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Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean

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[1] Increases in high-latitude river discharge over the 20th century and projected continued increases during the 21st century may have an impact on the Atlantic meridional overturning circulation (AMOC), which could feed back to regional and global climate. Although the general trend in high-latitude river discharge is positive, there is important geographical spread in the trends. While Eurasian rivers draining into the Arctic Ocean show positive trends over the 20th century, rivers draining into Hudson Bay show negative trends since 1964. Here the sensitivity of AMOC to changes in river discharge into Hudson Bay and the Arctic Ocean is studied with an intermediate-complexity Earth system model. It is found that ocean freshening originating from Arctic rivers is more effective in slowing down the AMOC than freshening originating from Hudson Bay rivers, given the same magnitude of freshening in both regions. The lesser impact of Hudson Bay river discharge on AMOC is the result of a buildup of freshwater anomalies in the Labrador Sea affecting the northward flow of the Gulf Stream. This work highlights that not only the freshening magnitude but the region where this freshening takes place is crucial for the AMOC response to altered river discharge climatology.

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1. Introduction

[2] Warming due to anthropogenic greenhouse gas emissions is expected to be most pronounced in the Arctic region [*Meehl et al.*, 2007]. Arctic warming and climate change is already underway as indicated by observations of sharp increases in Arctic surface air temperature in the late 20th century [*Johannessen et al.*, 2004], and 20th century trends in a range of climatological and ecological variables [*Hinzman et al.*, 2005; *Serreze et al.*, 2000]. One aspect of the Arctic climate that shows signs of change taking place is the cycle of freshwater between land, atmosphere and ocean [*White et al.*, 2007]. Changes to the Arctic freshwater cycle could ultimately affect the climate of regions outside the Arctic through its effect on the Atlantic meridional overturning circulation (AMOC).

[3] The AMOC is an integral part of the climate system through its role in the global system of surface and deep ocean currents called the global conveyor belt [*Broecker*, 1997]. The part of the conveyor belt that takes place in the North Atlantic is considered especially important for climate and is often referred to as the AMOC or the thermohaline circulation. The AMOC describes the strength of North Atlantic deep water formation, which involves the sinking of surface water masses brought northward with the Gulf Stream and formation of a southward deep water current. Disruption or weakening of AMOC and the associated northward transport of heat transport may cool the climates of the Northern Hemisphere [*Manabe and Stouffer*, 1997; *Vellinga and Wood*, 2002] and decrease nutrients and plankton stocks of the North Atlantic [*Schmittner*, 2005].

[4] The AMOC's sensitivity to freshwater surface forcing has been shown by many high and intermediate complexity general climate models (GCMs) [*Rahmstorf et al.*, 2005; *Stouffer et al.*, 2006]. Ocean circulation sensitivity to ocean freshwater surface flux is also supported by paleoclimate studies. A cold spell during Younger Dryas, at the end of the last deglaciation (~12.9–11.5 Ka before present), is believed to have been caused by an AMOC reduction triggered by a catastrophic freshwater release into the North Atlantic [*Broecker*, 2006]. The freshwater release originated from Lake Agassiz, which accumulated meltwater from the receding Laurentide ice sheet [*Broecker et al.*, 1989]. The inability to find geomorphologic evidence of the proposed Younger Dryas freshwater release has raised question on the cause of the Younger Dryas event [*Lowell et al.*, 2005].

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However, the absence of geomorphologic evidence may simply just indicate that the Laurentide meltwater was not released as a catastrophic flooding event but rather as a slow discharge release leaving few geomorphologic traces [*Meissner and Clark*, 2006]. A cooling event in the Holocene at 8.2 Ka before present (Ka B.P.), known as the 8.2 Ka event, may have been triggered by freshwater pulses from meltwater lakes by the Laurentide ice sheet [*Barber et al.*, 1999]. There is some evidence for the link between increased freshwater fluxes, AMOC slowdown and the 8.2 Ka cooling given by *Ellison et al.* [2006] who studied a deep sea sediment core in subpolar Atlantic. Thus both paleoclimate and modeling studies indicate that AMOC is sensitive to surface freshwater fluxes.

[5] The AMOC is particularly sensitive to freshwater flux changes in the North Atlantic [*Manabe and Stouffer*, 1997]. Late 20th century North Atlantic freshwater anomalies in turn are strongly linked to changes in the Arctic freshwater cycle [*Peterson et al.*, 2006] suggesting the importance of Arctic freshwater fluxes on AMOC. Indeed, modeling studies have demonstrated significant AMOC sensitivity to Arctic freshwater changes in the form of sea ice export [*Holland et al.*, 2001] and river discharge [*Rennermalm et al.*, 2006].

[6] The total freshwater outflow from the Arctic Ocean is 9200 km^3 a^{-1} [*Serreze et al.*, 2006]. The most important losses from the Arctic Ocean to the North Atlantic are: sea ice and freshwater export through Fram Strait (4700 km^3 a^{-1}) east of Greenland and the Canadian Archipelago (3200 km^3 a^{-1}) (see detailed references in the work by *Serreze et al.* [2006]). The freshwater flow through the Canadian Archipelago enters the North Atlantic west of Greenland via Baffin Bay and the Labrador Sea and the magnitude of the flow is particularly uncertain [*White et al.*, 2007]. Additional freshwater from this route to the North Atlantic is added by the Hudson Bay rivers (gauged measurements $\sim$714 km^3 a^{-1} [*Déry et al.*, 2005]). The Arctic Ocean freshwater outflow is almost in balance with the inflows [*Serreze et al.*, 2006]. The largest inflows of freshwater into the Arctic Ocean are: Arctic river discharge (3200 km^3 a^{-1}), Bering Strait throughflow (2500 km^3 a^{-1}), and precipitation minus evaporation (2000 km^3 a^{-1}) (see detailed references in the work by *Serreze et al.* [2006]). Note that all ocean freshwater fluxes in the work of *Serreze et al.* [2006] are determined with respect to 34.8 psu reference salinity. By comparing the magnitude of the high-latitude freshwater fluxes, it can be noted that river discharge into the Arctic Ocean and Hudson Bay are substantial components of the high-latitude freshwater budget.

[7] On average, high-latitude river discharge has increased over the 20th century [*Shiklomanov and Shiklomanov*, 2003] and these trends are projected to amplify in the 21st century [*Arnell*, 2005]. The late 20th century river discharge trends vary geographically [*McClelland et al.*, 2006]. Eurasian rivers have positive trends [*Peterson et al.*, 2002], North American rivers draining into the Arctic Ocean show no significant trend [*Déry and Wood*, 2005], and North American rivers draining into Hudson Bay show decreasing discharge [*Déry et al.*, 2005]. The geographical spread in trends combined with the finding that the AMOC sensitivity differs when subjected to freshwater forcing in either the North or South Atlantic [*Manabe and Stouffer*, 1997] raises the question: What is the relative sensitivity of the AMOC to river discharge into Hudson Bay and the Arctic Ocean?

[8] This work focuses on this question by extending a previous study by *Rennermalm et al.* [2006] and compares the AMOC sensitivity to riverine freshwater fluxes from Arctic Ocean and Hudson Bay rivers. We adopt the experimental method of *Rennermalm et al.* [2006] and analyze the results from multiple simulations brought to steady state. Steady state analysis can give insights into how a system functions. This knowledge can be valuable in interpreting short-term and transient changes. To perform the multiple simulations the University of Victoria Earth system climate model (UVic ESCM) was employed. The model's relative short computational time makes it an attractive alternative to other global climate models (GCMs).

2. UVic ESCM Modeling System

[9] To examine the sensitivity of the Atlantic meridional overturning circulation (AMOC) to high-latitude river discharge a model is needed that can simulate the complex ocean dynamics and ocean interactions with land and atmosphere without requiring large computational resources. Low computational demand is needed to produce many sensitivity experiments with different riverine inflow configurations for the analysis. Earth system models, sometimes referred to as intermediate complexity general climate models, are a group of models that balance realistic climate simulation with relative fast and low computational demand [*Petoukhov et al.*, 2005].

[10] The UVic ESCM has been successfully evaluated against the present-day climate [*Weaver et al.*, 2001] as well as several past climates [*Schmittner et al.*, 2002a, 2002b]. It has also been used extensively to study aspects of ocean and climate dynamics [e.g., *Cottet-Puinel et al.*, 2004; *Holland et al.*, 2001; *Meissner et al.*, 2003; *Saenko et al.*, 2002]. The model simulates the climate system by coupling an ocean model based on GFDL's MOM 2.0 ocean model [*Pacanowski*, 1996], a sea ice model [*Bitz et al.*, 2001], a land surface model based on a simplified version of MOSES [*Cox et al.*, 1999; *Meissner et al.*, 2003] and a simple atmospheric model [*Weaver et al.*, 2001]. The latter is the major simplification of UVic ESCM compared to fully complex GCMs. As an example, the fully complex GFDL atmosphere model (AM2) discretizes the atmosphere into 24 layers and simulates the atmospheric dynamics and the states of the energy and water balance [*Anderson et al.*, 2004]. The UVic ESCM's atmospheric model is a one layer energy-water balance model where the atmospheric dynamics are prescribed by forcing data (wind speed and wind stress). The advantage of UVic ESCM's simple atmospheric component is that it allows for relatively fast computational times, which is needed for a sensitivity analysis. With respect to the time frame used in this study (i.e., thousands of years) the atmospheric response is secondary in importance to the oceanic response in importance. The ocean component used in UVic ESCM also serves as the ocean component in several GCMs [*Stouffer et al.*, 2006]. Thus, using a model, such as UVic ESCM, with a simplified atmosphere is acceptable and a comprehensive ocean model is highly desirable.

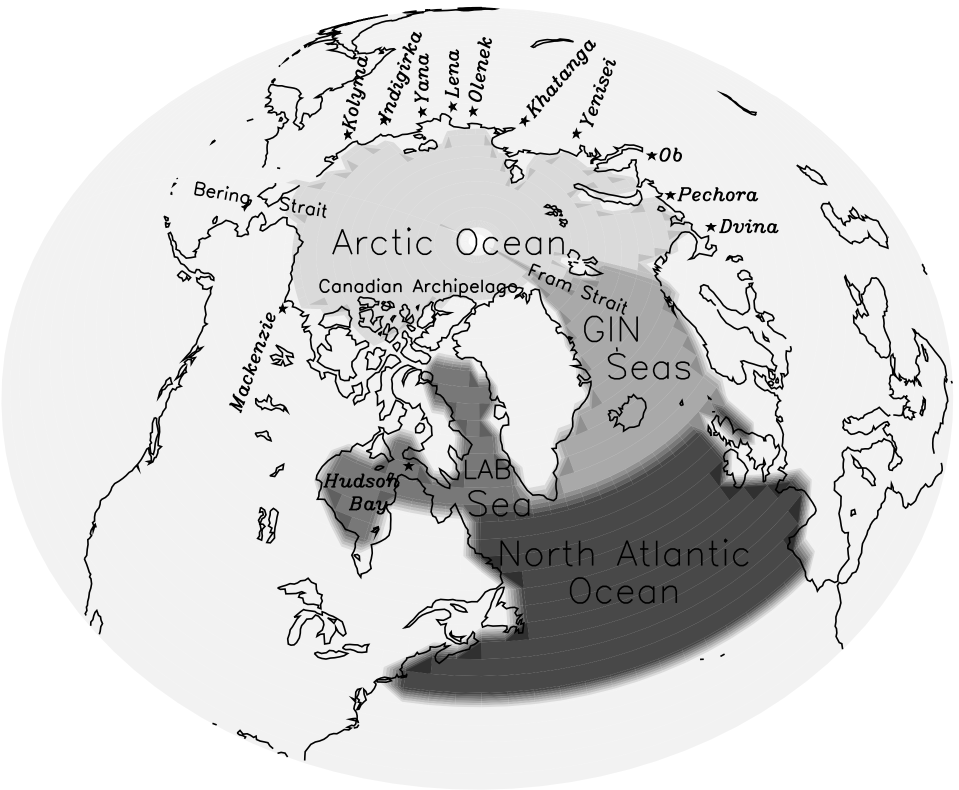

Figure 1. Map of the Northern Hemisphere with locations of rivers, seas, and oceans discussed in the text. The approximate locations of the river mouths where river discharge perturbations are made are marked with stars, and the river names are in italics. The discharge from all Hudson Bay rivers is lumped into one discharge point in Hudson Strait. The ocean gray scale shows the demarcation of the Arctic Ocean, Greenland-Iceland-Norwegian (GIN) seas, Labrador (LAB) Sea, and the North Atlantic Ocean, which were used in the data analysis and are discussed in the text. The North Atlantic "hosing" region falls between 50°N and 70°N, which is a 10° northward shift compared with the North Atlantic region presented on the map.

[11] In this study, we explore the sensitivity of AMOC to high-latitude river discharge by reconfiguring the UVic ESCM so that the original model's river discharge estimates are replaced with prescribed values for high-latitude river discharge. Replacing modeled river discharge with prescribed river discharge creates an imbalance in the global water balance. In the control simulation this imbalance was 611 km^3 a^{-1}, which is ~20% of the high-latitude river discharge estimated by *Serreze et al.* [2006]. To compensate for this gap, the global water budget is balanced by adjusting the surface salt flux for all ocean grid cells in the reconfigured model. Controlling the water balance by adjusting the ocean surface salt flux is a natural choice since the UVic ESCM does all ocean-land and ocean-atmosphere freshwater interactions through ocean surface salt flux (negative salt flux = positive freshwater flux).

[12] The potential pathways for riverine freshwater discharge to the North Atlantic are restricted in the model by the default closure of the passages through Bering Strait and Canadian Archipelago. River discharge into the Arctic Ocean may only reach the North Atlantic via Fram Strait and the Svalbard, Norway, passage. River discharge into Hudson Bay may only reach the North Atlantic via the Labrador Sea.

[13] In this study, the AMOC sensitivity is evaluated from a range of 33 UVic ESCM simulations with different configurations of prescribed river discharge. One of the configurations represents a steady state preindustrial climatology and is referred to as the control simulation. The control simulation's climatology is given by using preindustrial levels of carbon dioxide (i.e., 280 ppm). Furthermore, the control simulation is forced by monthly climatology (between 1948 and 2000) of wind stress and wind speed taken from the NCEP/NCAR Reanalysis (National Centers for Environmental Protection/National Center for Atmospheric Research) [*Kalnay et al.*, 1996]. The moisture advection option is activated in UVic ESCM to improve modeling of precipitation, sea surface salinity and surface temperature [*Weaver et al.*, 2001]. The moisture advection option requires input of monthly wind fields. These are calculated as a weighted average from NCEP/NCAR wind fields from a number of atmospheric levels where the weights are based on the specific humidity at each level to capture the decline in atmospheric moisture with height [*Meissner et al.*, 2003]. The river discharge is prescribed for 11 large Arctic rivers using the R-Arctic Net 2.0 data set [*Lammers et al.*, 2001] to construct monthly climatologically river discharge forcing data (Figure 1).

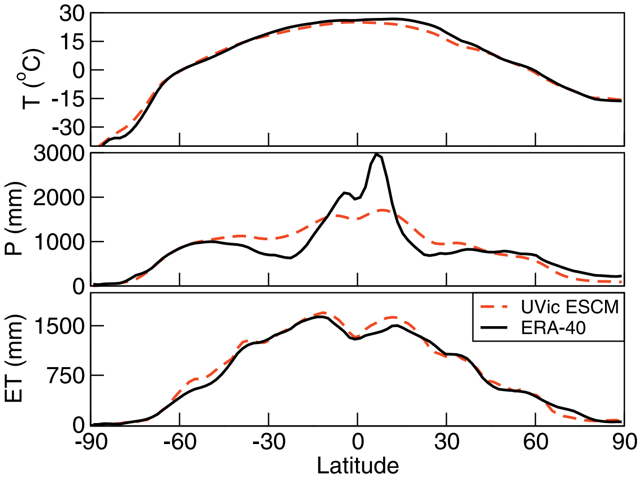

Figure 2. Comparison of zonal climatological conditions of annual values of temperature (T), precipitation (P), and evapotranspiration (ET) estimated with the UVic ESCM control simulation (preindustrial conditions) and ERA-40 reanalysis (1958–2001).

River discharge into Hudson Bay is prescribed using Environment Canada's Hydrometric Database as described by *Déry et al.* [2005]. The total river discharge was 2329 km^3 a^{-1} from the Arctic Ocean rivers and 727 km^3 a^{-1} from the Hudson Bay rivers that are lumped into one and released directly into Hudson Strait. The river discharge estimates for Arctic Ocean and Hudson Bay rivers are not adjusted for ungauged basins.

[14] The other 32 simulations are configured with the same setup and forcing data as the control simulation, but with a freshwater surface flux that varies in magnitude at three different regions: the Arctic Ocean drainage basin, the Hudson Bay drainage basin and the North Atlantic. The 32 simulations are in a steady state after running the model between 1000 and 6000 a after changing the freshwater surface flux relative to the control simulation. The sensitivity simulations fall into three categories:

[15] 1. Changes in river discharge from rivers draining into the Arctic Ocean. A total of 16 simulations are made with the discharge set to a fraction that ranges between 0 and 2 of the control simulation's Arctic Ocean river discharge. These correspond to changes in annual river discharge of ±2329 km^3 a^{-1}. These simulations were also presented by *Rennermalm et al.* [2006].

[16] 2. Changes in the discharge from rivers draining into Hudson Bay. A total of 12 simulations are made. In 9 of these the river discharge is changed between a reduction of -239 km^3 a^{-1} and increases up to +2329 km^3 a^{-1}. These changes were identical in magnitude to the changes made for the Arctic Ocean river discharge. Reducing the Hudson Bay discharge below a fraction of 0.9 (239 km^3 a^{-1}) of the control run's Arctic Ocean discharge results in negative discharge for some months. Therefore, in the remaining 3 simulations, the river discharge from Hudson Bay is set to a fraction between 0 and 0.5 of the control simulation's Hudson Bay discharge.

[17] 3. Changes in freshwater surface flux over the North Atlantic between 50°N and 70°N. A total of 13 simulations are made where the changes in freshwater flux varies between -1863 km^3 a^{-1} and +2329 km^3 a^{-1}. All changes are identical in relative magnitude as the changes made for the Arctic Ocean river discharge.

3. Results

3.1. UVic ESCM Climatology Simulation

[18] The value of the sensitivity studies made with UVic ESCM depends on the model's ability to simulate the climate system and its response to change. This can be determined by evaluating its capacity to simulate a known climate state such as the present-day climatology. Here this is represented by the European Centre for Medium-Range Weather Forecasts 40 a reanalysis (ERA-40) data set (1958–2001) (ECMWF 40: A re-analysis, 2004, available at http://data.ecmwf.int/data/d/era40_daily) [*Uppala et al.*, 2005], and the *World Ocean Atlas 2001* (WOA-01) [*Conkright et al.*, 2002]. The UVic ESCM control simulation is compared with present-day climatology despite the fact that the control simulation represents a preindustrial climate since it is in steady state with 1850s level of atmospheric carbon dioxide concentration.

[19] The UVic ESCM represents well the general characteristics of the atmospheric climate (Figure 2). In the Northern Hemisphere the model captures the northward decrease of temperature, precipitation and evapotranspiration. The tropical precipitation estimates compare poorly. The poor agreement is not an indication of poor UVic ESCM performance rather it reflects ERA-40's known overestimation of tropical precipitation stemming from problems with determining humidity from satellite observations [*Troccoli and Kållberg*, 2004].

[20] The model captures the general characteristics of ocean currents in the North Atlantic. The Gulf Stream, the North Atlantic Drift, the East Greenland, the Labrador currents and the sub polar gyre are represented (Figure 3). However, the Norwegian Current is not represented and the Gulf Stream's departure from the North American continent is about 10° north of its actual departure point at Cape Hatteras at 35°N. These shortcomings are common features of low-resolution climate models [*Weaver et al.*, 2001]. The lacking Norwegian current and the southward shift of the AMOC reduce the oceanic heat transport into the Greenland-Iceland-Norwegian (GIN) Seas and causes a cold climate bias in the GIN Seas resulting in a too extensive GIN sea ice cover. The general features of AMOC are well depicted (Figure 4). The maximum overturning is 19 Sv (6.0×10^5 km^3 a^{-1}) at 40°N (Figure 4), which compares well with other estimates that range between 12 Sv (3.8×10^5 km^3 a^{-1}) and 26 Sv (8.2×10^5 km^3 a^{-1}) [*Stouffer et al.*, 2006]. The model represents the major water masses in the North Atlantic. North Atlantic Deep Water (NADW) mostly forms between 58°N and 63°N in the Irminger and Iceland basins and in the Norwegian and Labrador Seas. The deep water is transported southward between 1500–2500 m depth and below 2500 m Antarctic Intermediate Water is found.

[21] A comparison of the control simulation and WOA-01 shows that UVic ESCM represents with accuracy the salinity and temperature profiles in the North Atlantic (including GIN Seas and the Labrador Sea) and the Arctic

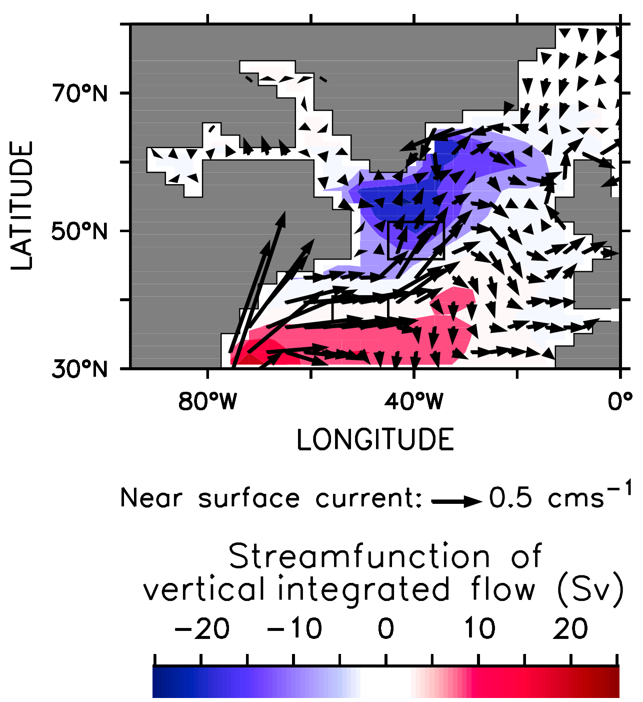

Figure 3. North Atlantic near-surface currents at 81.5 m depth (arrows) and regions of downwelling (shaded, negative values) and upwelling (shaded, positive values) estimated with UVic ESCM control simulation. Upwelling and downwelling are determined by the stream function of vertical integrated flow between 200 and 2000 m depth. Two boxes centered at 40°N, 50°W and 50°N, 40°W demarcate regions used to study the sensitivity of surface current strength to freshwater forcing.

Ocean (Figures 5 and 6). The model shows the strong stratification of the Arctic Ocean where a fresh, cold surface layer is overlying a more saline, warmer water mass. The fresh, cold surface water of the Arctic Ocean is in sharp contrast with the much more saline, warm waters of the North Atlantic.

[22] Further comparisons show that UVic ESCM reasonably captures the observed sloping steric height surface from the peak in the equatorial Atlantic to higher latitudes (Figure 7). The steric height is the vertical integration of a reference density and the difference in volume between a unit water mass at temperature T and salinity S and the unit water mass at temperature 0°C and salinity 35 psu down to a reference depth [e.g., *Tomczak and Godfrey*, 1994]. The steric height will increase (decrease) when the water becomes fresher and/or warmer (saltier and/or colder) and can be considered a representation of sea level height.

3.2. Freshwater Sensitivity Experiments

[23] The above comparisons show that the general characteristics of climate, ocean circulation and ocean water properties in the North Atlantic are well represented by UVic ESCM. The model's capacity to represent the AMOC sensitivity to riverine freshwater discharge is more difficult to evaluate. One way to analyze this feature is to compare the sensitivity experiments with UVic ESCM to similar experiments made with other models. Many modeling studies of AMOC sensitivity to freshwater forcing have been made with so-called hosing experiments where the surface freshwater flux of the North Atlantic has been varied [e.g., *Rahmstorf et al.*, 2005; *Stouffer et al.*, 2006].

[24] The North Atlantic hosing experiment made with UVic ESCM shows the typical response seen in other models [e.g., *Rahmstorf et al.*, 2005; *Stouffer et al.*, 2006]. The response is characterized by a gradual reduction and eventual shutdown of the AMOC with increasing freshwater flux input (Figure 8). Thus it is concluded that UVic ESCM does a realistic representation of the climate and ocean system, and also captures the expected response of altered ocean surface freshwater fluxes.

[25] The AMOC sensitivity to river discharge has different characteristics depending on the region of the river discharge forcing and on whether the freshwater flux is increased or decreased compared to the control simulation (Figure 8). Decreasing freshwater flux by altering Hudson Bay river discharge has a greater impact on intensifying the AMOC compared to altering Arctic Ocean rivers. The opposite pattern is seen when freshwater forcing is increased. Increases in Arctic Ocean river discharge result in a strong reduction in AMOC. The freshwater magnitude that results in AMOC shutdown is 800 km^3 a^{-1} less when the additional freshwater comes from Arctic Ocean compared to when it originates form Hudson Bay.

3.3. General Mechanisms Controlling AMOC

[26] Before possible explanations to the AMOC freshwater sensitivity dependence on location of freshwater forcing are examined, the general mechanisms controlling AMOC are explored. The steric height anomaly difference between the equatorial and northern Atlantic has been suggested as a

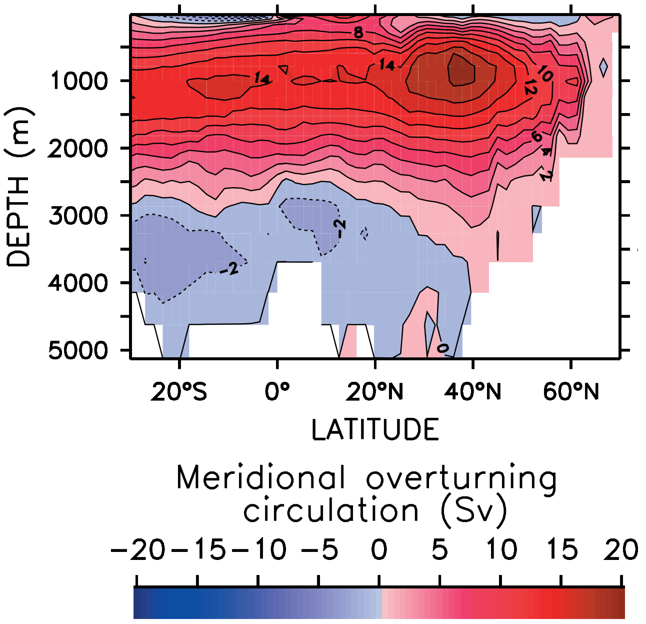

Figure 4. North Atlantic meridional overturning circulation (AMOC) estimated with the UVic ESCM control simulation. Maximum AMOC is at 1000 m depth at 40°N. Formation of North Atlantic Deep Water (NADW) takes place between 40°N and 60°N and is transported southward at 1500–2500 m depth.

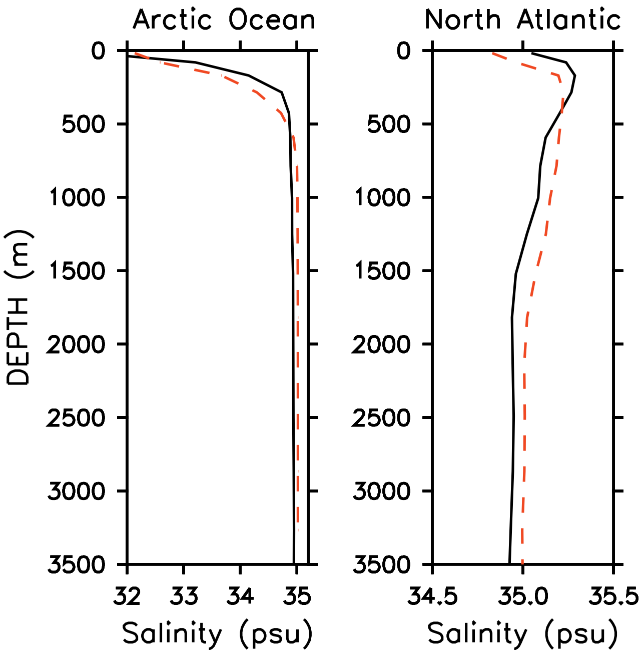

Figure 5. Salinity profiles in the Arctic Ocean and the North Atlantic estimated with the UVic ESCM (dashed curves) and the *World Ocean Atlas 2001* (solid curves).

possible driving force for the AMOC [*Hughes and Weaver*, 1994; *Thorpe et al.*, 2001]. This is confirmed by this work where a strong linear relationship is observed between AMOC and the steric height anomaly difference between the steric height peak off the coast of Florida (calculated as the average steric height in a box centered at 26°N, 70°W) and the steric height in the region of most downwelling (calculated as the average steric height in a box centered at 54°N, 42°W) (Figure 9). This steric height anomaly difference is hereafter referred to as the steric height difference.

[27] The steric height controls the AMOC by influencing the geostrophic ocean currents that are, in turn, driven by pressure gradients set up by the sea level differences determined by the steric height. In the equatorial Atlantic, the warm, dense water results in an elevated sea level compared to the colder waters in the North Atlantic. The sloping sea level from the subtropical to the subpolar Atlantic is part of the driving force of the Gulf Stream Current.

[28] This study verifies that the steric height difference affects the strength and the location of the Gulf Stream and its northern extension, the North Atlantic Drift. Here, this is illustrated by analyzing the effect of Atlantic steric height difference on the Gulf Stream strength at two locations (locations are shown in Figure 3). In the control simulation, the Gulf Stream has a strong eastward component in region 1 (centered at 40°N, 50°W) and a weaker northward component in region 2 (centered at 50°N, 40°W). Increasing the freshwater surface flux and thus reducing the Atlantic steric height difference reduces the strength of the eastward Gulf Stream component in region 1 (Figure 10). In experiments with decreased freshwater flux the eastward Gulf Stream strength is largely independent of Atlantic steric height difference. Contrary to region 1, in region 2 (50°N, 40°W) the Gulf Stream strength is largely independent of the Atlantic steric height difference in experiments with increased freshwater flux. However, in response to decreasing the freshwater flux a northeastward current develops in region 2 that increases linearly with increasing Atlantic steric height difference. Thus increasing freshwater flux reduces the Gulf Stream's eastward component, limiting the flow toward the deep water formation regions.

3.4. Explanation of the AMOC Sensitivity to Freshwater Forcing Region

[29] Increased freshwater forcing from the high northern latitudes reduces the slope of the steric height from the subtropical to the subpolar Atlantic. The smaller slope slows down the Gulf Stream and the North Atlantic Drift's northward transport of warm, saline water, reducing the buoyancy of the waters in the subpolar Atlantic. The steric height gradient exhibits a linear relationship with the AMOC (Figure 9), but not with the changes to river discharge (Figure 11). Changes of similar magnitude in river discharge applied at different regions yields disparate AMOC responses. The AMOC intensifies much more if the Hudson Bay riverine freshwater discharge is decreased compared to Arctic Rivers.

[30] The high-latitude riverine freshwater discharge affects the Atlantic steric height surface in the polar, subpolar and the subtropical region. However, the effect on the polar and subpolar region's steric height is distinctly different depending on the location of freshwater forcing (Figure 11). Hudson Bay freshening lowers the steric height by East Greenland and elevates the steric height in a region around 50°N, 40°W relative to Arctic Ocean freshening. On the other hand, Hudson Bay freshwater reduction lowers the

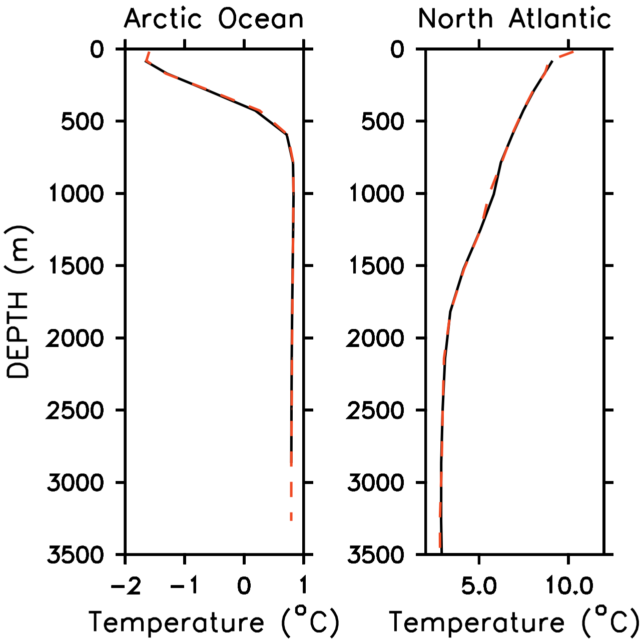

Figure 6. Ocean temperature profiles in the Arctic Ocean and the North Atlantic estimated with the UVic ESCM (dashed curves) and the *World Ocean Atlas 2001* (solid curves). The two estimates are almost identical, and the two lines are hard to distinguish from each other.

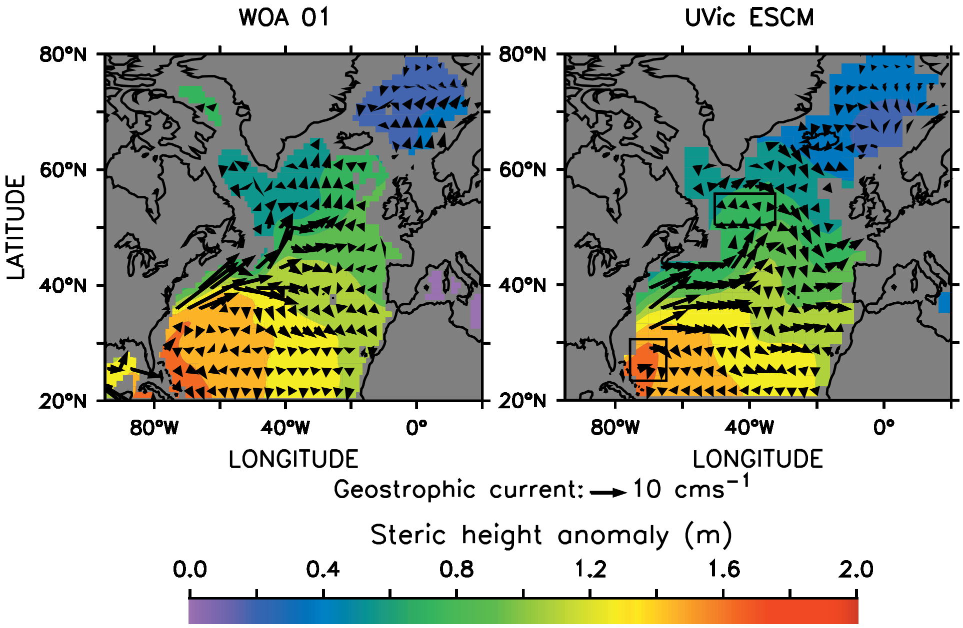

Figure 7. Steric height anomaly (shaded) and geostrophic currents (arrows) estimated with UVic ESCM and *World Ocean Atlas 2001* (WOA 01). The steric height anomaly and geostrophic currents are calculated with a reference depth of 1000 m. The boxes in the right plot outline the regions that are used in the calculation of steric height difference between the South and North Atlantic.

Labrador Sea steric height and elevates the GIN Sea steric height relative to Arctic Ocean freshwater reductions. The different response in steric height anomaly has important consequences for the currents connecting the Labrador Sea to the North Atlantic (Figure 12), and influences the buildup of freshwater anomalies in the Labrador Sea (Figure 13).

[31] Hudson Bay freshening elevates the Labrador Sea steric height surface, which reduces the gradient between the steric height in the Labrador Sea and in the North Atlantic. In the control simulation the steric height surface in the North Atlantic is higher than in the Labrador Sea. The gradient reduction weakens the east Greenland and the Labrador currents strength (Figure 12, left plot). Freshening of the Labrador Sea results in less exchange of the relative fresh water masses from the Labrador Sea with the North Atlantic compared to when freshening is applied at the Arctic Ocean. No similar freshwater anomaly is built up when freshwater forcing is altered at the Arctic Ocean rivers (Figure 13). Thus freshwater changes in the Arctic Ocean directly affect the salinity of the deep water formation regions while a significant part of the freshwater changes in Hudson Bay builds up in the Labrador Sea.

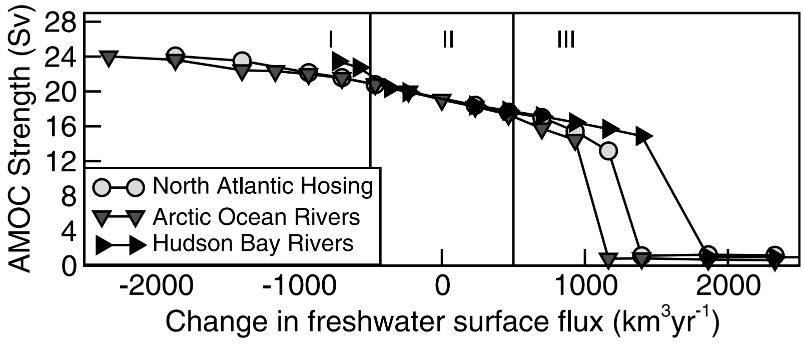

Figure 8. Maximum Atlantic meridional overturning circulation (AMOC) sensitivity to changes in freshwater surface flux made at three different locations: North Atlantic Ocean surface between 50° and 70°N, Arctic Ocean rivers, and Hudson Bay rivers. The change in freshwater surface flux is the change relative to the control simulations; that is, zero change in freshwater surface flux corresponds to the control simulation. The sensitivity of AMOC to changes in freshwater surface flux has three characteristic regimes. In regime II, AMOC is a linear function of changes in freshwater surface flux and is independent of the location of the forcing. In regimes I and III, AMOC is a nonlinear function of changes in surface flux with a distinct dependence on location.

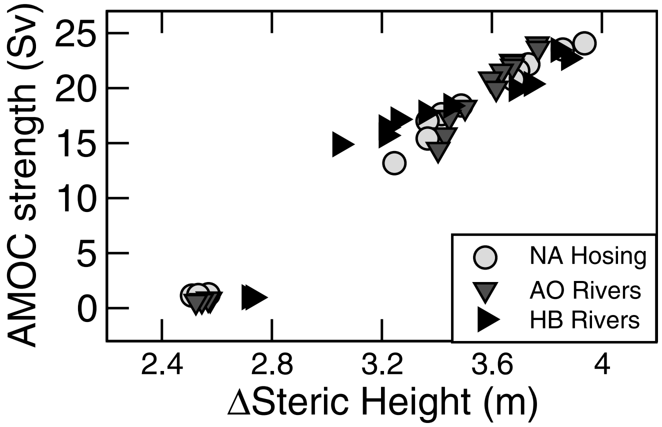

Figure 9. Linear relationship between Atlantic meridional overturning circulation (AMOC) strength and the steric height anomaly difference between South and North Atlantic forced by freshwater changes in the North Atlantic (NA), Arctic Ocean (AO), or the Hudson Bay (HB). The steric height anomaly difference is the difference between the steric height anomaly peak off the coast of Florida (calculated as the average steric height anomaly in a box centered at 26°N, 70°W) and the steric height anomaly in the region of deep water formation (calculated as the average steric height anomaly in a box centered at 54°N, 42°W).

[32] Decreases in Hudson Bay river discharge lower the steric height surface that enhances the steric height gradient between the Labrador Sea and the North Atlantic. This weakens the Labrador current and enhances the East Greenland current inflow into the Labrador sea (Figure 12, right plot). As a result a negative freshwater anomaly builds up in the Labrador Sea compared to when the freshening comes from the Arctic Ocean (Figure 13). Since the Labrador Seawater is fresher than the North Atlantic water the reduction in water mass exchange with the North Atlantic brings less freshwater to the deep water formation regions. When the freshening is coming from the Arctic Ocean the water mass exchange from the Labrador Sea is stronger and relatively more freshwater reaches the deep water formation regions, enhancing the effect of discharge increases on reducing AMOC.

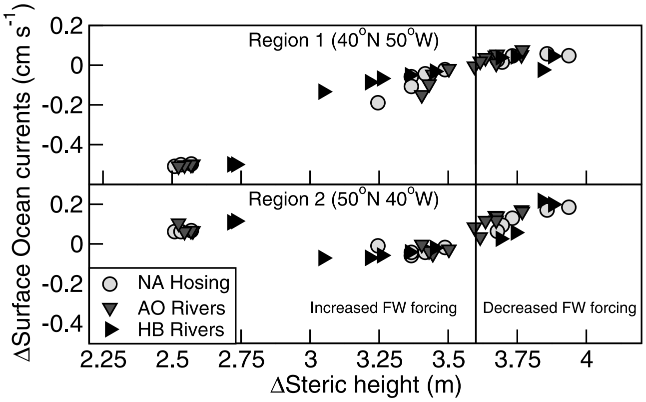

Figure 10. Change in surface ocean current strength versus the steric height anomaly difference between South and North Atlantic. The vertical line separates data from experiments with decreasing and increasing freshwater (FW) forcing. The outline of regions 1 and 2 is shown in Figure 3. The change in surface ocean current strength is the change in current strength relative to the control simulations current strength.

4. Discussion

[33] The relative sensitivity of AMOC to changes in river discharge into Hudson Bay versus the Arctic Ocean was studied with an intermediate complexity Earth system model. In accordance with previous works by *Hughes and Weaver* [1994] and *Thorpe et al.* [2001] this study confirms that the north-south difference in Atlantic Ocean steric height is an important driver of the AMOC. It was shown how the steric height gradient controls the thermohaline component of the Gulf Stream and thus the transport of saline, warm waters northward to the deep water formation

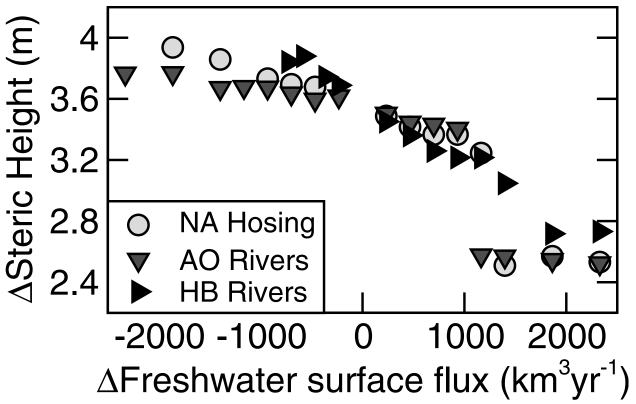

Figure 11. Sensitivity of the south-north difference in steric height anomaly in the Atlantic to changes in freshwater surface flux. The change in freshwater surface flux is the change relative to the control simulations; that is, zero change in freshwater surface flux corresponds to the control simulation.

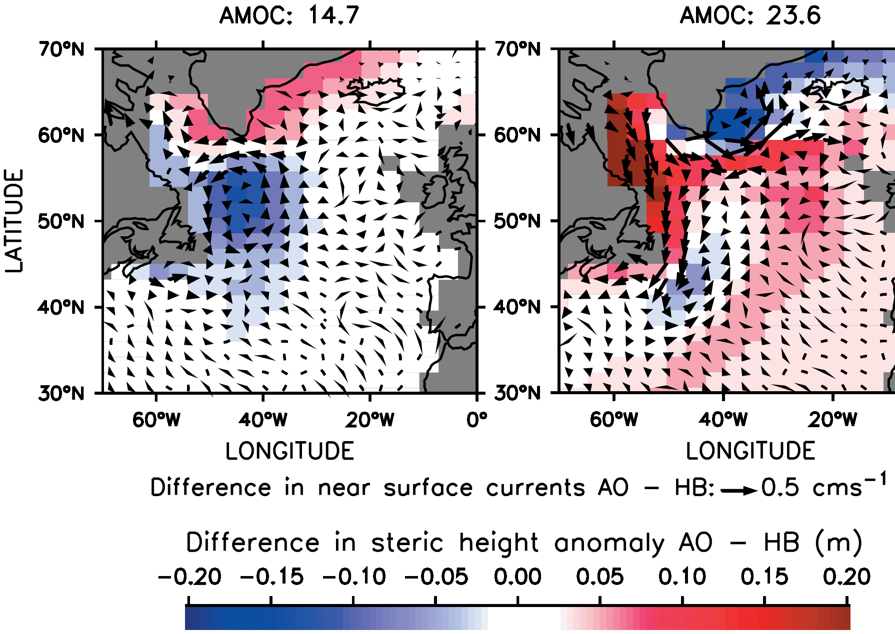

Figure 12. Impact of freshwater forcing region on steric height anomaly (shaded areas) and near-surface currents at 81.5 m depth (arrows). The steric height anomaly and the near-surface currents in the figure are the differences between the Hudson Bay (HB) freshwater flux experiment and the Arctic Ocean (AO) freshwater experiment. Both the Hudson Bay and the Arctic Ocean experiments had comparable AMOC strength but employed different magnitudes of riverine freshwater forcing. The response of the steric height anomaly and near-surface currents are shown for (a) an AMOC slow-down situation (AMOC, 14.7 Sv) due to increased riverine freshwater flux and (b) an AMOC intensification situation (AMOC, 23.6 Sv) due to decreased riverine freshwater flux.

regions. Although there is a linear relationship between AMOC and the Atlantic steric height difference, a similar relationship is not observed between steric height and changes to freshwater forcing. Instead, we showed that the AMOC sensitivity to changes in freshwater forcing is highly dependent on the region where the freshwater forcing was altered. For example, much more Hudson Bay riverine discharge than Arctic Ocean discharge is needed to reduce the AMOC. The reverse is true for reductions in riverine discharge; a small reduction in the Hudson Bay region was more effective in intensifying the AMOC than a small reduction in the Arctic Ocean region. We found that the importance of the region of altered river discharge was connected to distinctly local changes in steric height surface. When Hudson Bay river discharge was altered the steric height of the Labrador Sea changed and disconnected the Labrador Sea from the North Atlantic compared to when discharge was altered at Arctic Ocean rivers. The disconnection of the Labrador Sea from the North Atlantic resulted in a buildup of a freshwater anomaly in the Labrador Sea. The anomaly buildup resulted in a greater AMOC intensification and lesser AMOC reduction. Thus the relative isolation of the Labrador Sea explains how changes in Hudson Bay discharge could result in the same AMOC as changes in Arctic Ocean river discharge, despite the fact that Hudson Bay river discharge reductions were smaller and the river discharge increases were greater. This work adds to an expanding literature on AMOC sensitivity to changes in riverine discharge [*Otterå et al.*, 2003, 2004; *Rennermalm et al.*, 2006], where none of the previous studies compared the relative sensitivity of Hudson Bay discharge to Arctic Ocean discharge as done here.

[34] Some uncertainty about the results is introduced by the model's simulation of too extensive sea ice extent in the Norwegian Sea and lack of passages through Bering Strait and the Canadian Archipelago. The uncertainty could not easily have been rectified by using another model. More comprehensive GCM models that potentially could improve the simulation are unsuitable because of their computational demands. Although some GCMs may better simulate Norwegian sea ice extent [*Parkinson et al.*, 2006], GCMs too suffer from model shortcomings biasing the result. For example, many GCMs do not allow for passage through the Canadian Archipelago, and modeling of Bering Strait freshwater throughflow, sea ice extent and salinity distribution in the Arctic Ocean is highly variable between the models and sometimes compare poorly with observations [*Holland et al.*, 2007].

[35] Although river discharge is a major freshwater source to high-latitude oceans, the 20th century changes in riverine freshwater discharge is minor compared to other ocean freshwater sources. *Peterson et al.* [2006] studied 20th century freshwater anomalies from several of these sources to explain a recent freshening of the North Atlantic Ocean [*Curry et al.*, 2003]. They found that the increased North Atlantic freshwater storage in the latter part of the 20th century can be explained by Arctic sea ice melt and changes in P-E in both the Arctic and the North Atlantic. The dominance of sea ice as a freshwater source is reflected in a comparison of the recent anomalies. In the 1990s the

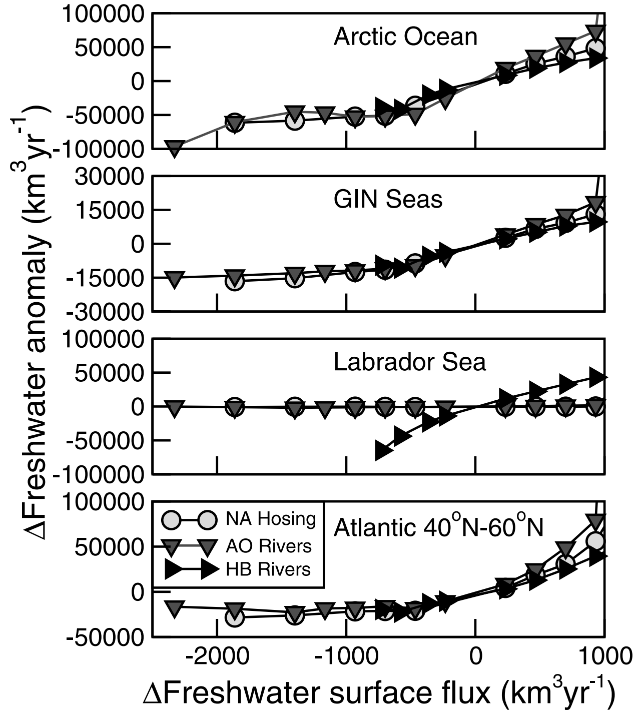

Figure 13. Change in freshwater anomaly in different high-latitude seas and oceans in response to change in freshwater surface flux at either the North Atlantic surface, Arctic Ocean rivers, or Hudson Bay rivers. The outline of the Arctic Ocean, GIN seas, Labrador Sea, and the North Atlantic can be found in Figure 1, and the freshwater anomaly is calculated from the surface to the ocean bottom. The change in freshwater surface flux and freshwater anomaly is the change relative to the control simulations; that is, zero change in freshwater surface flux and freshwater anomaly corresponds to the control simulation.

average sea ice melt anomaly was 817 km^3 a^{-1}, which is larger than the combined high-latitude P-E anomaly (608 km^3 a^{-1}), and much larger than high-latitude river discharge anomaly (104 km^3 a^{-1}) and Greenland ice sheet melt anomaly (81 km^3 a^{-1}). Although the present river discharge anomaly is small compared to sea ice and P-E anomalies, the importance of the various sources may change in response to global warming.

[36] There is a large potential for significant changes to the high-latitude freshwater surface fluxes in response to global warming. Arctic Sea ice is estimated to store ~10,000 km^3 freshwater [*Serreze et al.*, 2006]. In the latter part of the 20th century, the sea ice cover has both diminished in extent [*Parkinson et al.*, 1999] and in thickness [*Rothrock et al.*, 1999]. Climate models predict a continued loss of sea ice in response to global warming [*Berner et al.*, 2005]. The Greenland ice cap is the largest ice mass in the Arctic and climate models predict a sea level rise of 4 cm in response to melting due to 21st century global warming [*Berner et al.*, 2005]. At present river discharge from Arctic Ocean and Hudson Bay rivers contribute ~5250 km^3 a^{-1} riverine freshwater to the high-latitude ocean and seas [*Shiklomanov and Shiklomanov*, 2003]. In response to global warming the river discharge might increase by as much as 31% [*Arnell*, 2005], which corresponds to an increase of 1575 km^3 a^{-1}.

[37] The present and possible future freshwater anomalies from river discharge are small compared to other sources of ocean freshwater. This raises the question about the importance of studying AMOC response to river discharge changes. However, there is an important fundamental difference between river discharge and melting sea ice and glacier ice as sources of ocean freshwater. Sea ice and glacier ice stores a finite amount of freshwater. In response to global warming, a large fraction of the ice mass may be released to the ocean as freshwater, but the release will stabilize when the ice mass equilibrates with a warmer climate. In contrast, increased river discharge reflects an acceleration of the Arctic hydrological cycle that will continue to supply the ocean with anomalously high riverine freshwater. While obviously model-dependent, our modeling study projects that a sustained increase of riverine discharge of 1575 km^3 a^{-1} could result in a collapse of the AMOC regardless of where it originated (i.e., from Hudson Bay or the Arctic Ocean). However, in our control simulation river discharge is less than other estimates [*Shiklomanov and Shiklomanov*, 2003]. If the future river discharge would be 31% larger than the control simulation river discharge, it could only lead to the AMOC collapse if the source of the freshwater were the Arctic Ocean rivers.

[38] In our study, the river discharge increase leading to AMOC shutdown is less than in the work by *Rahmstorf et al.* [2005]. *Rahmstorf et al.* [2005] present the hysteresis response of AMOC to ocean surface freshwater forcing for 11 intermediate complexity climate models. Their study is similar to ours because they also analyze the steady state AMOC response to sustained changes in freshwater flux. Although the amount of freshwater forcing needed for AMOC shutdown varies between the 11 models, it is greater than the 1575 km^3 a^{-1} (0.05 Sv) that caused an AMOC shutdown in our study. There are two important factors that can explain why our study shows greater AMOC sensitivity to freshening. First, the amount of freshwater needed to shut down AMOC is relative to a baseline simulation representing a certain climate. In our study the baseline climate is determined by present-day wind climatology and 1850s atmospheric carbon dioxide concentration while the baseline climate of *Rahmstorf et al.* [2005] is the present-day climate. The UVic ESCM model is featured as one of the 11 models of *Rahmstorf et al.* [2005], which enables us to compare the two studies in detail. *Rahmstorf et al.* [2005] give the UVic ESCM baseline AMOC strength as ~25 Sv (8.2×10^5 km^3 a^{-1}) while it was only 19 Sv (6.0×10^5 km^3 a^{-1}) in this study. Hence, because the baseline climate is different, more freshwater needs to be added to the former study to reduce the AMOC strength to the same level. Second, *Rahmstorf et al.* [2005] apply freshwater forcing to a region in the Atlantic Ocean between 20°N and 50°N. This region is south of the regions where freshwater fluxes changes are made in this study, which demonstrate our point that AMOC strength is sensitive to the region where freshwater changes take place.

[39] In this specific model study, the AMOC strength dependence on the region where riverine freshwater fluxes were altered may be independent of the type of freshwater source. For example by using the same model and a similar

experiment setup as here, the AMOC response to river discharge changes within the Arctic Ocean was found to be a function of the magnitude of the freshwater flux and independent on the location of the river mouth where those changes were applied [*Rennermalm et al.*, 2006]. The model's long integration time and coarse resolution may dilute intra regional heterogeneity in freshwater surface flux. Therefore it is hypothesized that the AMOC sensitivity to region of freshwater forcing changes, shown in the modeling study here, may apply not only to changes in river discharge but any changes to freshwater storage such as P-E or sea ice.

[40] The importance of the region where ocean freshening originates from is important for interpreting present changes in high-latitude freshwater fluxes, in light of past changes. It is believed that the cooling event in the Younger Dryas was caused by an AMOC slow down triggered by meltwater release from the receding Laurentide ice sheet. The meltwater release is estimated to $\sim$9500 km^3 [*Leverington et al.*, 2000], which is roughly three times the annual river discharge into the Arctic Ocean (3200 km^3 a^{-1} [*Serreze et al.*, 2006]). The actual freshwater flux is unknown and depends on the duration of the flood [*Meissner and Clark*, 2006]. However, there is a debate on where the meltwater discharged, the prevailing theory has been that the discharge was routed via eastern North America to the North Atlantic [*Broecker*, 2006]. Our work suggests that had this freshwater anomaly originated from the Arctic Ocean a lesser amount would have been required to cause AMOC shut down. This is in contradiction with *Peltier et al.* [2006], who showed that AMOC responded similarly to a freshening from Mackenzie River outflow or Hudson Strait outflow. However, *Peltier et al.* [2006] examined the transient AMOC response to a freshening pulse, whereas we studied the steady state response to a new climate state with sustained altered Arctic riverine freshwater fluxes, which may explain the differences between the studies.

[41] Today, the Laurentide ice sheet is long ago melted and the freshwater sources with the potential to regulate the AMOC come from the North. Significant increase in Arctic Ocean freshwater storage, and export to the North Atlantic is projected for the 21st century by a range of GCMs [*Holland et al.*, 2007]. Few of these GCMs allow for Canadian archipelago throughflow, west of Greenland, and channel most of the increased freshwater export through the Fram strait, east of Greenland [*Holland et al.*, 2007]. In reality freshwater from melting sea ice and glacier ice and increased river discharge could flow toward the North Atlantic both east and west of Greenland. One model study found that when both these pathways are represented the increased freshwater export occurs through the Canadian Archipelago [*Koenigk et al.*, 2007].

[42] The work presented here suggests that the freshwater anomaly partitioning between east and west Greenland is crucial for the sensitivity of AMOC. Therefore it is important to understand the pathways of 21st century freshwater export from high latitudes to the North Atlantic. Given the large variability between models in representing Arctic Ocean freshwater budget and fluxes [*Holland et al.*, 2007], it is recommended that experiments similar to *Koenigk et al.* [2007] be undertaken with other GCMs. Such studies could enhance our understanding of the impacts of Arctic freshwater budget changes on AMOC in the 21st century.

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References

Anderson, J. L., et al. (2004), The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations, *J. Clim.*, *17*, 4641–4673.

Arnell, N. W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean, *J. Geophys. Res.*, *110*, D07105, doi:10.1029/2004JD005348.

Barber, D. C., et al. (1999), Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, *400*, 344–348.

Berner, J., et al. (2005), *Arctic Climate Impact Assessment: Scientific Report*, Cambridge Univ. Press, Cambridge.

Bitz, C. M., M. M. Holland, A. J. Weaver, and M. Eby (2001), Simulating the ice-thickness distribution in a coupled climate model, *J. Geophys. Res.*, *106*, 2441–2464.

Broecker, W. S. (1997), Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO$_2$ upset the current balance?, *Science*, *278*, 1582–1588.

Broecker, W. S. (2006), Was the Younger Dryas triggered by a flood?, *Science*, *312*, 1146–1148.

Broecker, W. S., et al. (1989), Routing of meltwater from the Laurentide Ice-Sheet during the Younger Dryas cold episode, *Nature*, *341*, 318–321.

Conkright, M. E., et al. (2002), World Ocean Atlas 2001: Objective analysis, data statistics, and figures CD-ROM documentation, *Natl. Oceanogr. Data Cent. Internal Rep. 17*, http://www.nodc.noaa.gov/OC5/WOA01/readme.pdf, Natl. Oceanogr. Data Cent., Silver Spring, Md.

Cottet-Puinel, M., et al. (2004), Variation of Labrador Sea Water formation over the Last Glacial cycle in a climate model of intermediate complexity, *Quat. Sci. Rev.*, *23*, 449–465.

Cox, P. M., et al. (1999), The impact of new land surface physics on the GCM simulation of climate and climate sensitivity, *Clim. Dyn.*, *15*, 183–203.

Curry, R., et al. (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, *426*, 826–829.

Déry, S. J., and E. F. Wood (2005), Decreasing river discharge in northern Canada, *Geophys. Res. Lett.*, *32*, L10401, doi:10.1029/2005GL022845.

Déry, S. J., et al. (2005), Characteristics and trends of river discharge into Hudson, James, and Ungava bays, 1964–2000, *J. Clim.*, *18*, 2540–2557.

Ellison, C. R. W., et al. (2006), Surface and deep ocean interactions during the cold climate event 8200 years ago, *Science*, *312*, 1929–1932.

Hinzman, L. D., et al. (2005), Evidence and implications of recent climate change in northern Alaska and other arctic regions, *Clim. Change*, *72*, 251–298.

Holland, M. M., et al. (2001), The role of ice-ocean interactions in the variability of the North Atlantic thermohaline circulation, *J. Clim.*, *14*, 656–675.

Holland, M., J. Finnis, A. P. Barrett, and M. C. Serreze (2007), Projected changes in Arctic Ocean freshwater budgets, *J. Geophys. Res.*, *112*, G04S55, doi:10.1029/2006JG000354.

Hughes, T. M. C., and A. J. Weaver (1994), Multiple equilibria of an asymmetric 2-basin ocean model, *J. Phys. Oceanogr.*, *24*, 619–637.

Johannessen, O. M., et al. (2004), Arctic climate change: Observed and modelled temperature and sea-ice variability, *Tellus, Ser. A*, *56*, 559–560.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Koenigk, T., U. Mikolajewicz, H. Haak, and J. Jungclaus (2007), Arctic freshwater export in the 20th and 21st centuries, *J. Geophys. Res.*, doi:10.1029/2006JG000274, in press.

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, B. M. Fekete, and B. J. Peterson (2001), Assessment of contemporary Arctic river runoff based on observational discharge records, *J. Geophys. Res.*, *106*, 3321–3334.

Leverington, D. W., et al. (2000), Changes in the bathymetry and volume of glacial Lake Agassiz between 11000 and 9300 C-14 yr BP, *Quat. Res.*, *54*, 174–181.

Lowell, T. V., et al. (2005), Testing the Lake Agassiz meltwater trigger for the Younger Dryas, *Eos Trans. AGU*, *86*, 365.

Manabe, S., and R. J. Stouffer (1997), Coupled ocean-atmosphere model response to freshwater input: Comparison to Younger Dryas event, *Paleoceanography*, *12*, 321–336.

McClelland, J. W., S. J. Déry, B. J. Peterson, R. M. Holmes, and E. F. Wood (2006), A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century, *Geophys. Res. Lett.*, *33*, L06715, doi:10.1029/2006GL025753.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, et al., pp. 747–45, Cambridge Univ. Press, Cambridge, U. K.

Meissner, K. J., and P. U. Clark (2006), Impact of floods versus routing events on the thermohaline circulation, *Geophys. Res. Lett.*, *33*, L15704, doi:10.1029/2006GL026705.

Meissner, K. J., et al. (2003), The role of land surface dynamics in glacial inception: A study with the UVic Earth system model, *Clim. Dyn.*, *21*, 515–537.

Otterå, O. H., H. Drange, M. Bentsen, N. G. Kvamstø, and D. Jiang (2003), The sensitivity of the present-day Atlantic meridional overturning circulation to freshwater forcing, *Geophys. Res. Lett.*, *30*(17), 1898, doi:10.1029/2003GL017578.

Otterå, O. H., et al. (2004), Transient response of the Atlantic meridional overturning circulation to enhanced freshwater input to the Nordic Seas–Arctic Ocean in the Bergen climate model, *Tellus, Ser. A*, *56*, 342–361.

Pacanowski, R. C. (1996), MOM 2 documentation user's guide and reference manual, *GFDL Ocean Tech. Rep. 3.2*, 232 pp., Geophys. Fluid Dyn. Lab., Princeton, N. J.

Parkinson, C. L., D. J. Cavalieri, P. Gloersen, H. J. Zwally, and J. C. Comiso (1999), Arctic sea ice extents, areas, and trends, 1978–1996, *J. Geophys. Res.*, *104*, 20,837–20,856.

Parkinson, C. L., K. Y. Vinnikov, and D. J. Cavalieri (2006), Evaluation of the simulation of the annual cycle of Arctic and Antarctic sea ice coverages by 11 major global climate models, *J. Geophys. Res.*, *111*, C07012, doi:10.1029/2005JC003408.

Peltier, W. R., G. Vettoretti, and M. Stastna (2006), Atlantic meridional overturning and climate response to Arctic Ocean freshening, *Geophys. Res. Lett.*, *33*, L06713, doi:10.1029/2005GL025251.

Peterson, B. J., et al. (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.

Peterson, B. J., et al. (2006), Trajectory shifts in the Arctic and subarctic freshwater cycle, *Science*, *313*, 1061–1066.

Petoukhov, V., et al. (2005), EMIC Intercomparison Project (EMIP-CO2), comparative analysis of EMIC simulations of climate, and of equilibrium and transient responses to atmospheric CO_2 doubling, *Clim. Dyn.*, *25*, 363–385.

Rahmstorf, S., et al. (2005), Thermohaline circulation hysteresis: A model intercomparison, *Geophys. Res. Lett.*, *32*, L23605, doi:10.1029/2005GL023655.

Rennermalm, A. K., E. F. Wood, S. J. Déry, A. J. Weaver, and M. Eby (2006), Sensitivity of the thermohaline circulation to Arctic Ocean runoff, *Geophys. Res. Lett.*, *33*, L12703, doi:10.1029/2006GL026124.

Rothrock, D. A., Y. Yu, and G. A. Maykut (1999), Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 3469–3472.

Saenko, O. A., et al. (2002), Distinguishing the influence of heat, freshwater, and momentum fluxes on ocean circulation and climate, *J. Clim.*, *15*, 3686–3697.

Schmittner, A. (2005), Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation, *Nature*, *434*, 628–633.

Schmittner, A., K. J. Meissner, M. Eby, and A. J. Weaver (2002a), Forcing of the deep ocean circulation in simulations of the Last Glacial Maximum, *Paleoceanography*, *17*(2), 1015, doi:10.1029/2001PA000633.

Schmittner, A., et al. (2002b), Instability of glacial climate in a model of the ocean-atmosphere-cryosphere system, *Science*, *295*, 1489–1493.

Serreze, M. C., et al. (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207.

Serreze, M. C., A. P. Barrett, A. G. Slater, R. A. Woodgate, K. Aagaard, R. B. Lammers, M. Steele, R. Moritz, M. Meredith, and C. M. Lee (2006), The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, *111*, C11010, doi:10.1029/2005JC003424.

Shiklomanov, I. A., and A. I. Shiklomanov (2003), Climatic change and the dynamics of river runoff into the Arctic Ocean, *Water Resour.*, *30*, 593–601.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*, 1365–1387.

Thorpe, R. B., et al. (2001), Mechanisms determining the Atlantic thermohaline circulation response to greenhouse gas forcing in a non-flux-adjusted coupled climate model, *J. Clim.*, *14*, 3102–3116.

Tomczak, M., and J. S. Godfrey (1994), *Regional Oceanography: An Introduction*, 391 pp., Elsevier, Oxford, U. K.

Troccoli, A., and P. Kållberg (2004), Precipitation correction in the ERA-40 reanalysis, *ERA-40 Proj. Rep. Ser. 12*, 10 pp., Eur. Cent. for Medium Range Weather Forecasts, Reading, U. K. (Available at http://www.ecmwf.int/publications/library/do/references/list/192)

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

Vellinga, M., and R. A. Wood (2002), Global climatic impacts of a collapse of the Atlantic thermohaline circulation, *Clim. Change*, *54*, 251–267.

Weaver, A. J., et al. (2001), The UVic Earth system climate model: Model description, climatology, and applications to past, present and future climates, *Atmos. Ocean*, *39*, 361–428.

White, D., et al. (2007), Arctic freshwater system: Changes and impacts, *J. Geophys. Res.*, doi:10.1029/2006JG000353, in press.

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