2001) do not take into account land-ice melting, notably from Greenland, despite its potential to further enhance AMOC weakening. How such a melting might affect the AMOC under CO_2 stabilization remains a crucial issue. Here we show, using a fully coupled ocean-atmosphere-land-sea-ice GCM, that incorporating land-ice melting can lead to an AMOC collapse during the next 500 years, while the AMOC recovers when this effect is not considered. Our results show that the impact of AMOC weakening on surface temperature is important in the northern hemisphere mid and high latitudes, although atmosphere heat transport compensates part of the oceanic heat transport weakening. We further evaluate some features of the possible bistability of the AMOC. After a collapse of the AMOC, if the land-ice melting is switched off, the AMOC recovers. This shows that the AMOC is mono-stable in this model under $2 \times CO_2$.

1. INTRODUCTION

The Atlantic Ocean Meridional Overturning Circulation (AMOC) is a part of the global thermohaline circulation that carries vast amounts of heat and freshwater (*Wunsch*, 2002). It has undergone lots of changes during the past glacial-interglacial cycles (*Labeyrie et al.*, 1992; *Duplessy*, 2004). These changes appear to be correlated with large glacial ice discharges in the North Atlantic (*Bond et al.*, 1993; *McManus et al.*, 2002), which decrease the salinity there. Therefore, the buoyancy of surface water is diminished and the process of convection is reduced. This process is central for the production of dense water that feeds the AMOC. This may explain why the AMOC has slowed down after such discharges (*Manabe and Stouffer*, 1988; *Marotzke and Willebrand*, 1991). However the AMOC is a very complex phenomenon that could have a non-linear response. This non-linear behavior is caused by the existence of feedbacks governing the AMOC. These feedbacks are related to salinity (positive) and heat (negative) transport, but could also involve more complex processes where sea-ice and atmospheric interactions play a role.

The climate of last century has warmed by 0.6 K due to release of greenhouse gases, such as CO_2 and CH_4 in the atmosphere (*IPCC*, 2001). The coming century will certainly experience an increase of the greenhouse gases, which will enhance the global warming and lead to a global increase of temperature whose range lies between 1.4 K and 5.8 K (IPCC, 2001). Global warming will impact the large ice-sheet located in the Greenland and could lead to a massive discharge of

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freshwater and dramatically alter the AMOC as in the past. The consequences of such a discharge are not well known. Predictions from ocean-atmosphere Coupled General Circulation Model (CGCM) participating to IPCC (2001) do not take into account this melting. Here we propose to evaluate the effect of this discharge in the coming centuries thanks to a comprehensive atmosphere-ocean-land-sea-ice coupled GCM into which land-ice melting is parameterized.

In the following we first review the evaluation of land-ice melting and we explain some important features of the AMOC dynamics like the so-called hysteresis diagram (section 2). Then we briefly introduce the model and experimental design (section 3). Our results show the impact of land-ice melting on the AMOC in scenarios and a discussion of the key processes at play for the AMOC response is presented (section 4). We then clarify the mechanisms of climate impact of the AMOC. We also give some clues about the hysteresis cycle width in the IPSL-CM4 model under global warming conditions. A discussion (section 5) and a conclusion (section 6) end the paper.

2. LAND-ICE MELTING AND AMOC DYNAMICS

2.1. Greenland Melting Evaluation

Nowadays, observations of Greenland ice-sheets have benefited from satellites (*Thomas et al*., 2000). Interferometers measure the horizontal movement of ice while altimeters evaluate the vertical changes. This gives precise estimation of Greenland volume variations and therefore of the melting during the past few years. It appears that Greenland melting is about twice as fast as previously announced and modeled by state-of-the-art ice-sheet models (*Parizek and Alley*, 2004; *Rignot and Kanagaratnam*, 2006). Some crucial processes such as lubrication by meltwater, not well represented in ice-sheet models, can accelerate the melting and explain this underestimation. Rate of melting in past climate also pleads for a rapid melting from ice-sheet (*Chen et al*., 1991). The conditions were however different since ice-sheets were more extensive than today. *Bard et al*. (1996) evaluate this rate in the coral reef of Tahiti to be about 0.12 Sv during the Younger Dryas (~11 500-13 000 calendar years ago), while *Roche et al*. (2004) find a figure of 0.09 Sv for the Heinrich event 4 (~38 000 calendar years ago).

IPCC (2001) evaluates Greenland melting to be very small at the end of the 21st century. Studies by *Huybrechts and de Wolde* (1999) and *Greve* (2000) with ice-sheet models alone actually find some values of melting that do not exceed 0.1 Sv even for extreme warming of 12 K. However limitation in ice-sheet modelling implies a very large uncertainty in these values so that faster melting could be possible as confirmed by the rate of melting observed during ice age. Moreover the coupling with ocean-atmosphere system could imply positive feedbacks (like changing ice topography and albedo) not included in ice-sheet-only model.

The effect of such melting on the AMOC has been evaluated in different ways with rather simple models but has however revealed interesting features of the AMOC.

2.2. AMOC Hysteresis Cycle

Stommel's pioneering work (1961) has shown, using a simple two boxes model representing the high and low ocean latitude, that the AMOC could have multiple stable steady states. This means that under a similar ocean forcing, the AMOC could exhibit different circulations, one being toward the north in surface as in actual climate, and the other being less intense and orientated toward the south at the surface. This behavior is summarized on Figure 1. It represents the stable AMOC states that depend on the freshwater forcing in the North Atlantic. For a particular forcing, two equilibriums are possible. This figure thus illustrates the so-called hysteresis behavior of the AMOC. The existence of these multiple equilibriums is classical of non-linear systems. A freshwater perturbation in the North Atlantic can lead to an AMOC collapse, which does not recover after the perturbation, due to the bistability phenomenon. The non-linearity of the AMOC can be explained by the different feedbacks that govern its dynamics. For example the salinity transport related to AMOC strongly influences buoyancy in the convection sites. A decrease of the AMOC reduces the salinity transport in these sites, which further decreases salinity and convection there and thus the AMOC. This positive feedback is the process that leads to such a collapse in the Stommel's two boxes model. Other complex feedbacks are related to changes in the AMOC but are not taken into account in this simple model.

More recent studies using Earth Model of Intermediate Complexity (EMIC) have shown that this behavior is robust in these more complex models. The inter-comparison of the state-of-the-art EMICs, with 3D ocean model, shows that the hysteresis loop width is of about 0.2 Sv (*Rahmstorf et al*. 2005). It is hard for comprehensive CGCMs to evaluate the existence of the hysteresis loop because of the computational cost. Some studies have however tried to evaluate the existence of double equilibriums. *Manabe and Stouffer* (1988) find two equilibriums in the GFDL model, but this model was flux adjusted which can seriously affect the models' behavior. Moreover for high values of diapycnal mixing, the bistability in their model was removed (*Manabe and Stouffer*, 1999). More recently *Vellinga et al*. (2002) did not find such a behavior in the HadCM3 model, because in this model wind-driven transport of salinity stabilizes the AMOC. CGCMs thus suggest that several stabilizing processes could

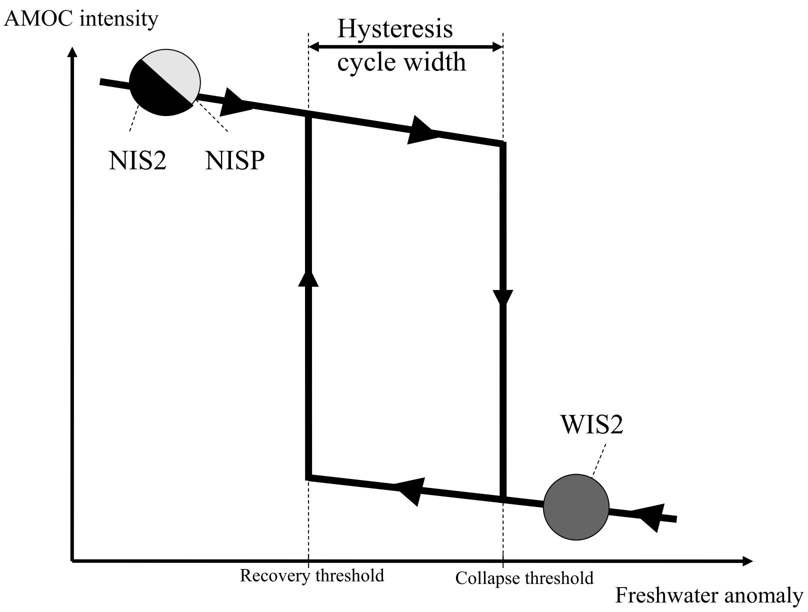

Figure 1. Scheme of AMOC intensity as a function of freshwater forcing in the North Atlantic. The result is a hysteresis loop illustrating the non-linearity of the system and the possibility of bi-stable state of the AMOC. We have noted on the scheme the collapse and recovery threshold. The circle represents a qualitative position of experiments WIS2 and NIS2 on this diagram deduced from the results we present.

be at work in the real world. They need to be taken into account when evaluating the possibility of bistable state of the AMOC. The use of CGCM thus appears important to investigate the future of the AMOC.

2.3. Global Warming Scenarios and Land-Ice Melting

The effect of global warming on the AMOC is complex to understand because surface flux changes due to temperature increase and associated modification in the hydrological cycle modify both temperature and salinity in the ocean. Most CGCMs show a weakening of the AMOC for the coming century under global warming conditions but there is a large spread among CGCMs (*Schmittner et al*., 2005). *Gregory et al*. (2005) have shown that the AMOC weakening due to increasing greenhouse gases is mostly due to temperature increase in the ocean, while salinity changes effect is more complex among CGCMs and is at the origin of the spread of the responses. Nevertheless none of these CGCMs take into account land-ice melting, a process that can further decrease the AMOC.

Fichefet et al. (2003) analyze the effect of land-ice melting in a scenario using a CGCM coupled to an ice-sheet model. They integrate a scenario where greenhouse gas increases over the 21st century (SRES B2, IPCC 2001) and find a noticeable effect on the AMOC at the far end of the simulation for a relatively small amount of land-ice melting. The climatic impact associated to this AMOC weakening appears to be locally important around the North Atlantic. *Swingedouw et al*. (2006, henceforth termed S2006), using an idealized scenario 1% per year CO_2 increase up to 4 × CO_2, find a stronger effect on the AMOC but with a higher rate of land-ice melting. They also find an important climatic impact of such an AMOC weakening, which is related to sea-ice interaction and albedo feedback, mostly in the Barents Sea. Nonetheless, *Ridley et al*. (2005) using HadCM3 coupled with and ice-sheet model at 4 × CO_2 and *Jungclaus et al*. (2006) using MPI model with prescribed land-ice melting in an A1B scenario both find a negligible impact of this melting.

The present study extends the study of S2006 and analyses the longer time scale of a scenario stabilized at 2 × CO_2, which is a less extreme warming scenario than in S2006.

3. MODEL AND METHODOLOGY

We use the IPSL-CM4 ocean-atmosphere-sea-ice-land coupled GCM (*Marti et al*., 2005). This state-of-the-art comprehensive CGCM incorporates a global and local closure of the freshwater budget as described below. It couples the atmosphere general circulation model LMDz (*Hourdin et al*., 2006) and the ocean general circulation model ORCA/OPA (*Madec et al*., 1998). A sea-ice model

(*Fichefet and Morales-Maqueda*, 1997), which computes ice thermodynamics and dynamics, is coupled with the ocean-atmosphere model. The atmospheric model is coupled to the ORCHIDEE land-surface scheme (*Krinner et al*., 2005). The ocean and atmosphere exchange surface temperature, sea-ice cover, momentum, heat and freshwater fluxes once a day, using the OASIS coupler (*Valcke et al*., 2004). None of these fluxes are corrected or adjusted. A complex river runoff scheme considers the water transport from land to the ocean. The model is run with an horizontal resolution of 96 points in longitude and 71 points in latitude (3.7° × 2.5°) for the atmosphere and 182 points in longitude and 149 points in latitude for the ocean, corresponding to a resolution of about 2°, with higher latitudinal resolution of 0.5° in the equatorial ocean. There are 19 vertical levels in the atmosphere and 31 levels in the ocean with the highest resolution (10m) in the upper 150m.

The IPSL-CM4 model includes a parameterization of land-ice melting through iceberg or direct runoff. This parameterization is rather crude: while it is based on the thermodynamic laws, it does not incorporate any dynamical device. The land-ice areas are therefore fixed to the actual observed distribution. When the glacial surface is snow free and the surface temperature is greater than 0°C, the surface temperature is set to 0°C and the excess of heat is used to melt the land-ice. This meltwater enters to the ocean as a freshwater flux but the elevation and volume of the glacier remains unchanged. The freshwater is not directly distributed along the ice sheet, but routed to the ocean uniformly over a wider region. Earth is divided into three latitude bands with limits at 90°S/50°S/40°N/90°N. For the northern band, the freshwater is sent to the Atlantic and the Nordic Seas, but not to the Pacific and the Arctic.

In order to analyze the impact of land-ice melting in a warming world, we perform two scenarios starting from pre-industrial conditions (280 ppm), in which CO_2 concentration increases by 1%/year up to doubling pre-industrial concentration after 70 years. The concentration is then kept constant for another 430 years. We thus focus on the stabilization of the AMOC after transient increase of CO_2 in a classical scenario (*Meehl et al*., 2005). In order to isolate the effect of land-ice melting, in one case (experiment WIS2: With Ice Sheet melting at 2 × CO_2) the meltwater enters the ocean (assumes all meltwater goes to the ocean); in the other case (experiment NIS2: No Ice Sheet) no meltwater enters the ocean (assumes all meltwater refreezes the glacier or ice sheet). A control simulation (CTRL) under pre-industrial conditions completes the set of simulations. In this reference simulation, the AMOC index is 10.6 Sv (Figure 2), which is weaker than observation based estimates (*Ganachaud and Wunsch*, 2000) but in the range of IPCC models (*Schmittner et al*., 2005). A last experiment (NISP) begins from year 250 of WIS2 but with a model that does not include land-ice melting as in NIS2. It is designed to evaluate the effect of a stop of Greenland melting.

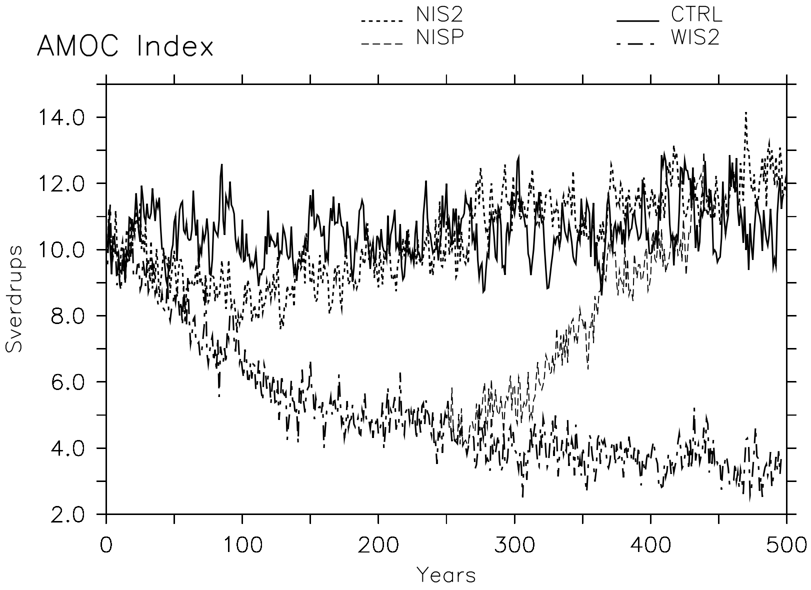

Figure 2. Time series of AMOC index in Sverdrup (1 Sv = $10^6 m^3/s$), defined as the maximum of the meridional overturning circulation in the Atlantic deeper than 500m. The difference between the scenarios in the AMOC index is 8.8 Sv after 500 years.

4. RESULTS

4.1. Different Response to Greenhouse Release

On Plate 1a is shown the increase in global temperature for the perturbation integrations and control. The rise in temperature in the experiments is globally 2.1 K in WIS2 and 2.2 K in NIS2 after 70 years. It reaches respectively 3.2 K and 3.5 K after 500 years. Over Greenland, the rise in temperature is larger due to polar amplification associated with albedo feedback effect of sea-ice and land snow melting. It reaches 3.8 K in WIS2 and 5.6 K in NIS2 after 500 years (Plate 1b). This rise in temperature over Greenland leads to a melting of the ice-sheet of 0.13 Sv after 200 years that mostly explains the difference in freshwater forcing north of 40°N between the experiments (Plate 1c). Elsewhere, the melting of glaciers is smaller than 0.02 Sv (not shown), so that we make the assumption that it does not affect the ocean dynamics compared to Greenland melting.

The AMOC response (Figure 2) is very different between the simulations showing the importance of land-ice melting on the future of the AMOC in this model. In WIS2, the AMOC strongly decreases and stabilizes at 3.3 Sv. In NIS2, when the land-ice is not considered, the AMOC decreases the first 100 years to a minimum of 7.8 Sv and then increases and recovers after 200 years. In NISP, the AMOC begins from 4 Sv at year 250 of experiment WIS2. Without land-ice meltwater impact on the ocean surface salinity, the AMOC recovers after about 100 years and stabilizes around CTRL value.

4.2. AMOC Changes Mechanisms

AMOC changes result from modifications in surface buoyancy that affect convection in the North Atlantic. These changes can be due (i) to global warming forcing or (ii) to AMOC related feedbacks, associated with temperature and salinity. To explain the origin of the simulated AMOC changes, and to disassociate the relative effect of processes (i) and (ii), we use *Swingedouw et al*. (2007, henceforth termed S2007) methodology based on the fact that the AMOC anomalies between projection simulations and CTRL are strongly correlated (0.98) to buoyancy changes in the convection sites. In both experiments the increase in ocean temperature weakens the AMOC. The role of salinity depends on the experiments considered. In NIS2, salinity increases at the convection sites and is responsible for AMOC recovery. In contrast, in WIS2, the salinity component contributes to the AMOC weakening (S2007). These results are in agreement with other CGCMs (*Gregory et al*., 2005) and show that the impact of salinity on the AMOC in the future can be either positive or negative. The origin of these different anomalies has also been analyzed in S2007. We give a short summary of this effect in the following.

In NIS2, the largest term leading the positive salinity anomalies is the increase in wind-driven transport of salty water from the tropics, which explains 36% of the recovery mechanisms (positive buoyancy anomalies integrated over 500 years, see Table 1). This transport results from the increase in salinity in the tropics associated with the increase in evaporation (*Latif et al*., 2000). The development of the anomaly and its transport to the convection sites require 100 years, which explains the lag of the AMOC recovery. Changes in sea-ice melting in the convection sites explain another 28% of the recovery. In the present climate, sea-ice is transported from the Arctic toward the convection sites, where it melts, decreasing salinity. In a warmer world, Arctic sea-ice is melted further north in the Arctic, causing a strong reduction of sea-ice transport toward the convection sites. Consequently, in a warmer climate, sea-ice melting is reduced at the convection sites and this contributes to the AMOC recovery. The gyre salinity transport and the sea-ice effects counteract the negative buoyancy anomalies, which are mainly related to two processes. Firstly, the warming by surface heat flux explains 32% of the negative buoyancy terms. Secondly and most importantly, the decrease in overturning salinity transport explains 55% of the negative buoyancy anomalies. This latter process is a positive feedback and amplifies the AMOC weakening during the first 200 years (not shown).

In WIS2, the AMOC decrease is due to land-ice meltwater flux, amplified by positive feedbacks, such as the overturning salinity transport. It has been shown (S2007) that the AMOC system amplifies the land-ice melting buoyancy signal by a factor of 2.5 in the IPSL-CM4 model.

4.3. AMOC Climatic Impact

The climatic impact of the differences in AMOC appears on Figure 3. The difference between WIS2 and NIS2 is a relative cooling centered over the Barents Sea. This impact can be explained through the northward oceanic heat transport reduction between WIS2 and NIS2 shown in Figure 4. This decrease in northward oceanic heat transport is observed at all latitudes from 40°S to 90°N. Most of this difference occurs in the Atlantic (not shown). The maximum decrease happens around 20°N and reaches 0.48 PW. This represents more than a half of the northward heat transport in CTRL simulation whose maximum in the Atlantic is around 0.7 PW. This value is a bit smaller compared to observationally based estimates of about 1 PW at 20°N (*Trenberth and Caron*, 2001). This is certainly related to the slow value of the AMOC in this particular model.

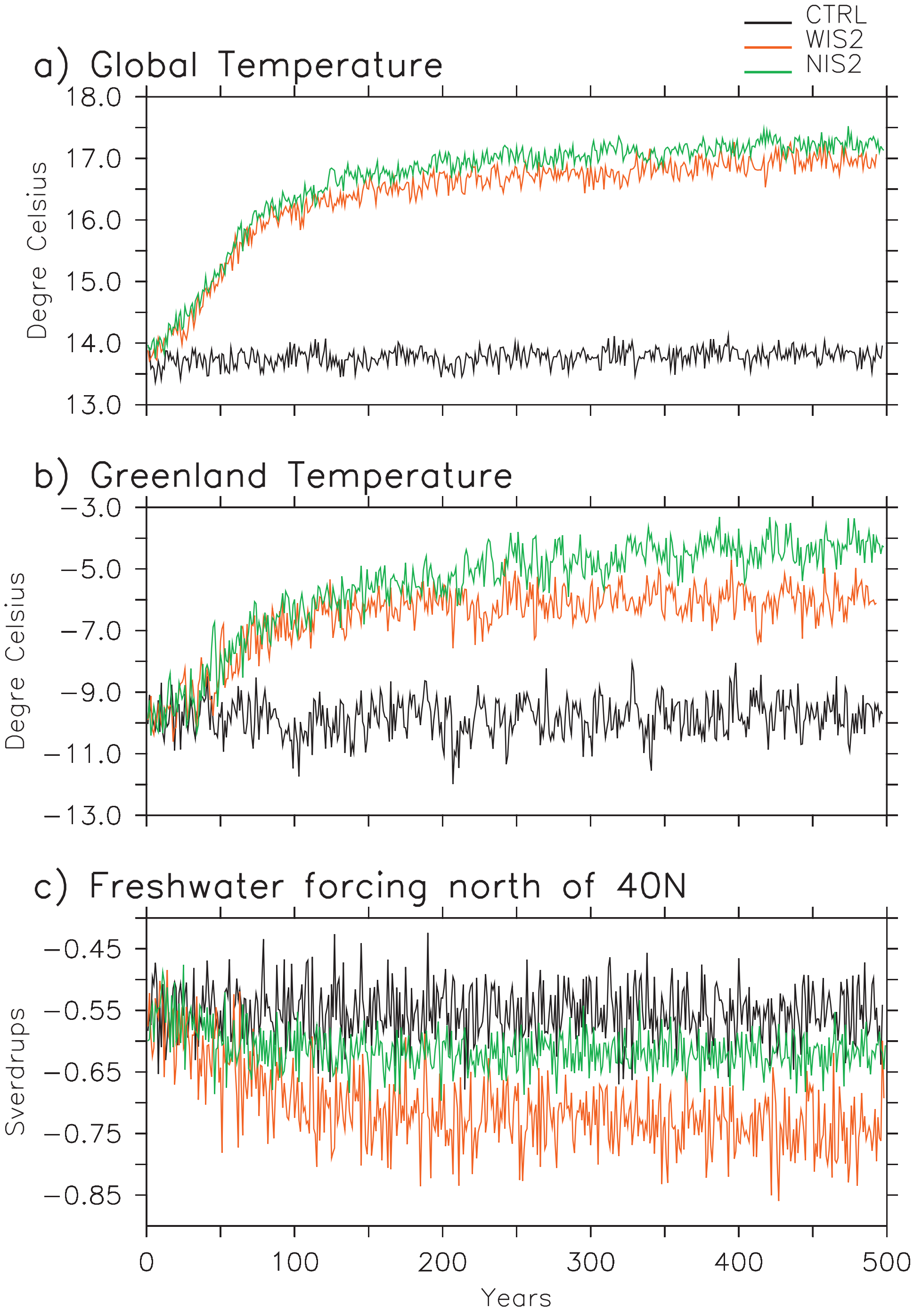

Plate 1. (a) Global temperature (in °C) for the three experiments. In black is CTRL, in red WIS2, and in green NIS2. (b) Greenland surface temperature (in °C). (c) Freshwater forcing in the Atlantic north of 40°N (in Sv).

Table 1. Density budget anomalies (in kg/m^3) in the convection sites region (north of 40°N and south of 80°N in the North Atlantic and Nordic Seas, see S2007 for details) due to different terms related to salinity (haline) or temperature (thermal) after 500 years. E-P-R represents evaporation minus precipitation minus runoff

	Haline					Thermal			
	Surface		Transport		Other Terms	Surface	Transport		Other Terms
	Sea-Ice	E-P-R	Gyre	Overturning		Net heat flux	Gyre	Overturning	
WIS2-CTRL	0.64	–0.08	2.27	–3.16	0.17	–3.33	–1.02	4.14	0.05
NIS2-CTRL	0.77	0.07	1.02	–1.52	0.05	–0.88	–0.37	0.68	0.21

In response to the decrease in oceanic heat transport in WIS2 compared to NIS2, the atmospheric heat transport reacts in the opposite way and increases its northward heat transport. However this increase does not totally compensate the decrease in oceanic heat transport. Thus at 40°N the total northward heat transport decreases by 0.15 PW. There is therefore a redistribution of energy in the mid and high latitude. This may influence the sea-ice cover in the North Atlantic, which enhances the relative cooling in WIS2 compared to NIS2 (S2006). Thus interaction with sea-ice is certainly a crucial amplification mechanism for the climatic impact of the AMOC on climate.

4.4. Implications Concerning the Hysteresis Loop Width

On Figure 1 the position of the different scenarios after 500 years adjustment in the hysteresis scheme is represented. These experiments are under global warming, and are not directly comparable to CTRL since surface conditions have changed. For example, due to global warming, sea surface temperature has increased, which has reduced the surface density compared to CTRL simulation if all other field were fixed. Thus, the position of the projection simulations on the hysteresis scheme stands for the position of the AMOC in future climate at 2 × CO$_2$. The position of each simulation is deduced from the following analysis.

The AMOC in NIS2 stabilizes to about 11 Sv under global warming. Thus NIS2 does not pass through the collapse threshold. Its position on the diagram is before this threshold. In WIS2 the AMOC has collapsed due to land-ice melting additional freshwater forcing of 0.13 Sv. Thus WIS2 passes the collapse threshold and its position is after this threshold. When freshwater forcing is suppressed, NISP recovers in 100 years. Thus NISP and NIS2 are not in the bi-stable part of the diagram but on the left part of it. We deduce from this analysis that the hysteresis width in IPSL-CM4 is less than 0.13 Sv

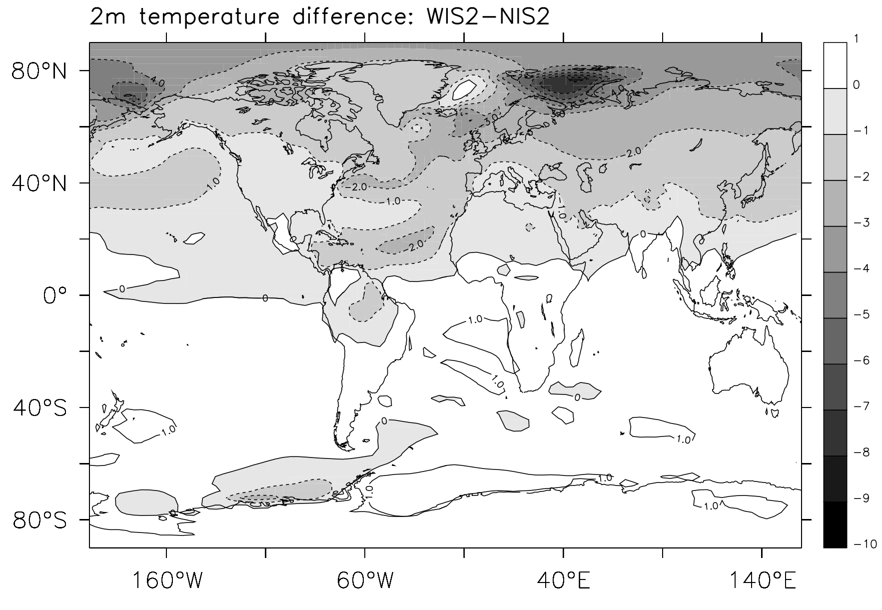

Figure 3. Difference in surface atmospheric temperatures in K for the last 30 years of simulation between WIS2 and NIS2.

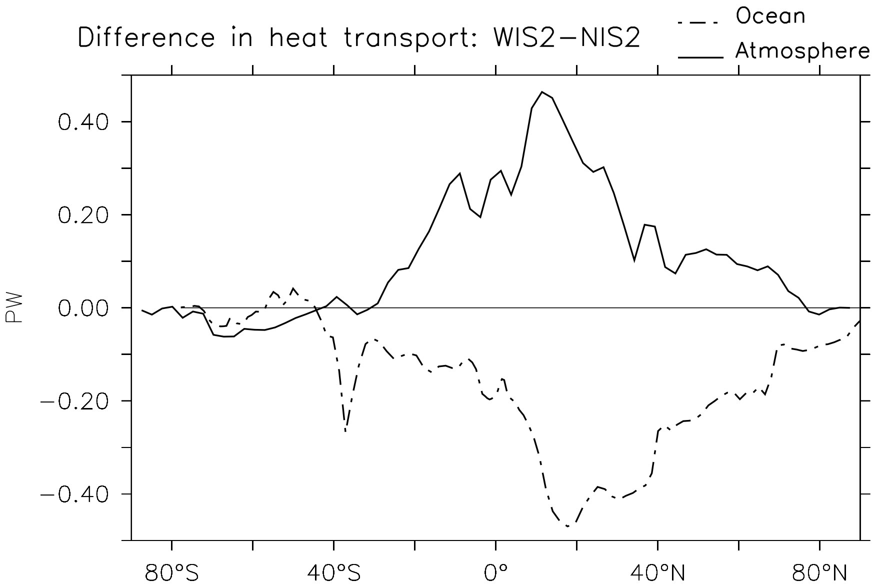

Figure 4. Difference between WIS2 and NIS2 in global meridional heat transport by the ocean (dashed line) and by the atmosphere (solid line) against latitude.

under global warming conditions. Nonetheless it is important to note that NISP and NIS2 are not equilibrated since the ocean needs thousands of years to reach its equilibrium. We therefore make the assumption that these experiments have nearly reached their equilibrium and that their behavior will not change.

5. DISCUSSION

Results from EMIC comparison have shown that the hysteresis loop width for present day conditions was about of 0.2 Sv (*Rahmstorf et al*., 2005). Here, using a comprehensive CGCM we have shown under global warming conditions that the width of the hysteresis loop does not exceed 0.13 Sv in the IPSL-CM4, if it exists. This result agrees with a study from *Vellinga et al*. (2002) where no bistable behavior for the AMOC has been found in the HadCM3 under present day condition. Our study considers multi-century simulations. This means that the steady state for the ocean is certainly not reached. Our results should be considered with caution in that regard. *Stouffer et al*. (2006) investigate the question of bistability of the present day state of the AMOC with different CGCMs on similar time scale. No clear consensus emerges except that some models do not exhibit such bistable state in present day climate. Nonetheless the experimental design of the "hosing experiment" with a freshwater input of 1 Sv during a century in the North Atlantic is certainly not long enough to induce an "off" mode of the AMOC. Longer experiments will be necessary to make that conclusion.

The land-ice melting prediction in the present study exceeds 0.1 Sv. It is higher than evaluations of IPCC (*Church et al*., 2001), but in the range of observations of past large discharge of glaciers (see section 2.2). The high value of melting found in this study is partly due to the crude parameterization of the ice-sheet melting with a fixed ice-sheet extension that does not consider refreezing processes and the change in ice-sheet geometry. However, by considering the uncertainty concerning the prediction of land-ice melting, our evaluation of the melting can be considered as an "extreme case" melting. This melting leads to a collapse threshold for the AMOC contrary to *Ridley et al*. (2005). One has to be careful since these results come from a particular model. Although the AMOC magnitude is in the range of IPCC CGCMs, the weakness of the AMOC is a matter of concern. It can lead this model to be more sensitive to additional freshwater than others.

The climatic impact of the AMOC collapse appears to be important in IPSL-CM4. It is explained by a change in northward oceanic heat transport, not compensated by atmospheric heat transport especially north of 40°N. This is certainly due to the fact that atmospheric transport north of 40°N is mostly due to transient eddies, contrary to tropical mechanisms. Moreover these results show that the climatic system develops a complex response to changes in oceanic heat transport that leads to a radiative adjustment (here notably due to sea-ice cover change). Such mechanism prevents a simple response where the atmosphere compensates the reduction in the oceanic heat transport.

6. CONCLUSION

In this study we have shown using a comprehensive CGCM that land-ice melting can strongly impact the AMOC under global warming in the coming centuries. The climatic impact of this change in the AMOC is centered on the Barents Sea and reaches 8 K due to sea-ice interaction. Moreover we have investigated the width of the hysteresis loop in a warmer climate and find this loop smaller than 0.13 Sv contrary to EMICs' evaluations but for present day climate.

These results are model dependent and it is important to note that our study uses a simple land-ice melting scheme within an idealized projection simulation. We strongly encourage other comprehensive CGCMs to investigate the impact of land-ice melting, in order to evaluate the uncertainty concerning the effect of this melting on the future of the AMOC. The possibility of an abrupt AMOC collapse remains an important issue for policy makers. Such a collapse could influence the North Atlantic climate and could impact the predicted global warming in this region. Contemporary observations of AMOC at different locations in the Atlantic (e.g. Ovide and Rapid projects) need to be pursued and reinforced in order to monitor possible changes in the AMOC. They also provide benchmarking for model-based estimates of any changes in this key climatic process.

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