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Sensitivity of the thermohaline circulation to Arctic Ocean runoff

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[1] Arctic Ocean river runoff increases over the 20th century raise concerns of the potential impact it may have on the thermohaline circulation (THC) and thus global climate. This study investigates how changes in Arctic river discharge may control THC by a series of experiments with an intermediate complexity global climate model. The experiments show an inverse relationship between THC strength and changes to riverine freshwater discharge, similar to the response of THC to surface freshening of the North Atlantic. Arctic Ocean freshwater export and volume were more sensitive to river runoff than sea ice export. A strong linear relationship between the THC strength and the steric height gradient (depth integrated density anomaly and an important driver for the western boundary current) suggests that the Arctic freshwater pools and fluxes are very effective in translating changes in runoff to THC strength by regulating the ocean water density in the North Atlantic. **Citation:** 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.

1. Introduction

[2] The Thermohaline Circulation (THC) is a major part of the global ocean circulation and climate system [e.g., *Broecker*, 1997]. Its strength is a measure of the effectiveness of convective deep water formation in the North Atlantic and has been found to be proportional to the gradient in depth integrated density anomaly (i.e., steric height gradient) from the equatorial region to the deep water formation site [*Hughes and Weaver*, 1994; *Thorpe et al.*, 2001]. The steric height gradient is a representation of a pressure gradient which, assuming geostrophy, has to be balanced by a current. This current is the western boundary current feeding warm saline water to the North Atlantic, where it loses its buoyancy and increases its ocean water density when the water is subjected to the cooling in the high latitudes. Freshening of the North Atlantic is assumed to reduce the THC strength because of its effect on sea water density [e.g., *Broecker*, 1997]. This has been demonstrated with several climate models [*Rahmstorf et al.*, 2005; *Stouffer et al.*, 2006] and studies of the Fram Strait sea ice export [*Holland et al.*, 2001].

[3] The ocean water in the North Atlantic is freshened from the north by water exported from the Arctic Ocean, channeled through either Fram Strait ($\sim$3600 km^3 yr^{-1} [*Aagaard and Carmack*, 1989]) or the Canadian Archipelago ($\sim$3311 km^3 yr^{-1} [*Prinsenberg and Hamilton*, 2005]). The freshwater export is balanced by input of freshwater into the Arctic Ocean from the Bering Strait ($\sim$2500 km^3 yr^{-1} [*Woodgate and Aagaard*, 2005]), river discharge ($\sim$3300 km^3 yr^{-1}), Arctic Ocean P-E (precipitation minus evapotranspiration/sublimation ($\sim$900 km^3 yr^{-1}), and the Norwegian Coastal current ($\sim$250 km^3 yr^{-1}), in addition to a net saline inflow through the Svalbard Norway passage (corresponding to a freshwater export of $\sim$540 km^3 yr^{-1}) [*Aagaard and Carmack*, 1989].

[4] The dominant role of river runoff in the Arctic Ocean freshwater budget, combined with observations of increasing Arctic river runoff in the 20th century [*Peterson et al.*, 2002], motivated this study of the sensitivity and links between riverine freshwater discharge and the THC. By using a computationally fast, intermediate complexity, global climate model, a wide range of experiments to study steady state conditions could be made.

2. Method

[5] For this study, the intermediate complexity global climate model used was the University of Victoria Earth System Climate Model 2.7 (UVic ESCM) [*Weaver et al.*, 2001]. The model has a global coverage with a grid resolution of 3.6° longitude × 1.8° latitude and couples a one layer energy moisture balance atmosphere model with GFDL's MOM 2.0 ocean model [*Pacanowski*, 1996] and a dynamic-thermodynamic sea ice model [*Bitz et al.*, 2001]. A full description of the model and its parameters are given by *Weaver et al.* [2001]. *Meissner et al.* [2003] extended the UVic ESCM by including a land surface model based on a simplified version of MOSES (Met Office Surface Exchange Scheme) [*Cox et al.*, 1999] and the dynamic vegetation model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) [*Cox*, 2001]. In this study the moisture advection option is activated to improve modeled precipitation, sea surface salinity and surface temperature [*Weaver et al.*, 2001]. The model is forced by seasonal variations in top of the atmosphere solar insolation and monthly climatological (1948–2000) wind stress and wind speed taken from NCEP/NCAR reanalysis (National Centers for Environmental Prediction/National Center for Atmospheric Research) [*Kalnay et al.*, 1996]. The wind speed fields are a weighted average of all NCEP/NCAR atmospheric levels up to about 10 km, where the weights are based on the specific humidity at each level to represent the decline in atmospheric moisture with height [*Meissner et al.*, 2003]. The major weakness of UVic ESCM is the simple atmosphere

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model, which also is an advantage since it allows for comparatively fast computational time.

[6] In the experiments presented here, the location and magnitude of riverine freshwater flux entering the Arctic Ocean is controlled using prescribed discharge at the river outlets. In the original model, river discharge generated from the land surface component is routed to the river outlets and applied as surface salt flux at the ocean boundary. Arctic river discharge is prescribed for 11 rivers. Data from R-Arctic Net version 2 [*Lammers et al.*, 2001] is used to calculate monthly river discharge climatology. As this study is a sensitivity analysis of changes in runoff from the mean climatology, we could neglect the runoff contribution from ungauged and small basins (which is assumed to be substantial; see Table 1), and the freshwater flux through the Bering Strait and Canadian Archipelago (represented as land and is thus closed in the model).

[7] The original climate model control run of Arctic runoff was 611 km^3 yr^{-1} less than the discharge climatology prescribing the Arctic river discharge. To ensure global water balance closure, the imbalance between the modeled and prescribed river discharge was compensated for by adjusting the surface salt flux for all ocean grid cells. On average, the adjustment is 1.7 mm yr^{-1} which should be negligible, even in the shallow shelf areas.

[8] In addition to the control run, a series of sensitivity experiments are performed, falling into three categories: (i) river discharge is eliminated from each Arctic river (sequentially) resulting in 11 simulations; (ii) river discharge is doubled from each river (sequentially) resulting in 11 simulations; and (iii) in the remaining simulations the river discharge from all Arctic rivers is changed simultaneously with the discharge set to a fraction ranging between 0 and 2 of the runoff climatology used in the control run. In all simulations the atmospheric carbon dioxide concentration is kept constant at pre-industrial levels to isolate the effects of river runoff. All experiments are run for between 800-3000 years in order for the model to approach steady state. The last 100 years of each model simulation are used to calculate the steady state Arctic Ocean freshwater storage and fluxes, the sensitivity of those pools and fluxes to changes in river discharge, the THC strength (i.e., North Atlantic maximum meridional overturning circulation), and the Atlantic steric height gradient.

[9] Assuming that the change in the two storage terms (ocean freshwater and sea ice volume) are zero, the Arctic Ocean freshwater budget at steady state can be described as:

$$P - E + R = ICE_{\mathrm{export\_FRAM}} + FW_{\mathrm{export\_FRAM}} + ICE_{\mathrm{export\_S-N}} + FW_{\mathrm{export\_S-N}} \qquad (1)$$

where P-E is precipitation minus evaporation over the ocean, R is runoff, ICE_{export_FRAM} and FW_{export_FRAM} are sea ice and liquid freshwater export through Fram Strait (demarked as a line connecting Svalbard and Greenland along 80°N) and ICE_{export_S-N} and FW_{export_S-N} are sea ice and liquid freshwater export through the Svalbard-Norway Passage (demarked as a line connecting Svalbard and Norway along 25°E). The freshwater export and storage terms are calculated with a reference salinity of 34.9 g salt l^{-1}.

Table 1. Estimates of Arctic Ocean Freshwater Pools and Fluxes With the UVic ESCM Control Run Compared With the Estimates by *Aagaard and Carmack* [1989] Who Used a Reference Salinity of 34.8 g Salt l^{-1}[a]

	Control Run	*Aagaard and Carmack* [1989]
Freshwater Pools, km^3		
Liquid freshwater	106,000	80,000
Sea ice	12,900	17,300
Freshwater Fluxes, km^3 yr^{-1}		
Runoff	2329	3300
Arctic Ocean P-E	600	900
Total freshwater export	−3060	−3900
ICE_{export_FRAM}	*−580*	*−2790*
FW_{export_FRAM}	*−870*	*−820*
ICE_{export_S-N}	*−620*	–
FW_{export_S-N}	*−990*	*−290*[b]
Closure	−131	–

[a] The components of freshwater export are shown in italics. Closure is the modeled net freshwater flux (i.e., inputs − exports).

[b] The freshwater export through the Svalbard-Norway (S-N) passage is a salty Atlantic inflow with the freshwater import by the Norweigan Coastal current subtracted from it.

[10] The sensitivity of the freshwater pools and fluxes to changes in river discharge is analyzed by calculating the relative sensitivity, which is a normalized sensitivity allowing for cross variable comparison [e.g., *McCuen*, 2003] given by:

$$S = \frac{\partial O/O_0}{\partial R/R_0} \approx \frac{\Delta O/O_0}{\Delta R/R_0} \qquad (2)$$

where S is the relative sensitivity, R is river discharge, and R_0 is control run river discharge. O is the variable investigated for sensitivity, and O_0 is the control run value.

[11] The steric height gradient is calculated as the difference between the steric height at 30°S and 60°N following *Thorpe et al.* [2001]. Specific volume anomaly and steric height were calculated using *Tomczak and Godfrey* [1994] with a reference depth of 1000-m, where ocean water density is calculated from modeled potential temperature and salinity according to the *Joint Panel on Oceanographic Tables and Standards* [1991].

3. Results

[12] The UVic ESCM model represents well the contemporary climate [*Weaver et al.*, 2001] and large scale Arctic Ocean freshwater fluxes and pools (Table 1). However, the details of freshwater export are not well simulated. Sea ice export is underestimated, liquid freshwater export is overestimated and shifted geographically toward the Svalbard-Norway passage. The problem of resolving the details of freshwater export can be explained by the well known shortcoming of coarse resolution, nonflux adjusted models, like the UVic ESCM model, where Arctic Ocean winter sea ice extends too far south [*Weaver et al.*, 2001] and a result of possibly unrepresentative wind stress forcing in this region. *Mysak et al.* [2005] represented Fram Strait sea ice export well using the same model but with daily instead of monthly wind forcing.

[13] Resolving the details of the freshwater export sources may not be important for this sensitivity study, since the deep water formation in UVic ESCM is shifted southward in

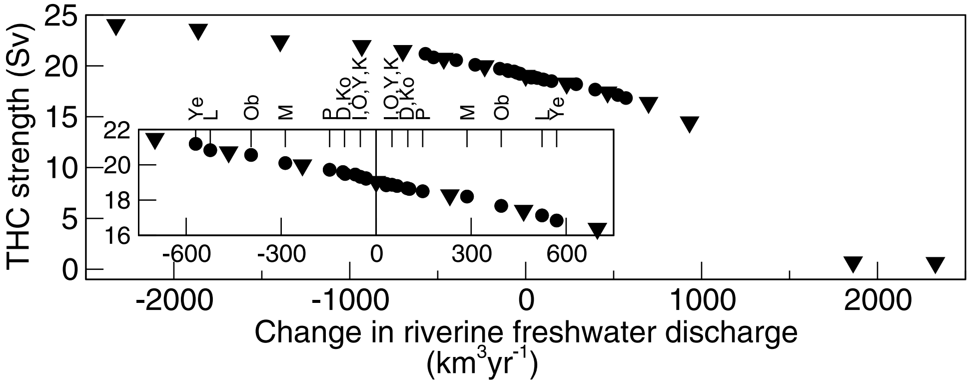

Figure 1. Relationship between THC strength and changes to Arctic riverine freshwater discharge from all rivers simultaneously (solid triangles) or individual rivers (solid circles). Discharge from individual rivers is either set to zero (negative change in freshwater input) or doubled (positive change in freshwater input). The inset figure is a subset of the larger figure and shows the linear trend between THC strength and changes to riverine freshwater input between +-700 km^3 yr^{-1}. The letters on the inset figures top axis refer to which river's runoff that was perturbed: Y-Yenisei, L-Lena, Ob-Ob, M-Mackenzie, P-Pechora, D-Dvina, Ko-Kolyma, I-Indigirka, O-Olenek, Y-Yana, K-Khatanga. The THC strength is computed as the maximum meridional overturning streamfunction in the North Atlantic.

the North Atlantic [*Weaver et al.*, 2001]. At this location, the East Greenland current transports freshwater from both the Fram Strait and the Svalbard-Norway passage.

[14] The THC strength has an inverse relationship with changes to riverine freshwater flux (Figure 1). The relationship follows a linear trend within runoff perturbations of ±700 km^3 yr^{-1} (30% of the control run's Arctic river discharge), with an effect on THC strength of ±2.6 Sv (14% of the control run THC strength). For runoff perturbations larger than ±700 km^3 yr^{-1}, the THC strength – freshwater relationship falls away from the linear trend and extreme freshening leads to a complete THC collapse. The steady state solution was similar for experiments where discharge was changed from one river or all rivers simultaneously, which indicates that the geographic location of the river has little impact compared to the freshwater forcing magnitude, possibly a result of the coarse model resolution.

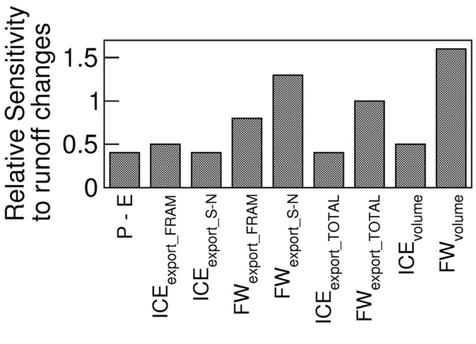

Figure 2. Average relative sensitivity to changes in river discharge calculated from all simulations. Ocean Precipitation-Evaporation (P-E), sea ice export (ICE_{export_FRAM}) and liquid freshwater export (FW_{export_FRAM}) through Fram Strait, sea ice export ($ICE_{export\_S\text{-}N}$) and liquid freshwater export ($FW_{export\_S\text{-}N}$) through Svalbard-Norway passage, sea ice export (ICE_{export_total}) and freshwater export (ICE_{export_total}) through both passages, Arctic Ocean sea ice volume (ICE_{volume}) and Arctic Ocean freshwater volume (FW_{volume}).

[15] Riverine freshwater fluxes influence the THC strength by modulating the Arctic Ocean freshwater pools and fluxes of which freshwater volume and freshwater export is most sensitive to changes in runoff (Figure 2). Large outflow of freshwater from the Arctic Ocean into the North Atlantic reduces the steric height gradient and slows down the northward transport of warm saline water that ultimately reduces the THC strength (Figure 3).

4. Concluding Discussion

[16] This study shows that riverine freshwater discharge into the Arctic Ocean can be an important controlling factor on the THC strength. The changes of riverine freshwater are propagated through the Arctic Ocean freshwater volume and freshwater export into the North Atlantic. Here, the ocean water density at the deep water formation site and steric height gradient driving the western boundary current are reduced by increased freshening. The inverse relationship of THC strength with riverine freshwater discharge follows the same pattern as THC strength as a function of North Atlantic surface freshening [*Rahmstorf et al.*, 2005]. The pattern, which ultimately leads to THC collapse, is driven by the positive feedback mechanism where reduced

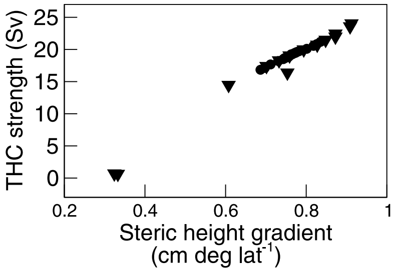

Figure 3. Linear relationship between THC strength and steric height gradient between north and south Atlantic (60°N and 30°S) relative to 1000-m depth from simulations where discharges are changed from all rivers simultaneously (solid triangles) and individual rivers (solid circles).

THC decreases the northward transport of salt resulting in lower salinity and density at the deep water formation site which further decreases the THC strength, referred to as the Stommel salt transport feedback [*Rahmstorf et al.*, 2005].

[17] This work extends a study by *Otterå et al.* [2003] by investigating several scenarios of changed river discharge regime. *Otterå et al.* [2003] used a global circulation model to study the impact of increasing river discharge into the Arctic Ocean by a factor of four, thereby increasing it from 3150 $\mathrm{km}^3\ \mathrm{yr}^{-1}$ to 12,600 $\mathrm{km}^3\ \mathrm{yr}^{-1}$. After the 150 year long simulation period the extra freshening resulted in a $\sim$2 Sv decrease in THC strength. In this study a reduction in THC strength of 2 Sv would correspond to a freshening of $\sim$600 $\mathrm{km}^3\ \mathrm{yr}^{-1}$ (26% of the Arctic river discharge). Thus, the model of *Otterå et al.* seems less sensitive to freshwater forcing than UVic ESCM.

[18] *Weatherly and Walsh* [1996] and *Prange and Gerdes* [1999] studied the sea ice volume response to riverine freshwater discharge. They showed that increased freshwater discharge reduced sea ice volume while only *Weatherly and Walsh* [1996] found decreasing discharge to increase sea ice volume. This work extends the previous studies by investigating the sensitivity of all freshwater pools and fluxes to river discharge. The model results showed that Arctic Ocean freshwater export and volume was the most sensitive to changes in river discharge of all freshwater pools and fluxes. Cross variable comparison was possible by using the relative sensitivity coefficient where data were normalized with control run values. The normalization allows neglecting the model overestimation of liquid phase freshwater export compared to ice phase export assuming that the deviation from the control run were accurately described.

[19] Between 1936–1999 Arctic river discharge increased by 7% ($\sim$130 km^3) [*Peterson et al.*, 2002]. Over a similar period, between 1957 and 2004, *Bryden et al.* [2005] found a 30% (8 Sv) decline in observed THC. Although, further evidence on an actual THC slow down taking place is needed, our results suggest that the decline in THC can partly be explained by Arctic river discharge increases. Another important Arctic factor controlling THC decline could be sea ice volume reduction. Sea ice thickness was reduced from 3.1 m to 1.3 m between 1958–76 and the 1990s, resulting in a loss of sea ice volume over the latter part of the 20th century [*Rothrock et al.*, 1999]. Further studies of the transient effect of river discharge on THC strength are needed, including studies of the observed changes in river runoff and sea ice volume, as well as studies using fully complex general circulation models that might capture effects not seen in the intermediate complexity model.

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