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Towards a more saline North Atlantic and a fresher Arctic under global warming

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[1] Most atmosphere-ocean general circulation models (GCMs) forced with increasing greenhouse gas concentrations predict enhanced atmospheric moisture transports to the high northern latitudes. Together with melting of Arctic sea ice and glaciers, this has led to the expectation of a gradual freshening of the northern North Atlantic, tending to reduce the strength of the Atlantic Meridional Overturning Circulation (AMOC). Here a multi-member greenhouse gas GCM experiment is used to demonstrate that both the salinity in the North Atlantic and the inflow of Atlantic Water to the Nordic Seas may increase despite a strong freshening of the Arctic Ocean and a reduced AMOC.
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1. Introduction

[2] There are increasing observation-based evidences for a large-scale redistribution of the freshwater contents of the World Oceans that is consistent with a spin-up of the hydrological cycle. These include positive salinity trends in the tropics [*Curry et al.*, 2003; *Boyer et al.*, 2005], and freshening trends in both the subpolar Atlantic [*Dickson et al.*, 2002; *Curry et al.*, 2003; *Curry and Mauritzen*, 2005; *Peterson et al.*, 2006] and Pacific [*Wong et al.*, 2001] ocean basins. Furthermore, the observations indicate increased atmospheric moisture transports from the Atlantic to the Pacific [*Boyer et al.*, 2005] and also enhanced transports to Siberia, the latter leading to increased river runoff to the Arctic [*Peterson et al.*, 2006]. A spin-up of the hydrological cycle, which is the expected outcome of higher air temperatures and by that enhanced evaporation in the tropics and increased capacity of the atmosphere to keep and transport water, is indeed simulated by most climate models forced with increasing levels of atmospheric greenhouse gases [e.g., *Cubasch et al.*, 2001; *Räisänen*, 2002]. At the high northern latitudes, a combination of warming and dilution of the surface ocean will slow down the formation rate of intermediate and deep water masses, and possibly result in weaker Atlantic meridional overturning circulation and a less efficient oceanic heat conveyor [*Cubasch et al.*, 2001].

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[3] Reports of a 20% reduction in the Faroe-Shetland overflow [*Hansen et al.*, 2001], a significantly fresher northern North Atlantic and weakened north-south density gradient in the deep ocean [*Curry and Mauritzen*, 2005], and a 50% reduced southward flow of lower North Atlantic Deep Water (NADW) across 25°N [*Bryden et al.*, 2005], all taking place over the last three to five decades, have been taken as evidence for an already slowing of the Atlantic heat conveyor [*Quadfasel*, 2005], with a cooling of northern Europe as a possible consequence. There are two apparent contradictions to this interpretation: First, neither the unique 10 year long current meter measurements of the inflow of Atlantic Water to the Nordic Seas [*Østerhus et al.*, 2005; *Orvik and Skagseth*, 2005], nor the current meter measurements of the deep overflow of dense water through the Faroe-Bank Channel [*Østerhus et al.*, 2005], show decreasing trends. Second, both the temperatures and salinities of the inflowing Atlantic Water to the Nordic Seas [*Hatun et al.*, 2005; *International Council for the Exploration of the Sea*, 2005] and in the central Norwegian Sea [*Drange et al.*, 2005; S. Østerhus, personal communication, 2006] have recently reached their highest values since reliable observations started half a century ago.

2. Model Simulations and Performance

[4] Six 80 year long model realizations with the Bergen Climate Model (BCM) [*Furevik et al.*, 2003], a state-of-the-art climate GCM [*Bentsen et al.*, 2004, *Mignot and Frankignoul*, 2004; *Otterå et al.*, 2004; *Sorteberg et al.*, 2005], have been analyzed to explore these apparent inconsistencies. The model experiments follow the protocol of the Coupled Model Intercomparison Project [*Covey et al.*, 2003] with a 1% per year increase in atmospheric CO_2, leading to a doubling after 70 years. All other atmospheric gasses, aerosols, and external forcing terms are kept constant throughout the integrations. Although highly idealized, the CMIP2 protocol may be taken as a first order approximation to more realistic global warming scenarios. Since the present state of the coupled atmosphere-sea ice-ocean system is poorly known, the starting points of the ensemble members are chosen to capture the maximum, minimum, increasing and decreasing phases of AMOC [*Sorteberg et al.*, 2005], the latter extracted from a 300 years control simulation of the present day climate [*Furevik et al.*, 2003]. In this way the model ensemble tends to maximize the decadal-scale climate variability in the Atlantic [e.g., *Collins et al.*, 2006], and possibly in the Arctic [*Sorteberg et al.*, 2005] as well.

[5] The strength and variability of AMOC [*Bentsen et al.*, 2004] and the net volume transports across the passages confining the Nordic Seas and the Arctic Ocean are all

Table 1. Simulated and Observed Volume Transports Through Selected Key Sections in the Control Simulation[a]

Section		Northward		Southward	
Bering Strait	sim.	1.41	(−2)	0.01	(0)
	obs.	0.8[b]			
Canadian Archipelago	sim.	0.02	(+3)	1.62	(+2)
	obs.			2.6[c], 1.7[d]	
Danmark Strait	sim.	0.89	(−42)	4.23	(−12)
	obs.	1[e], 0.75[f]		4.3[e]	
Iceland Faroe Ridge	sim.	3.48	(−10)	1.03	(−4)
	obs.	3.3[e], 3.5[f]			
Faroe Shetland Channel	sim.	3.75	(+26)	3.10	(−18)
	obs.	3.7[e], 3.2[f]			
English Channel	sim.	0.44	(−3)	0.00	(0)
Barents Sea Opening	sim.	2.75	(+22)	0.87	(−4)
	obs.	1.3–1.7[g]			
Fram Strait	sim.	4.45	(−180)	6.14	(−155)
	obs.	9–10[h]		12–13[h]	

[a]Units are in 10^6 m^3 s^{-1}. Simulated trends in 10^3 m^3 s^{-1} per decade are given in parentheses.
[b]*Woodgate and Aagaard* [2005].
[c]*Fissel et al.* [1988].
[d]*Cuny et al.* [2005].
[e]*Hansen and Østerhus* [2000].
[f]*Østerhus et al.* [2005].
[g]*Ingvaldsen et al.* [2004].
[h]*Schauer et al.* [2004].

realistically simulated (Table 1). Furthermore, the simulated fresh water budgets for the Arctic Ocean favorably compare with observation-based estimates [*Aagaard and Carmack*, 1989], with the exception of a too fresh Pacific inflow. Relative to a salinity of 34.80, the simulated (observation-based) Bering Strait inflow corresponds to 3300 (1670) km^3 yr^{-1} of fresh water, the precipitation minus evaporation is 1200 (900) km^3 yr^{-1}, and the runoff is 3400 (3300) km^3 yr^{-1}. For the latter, the simulated runoff to the Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas are 377, 1256, 815, 394, 126 and 435 km^3 yr^{-1}, respectively, and are close to the observation-based estimates by Macdonald [2000]. Based on more recent measurements [*Woodgate and Aagaard*, 2005], the Bering Strait inflow is equivalent to 2500 km^3 yr^{-1} of fresh water, bringing it closer to the simulated inflow.

[6] The net freshwater input to the Arctic Ocean is balanced by fresh water exports through the Barents Sea (4% of total), the Fram Strait (61%), and the Canadian Archipelageo (35%). The sea-ice cover in the Arctic is too thin in the model [*Furevik et al.*, 2003], causing only 20% of the freshwater export through the Fram Strait to be in solid form, in contrast to the estimated 75% based on historical data [*Aagaard and Carmack*, 1989]. With the exception of a too thin sea-ice cover, the BCM realistically simulates the main components of the Arctic Ocean fresh water budget.

3. Results

[7] The global mean precipitation trends for the ensemble-members are approximately +3% per decade (not shown). The simulated changes in the precipitation minus evaporation (P-E) field show a decrease (dryer climate) in the subtropical belts, and an increase (wetter climate) in the equatorial region and in the middle and high latitudes (Figure 1). The changes in the atmospheric fresh water flux show enhanced transports from the low northern latitudes in the Atlantic to the Pacific, and from the North Atlantic and North Pacific into the drainage areas of the Arctic Ocean. The response in the continental discharge to the Arctic Ocean and surrounding seas is a 100 km^3 yr^{-1} (2%) increase per decade with a relatively small spread between the model ensemble members (not shown).

[8] Comparing storage changes with cumulative flux changes, the temporal development of the simulated Arctic Ocean and Nordic Seas fresh water response can be divided into two regimes (Figure 2): During the first 30 years, here referred to as the early stage of the simulated hydrological spin-up, there are no significant trends in the ensemble mean fresh water contents. For this stage, inter-annual variability between the individual ensemble members is largely explained by the sum of cumulative liquid and solid freshwater net exports (not shown). Beyond year 30, the Arctic Ocean becomes gradually fresher and the Nordic Seas slightly more saline.

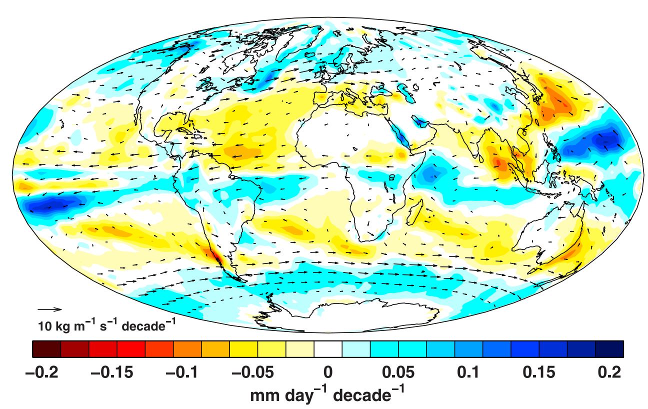

Figure 1. Ensemble mean trends in P-E (mm day^{-1} per decade, color scale) and water vapor transports (kg m^{-1} s^{-1}, arrows).

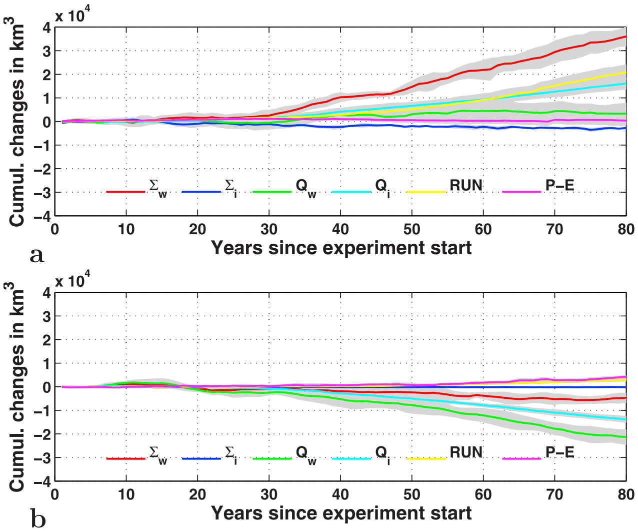

Figure 2. Freshwater storage changes versus cumulative freshwater flux changes for (a) the Arctic Ocean and (b) the Nordic Seas. The storage is in liquid (Σ_w) or solid (Σ_i) form, and the freshwater fluxes are due to liquid (Q_w) or solid transports (Q_i), continental runoff (RUN), and P-E (PE) changes. Changes are positive when more freshwater is added to the basins. Units are relative to a salinity of 34.80. The shading indicates one standard deviation of the ensemble spread. Note that the liquid freshwater fluxes (Q_w) are calculated from weekly averages. Thus in phase variations between volume and salinity fluctuations will cause additional fresh water fluxes not accounted for in these panels.

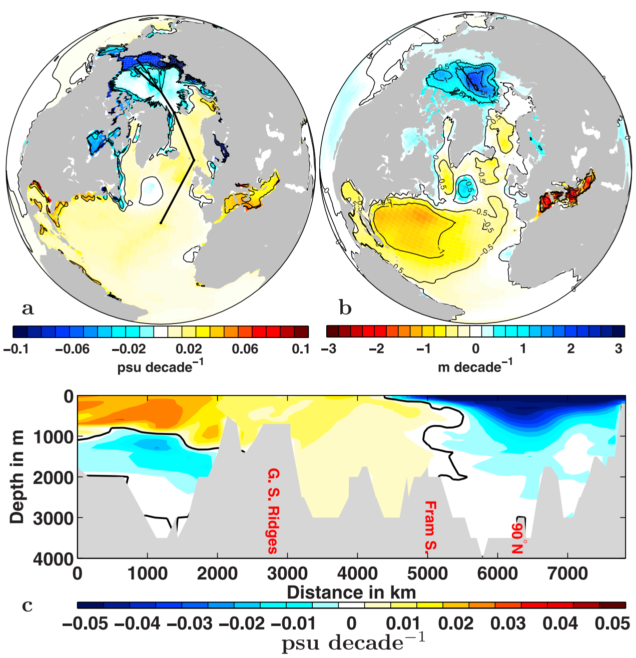

Figure 3. Projected changes in (a) vertical averaged salinity (psu per decade), (b) freshwater storage (m per decade), and (c) salinity (psu per decade) along the trans-Arctic section from the North Atlantic Ocean towards the Bering Strait. Values are computed as ensemble mean linear trends over the 80 years integration period.

[9] The spatial pattern of the simulated freshening is shown in Figures 3a and 3b. Strongest reductions in vertical averaged salinity occur on the Arctic shelves, in the Hudson Bay, and in the Baltic Sea, where the salinity in several locations drops at a rate of 0.05 or more per decade. These are contrasted by the northern North Atlantic and the Nordic Seas, where the northward transport of more saline Atlantic Water increases the salinity throughout most of the basins. In terms of total fresh water content, the changes are largest in the central Arctic Ocean where the added freshwater equates to 2 m per decade.

[10] Changes in the vertical freshwater distribution are highlighted with a section running from the North Atlantic through the Nordic Seas and across the Arctic Ocean (Figure 3c). Important features are a significantly fresher Arctic Ocean and slightly more saline Nordic Seas. South of the Greenland-Scotland ridge, the upper 1000 m of the water column becomes more saline while the intermediate and deep waters become fresher. The largest changes are found near the surface, suggesting that the changes originate from surface forcing such as P-E, sea-ice processes, and continental runoff.

[11] A second important forcing component driving long-term changes of the Arctic Ocean fresh water is the export of sea-ice. So far little attention has been paid to the potential consequence of a reduced sea-ice export in a warmer climate in terms of water mass properties and formation of intermediate to deep waters. Increased exports were present during the late 80s, which are now attributed to major atmospheric circulation shifts [*Lindsay and Zhang*, 2005]. The observed freshening of the northern North Atlantic Ocean [*Curry and Mauritzen*, 2005] and the more saline Arctic Ocean [*Swift et al.*, 2005] are likely consequences of this enhanced fresh water export. The simulations predict a strong reduction in sea-ice export due to a thinner Arctic ice sheet. This implies reduced production of new ice due to a shorter freezing season, or that most of the ice melts before being transported out of the Arctic. In fact, recent observational studies report a negative thickness

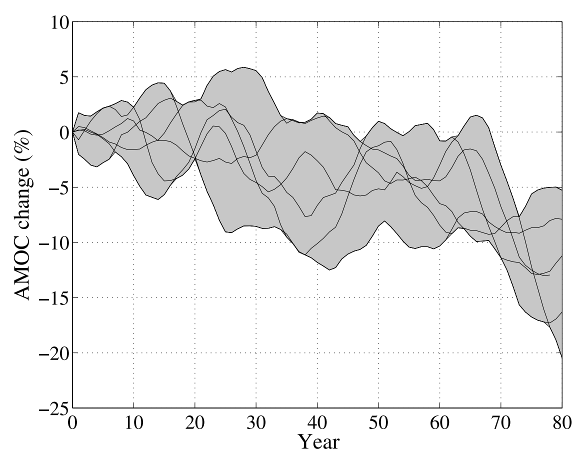

Figure 4. Simulated percentage changes in the maximum strength of the AMOC in each of the 6 ensemble members. Variations in the control integration have been subtracted. The curves have been smoothed with a ten years moving average.

trend of the exported sea-ice while the area transport primarily remains controlled by the local wind forcing [*Kwok*, 2004], which also may explain the observed weak decline in the northern North Atlantic freshwater storage after 1990 [*Curry and Mauritzen*, 2005].

[12] The ensemble members show 5 to 20% reduction in the AMOC strength over the 80 years simulations (Figure 4), with a mean value of 12%, causing a reduction in the deep flow in qualitatively agreement with *Bryden et al.* [2005]. The simulated freshening below 1000 m south of the Greenland-Scotland Ridge is related to a reduction in the deep winter mixing in the Labrador Sea, and is thus closely related to the AMOC changes [*Bentsen et al.*, 2004]. Despite the reduced overturning, all simulations show a modest (6% in average) increase in the Atlantic inflow through the Faroe Shetland Channel and also into the Barents Sea, and a substantial (32% in average) reduced northward flow through the Fram Strait. The net result is a reduced heat and salt transport to the Arctic Ocean (the Barents Sea branch is much colder than the Fram Strait branch), and also reduced solid and liquid freshwater exports south through the Fram Strait. Both of these changes act to enhance the freshening signal in the Arctic. Possible causes are changes in the local and large-scale wind field [*Nilsen et al.*, 2003] or even changes in the thermohaline component of the Arctic Ocean circulation.

4. Conclusions

[13] The Arctic Ocean's response to anthropogenic global warming accompanied by increased runoff and reduced exchange through the Fram Strait is simulated as a delayed, long-term freshening with little compensating freshwater export changes. After acting over a period of more than 30 years, increased runoff forcing and negative ice export trends eventually become compatible with or larger than the decadal variability in freshwater storage caused by contributions from Pacific and Atlantic waters. The accelerative character of the predicted long-term response is subject to the caveat that its detection becomes particularly difficult in an early stage of the anthropogenic global warming i.e. at the present time.

[14] Forming a seesaw, the simulated Arctic Ocean freshening is opposed by a tendency to more saline conditions in the Nordic Seas. Hence, it can be speculated that recent observed freshening trends in the Nordic Seas are part of the natural variability of the system and will reverse in the near future.

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