Influence of Arctic river runoff on the circulation in the Arctic Ocean, the Nordic Seas and the North Atlantic

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I. Introduction

Freshwater import from the Arctic Ocean plays a major role for the circulation and the hydrography in the Nordic Seas where convective regimes of major importance to the large-scale thermohaline circulation are located (Aagaard et al. 1985; Aagaard & Carmack 1989). One of the principal sources of freshwater to balance the budget for the Arctic Ocean is river runoff. Tracer studies reveal that the fraction of river water in the surface waters over the Eurasian Basin can exceed 14% (Bauch et al. 1995). Arctic runoff is expected to increase in the future due to climate change (Miller & Russell 1995) so that the role of Arctic freshwater will possibly be of even greater importance.

In a coupled ocean-sea ice model of the North Atlantic Ocean, the Nordic Seas and the Arctic Ocean the freshwater discharge of the 14 largest Arctic rivers is included. By a series of numerical experiments we shall study the effects of Arctic river water on sea ice formation, hydrography and ocean circulation with a particular eye towards Arctic freshwater transports into the Nordic Seas. Before we investigate the role of Arctic river discharge in interannual and decadal variability, we try to find out the fundamental effects of Arctic river water on the high-latitude ocean. Here we present first results of a comparative process study which consists of three experiments. The experiments differ in the total Arctic runoff included in the model.

II. Model description and experimental design

The ocean model is set up on the base of the hydrostatic Geophysical Fluid Dynamics Laboratory primitive equation model MOM-2 (Pacanowski 1995). An open surface formulation allows dynamic surface elevation and mass fluxes due to precipitation, evaporation and river runoff. The model domain spans the Arctic Ocean, the Nordic Seas and the Atlantic Ocean north of approximately 20°S. The model is formulated on a rotated grid (to avoid the singularity of geographical coordinates at the pole) with a horizontal resolution of about 100-110 km and 19 non-equidistant levels in the vertical. The ocean model is coupled to a dynamic-thermodynamic sea ice model with viscous-plastic rheology (Harder 1996) that is defined on the same horizontal grid.

The coupled system is forced with atmospheric fields representing a 'typical year' (Röske et al., in preparation). Except for daily wind stress data, all forcing fields are monthly varying. Additionally, the inflow of the 14 largest Arctic rivers is included in the model as mass fluxes with zero salinity. The river data were provided by the GRDC[1] and mean monthly discharge values for each river were calculated in order to compile a 'typical runoff year'. The total annual discharge from the 14 rivers amounts to 2460 km^3, representing 95% of the total gauged runoff into the Arctic Ocean. However, about 1700 km^3/yr of ungauged Arctic runoff (Vuglinsky 1997) as well as freshwater import through the Bering Strait (about 1670 km^3/yr according to Aagaard & Carmack 1989) are not included so far. These shortcomings should be kept in mind when interpreting the model results.

For a comparative study three experiments are performed: In experiment RRx0 river runoff is removed from the model, in experiment RRx1 runoff is included as described above, and in experiment RRx2 the discharge of each river is doubled so that the total Arctic runoff amounts to 4920 km^3. Since surface salinities are not restored, the salinity fields can evolve freely. The initial state is taken from a spin-up run. For each experiment the model is integrated 31 years. The following results apply to the last year of the integration period.

III. Results

a. Circulation in the Arctic Ocean and the Nordic Seas

The bulk of river water in the experiments RRx1 and RRx2 remains in the upper 100-150 m of the Arctic Ocean above and within the halocline. Mackenzie river water is transported westward by a distinct anticyclonic Beaufort Gyre that dominates the current system over the Canadian Basin. Over the East Siberian shelf Mackenzie river water joins with freshwater from the Kolyma and the Indigirka rivers. This water mass flows towards the Amundsen Basin where it meets river water from the Laptev Sea. On its way towards the

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Nordic Seas the combined water mass crosses the Eurasian Basin and joins with river waters from the Kara and Barents shelves before it leaves the Arctic Ocean. The river water concentrations in the topmost 20 m in Fram Strait (approximately 8°W, 79°N) amount to 4.5% and 14.5% in the experiments RRx1 and RRx2, respectively.

The surface circulation in the Arctic Ocean proper in experiment RRx2 is qualitatively similar to that of experiment RRx1. Important differences, however, are found in the Barents and the Nordic Seas. In experiment RRx2 an extremely strong ESC (East Spitsbergen Current) develops. Its mass flux is compensated chiefly by a strengthened Atlantic inflow through the Barents Sea. South of Spitsbergen the ESC flows westward and joins with the EGC (East Greenland Current), resulting in an intense and straight flow along the East Greenland shelf south of about 75°N. In experiment RRx2 there is no Jan-Mayen Current splitting off, whereas in experiment RRx1 the well-known circulation pattern with a distinct Greenland Sea Gyre is simulated.

In the runoff-free experiment RRx0 the surface circulation pattern in the Arctic Ocean differs strongly. The Beaufort Gyre is smaller, extending only to the Mendeleev Ridge, and no currents towards Fram Strait are present. There is only little exchange between the Nordic Seas and the Arctic Ocean. As in experiment RRx1 the circulation in the Nordic Seas is characterized by a cyclonic Greenland Sea Gyre.

b. Salinity distribution, halocline and sea ice

After 31 years of integration the Arctic Ocean mean salinity has almost reached an equilibrium with 34.78 psu in experiment RRx2. In the experiments RRx0 and RRx1 the Arctic Ocean mean salinity is still drifting with an increase of 0.008 psu/yr and 0.006 psu/yr, respectively. The Arctic Ocean mean salinity for RRx0 after 31 years of integration amounts to 35.02 psu, and for RRx1 34.90 psu. The salinity drift and the high mean salinity values reflect the lack of freshwater sources. The surface salinity in experiment RRx0 over the central Arctic is about 3.5 psu higher than observational values. In the Laptev Sea the salinity even exceeds 40.0 psu throughout the year. In all experiments the salinity over the Canadian Basin is too high due to the lack of Pacific water inflow through the Bering Strait.

In Figure 1 the annual mean surface salinity fields of the three experiments are compared. The largest differences are found on the shelves near the river mouths. Only small differences appear over the Canadian Basin in the centre of the Beaufort Gyre where the river water concentration is close to zero even in experiment RRx2. Considerable salinity differences are also apparent in the Nordic Seas, in Denmark Strait and south of Denmark Strait in the North Atlantic Ocean. The salinity differences are linked with different freshwater transports out of the Arctic Ocean both as liquid water and as sea ice. The ice melts during its way along the coast of Greenland with highest melt rates just south of Denmark Strait. Relatively large surface salinities are found in experiment RRx2 east of the EGC in the Nordic Seas due to the lack of the Jan-Mayen Current. However, a strong East Icelandic Current transports low-saline water to the east and reduces the surface salinity just north of Iceland.

A salient result of experiment RRx0 is the depletion of the Arctic halocline. Winter convection mixes the upper few hundred metres (up to 500 m) in the Arctic Ocean. Thus, heat and salt from the deeper ocean is incorporated in the surface layer and large ocean-ice heat fluxes occur. In the SON (September/October/November) season a thin low-saline layer covers the Arctic Ocean resulting chiefly from sea ice melt. In experiment RRx1 a distinct halocline restricts convective mixing to the top 150 m. In experiment RRx2 winter convection is even shallower, and warm Atlantic water is shielded from the upper layers. A low large-scale oceanic heat flux into the sea ice cover of about 0-3 W/m^2 averaged over the MAM (March/April/May) season results, whereas the large-scale ocean-ice heat flux in experiment RRx0 is 10-20 W/m^2 over the Canadian Basin and 30-40 W/m^2 over the Eurasian Basin. The mean large-scale heat flux in experiment RRx1 is about 1-6 W/m^2 during the MAM season. The ocean-ice heat fluxes affect the total sea ice volume as shown in Figure 2. Sea ice volume differences are linked with differences in the large-scale sea ice thickness. The difference in the mean sea ice thickness over the Arctic Ocean between RRx0 and RRx2 is about 1.5 m.

Sea ice extent in the MAM season differs only slightly between the three experiments, except for the Laptev Sea which is ice-free in

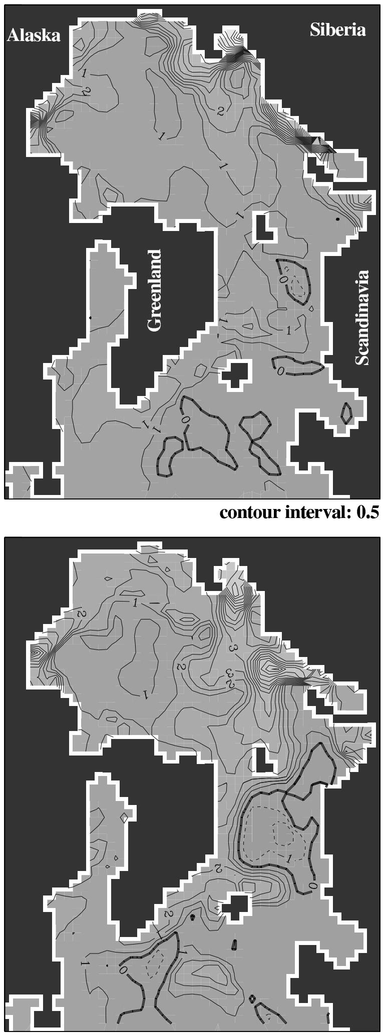

Figure 1: Annual mean surface salinity differences. Top: RRx0-RRx1. Bottom: RRx1-RRx2.

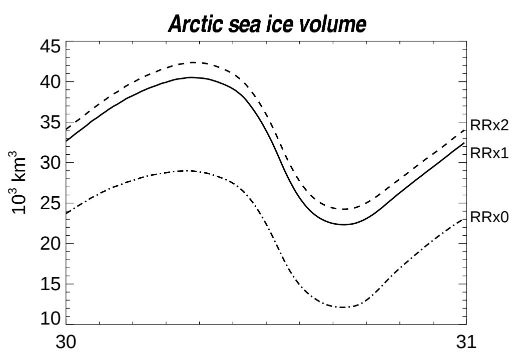

Figure 2: Total Arctic sea ice volume in the experiments RRx0, RRx1 and RRx2 over one year.

experiment RRx0 throughout the year. The sea ice retreat during summer, however, shows large differences. In experiment RRx0 the Eurasian Basin is almost ice-free during the SON season, while in experiment RRx2 ice-free regions are restricted to the Laptev, Kara and Barents shelves.

c. Freshwater transports

The small mean sea ice thickness in experiment RRx0 is linked with low sea ice export through Fram Strait (1742 km^3/yr). The corresponding transport for RRx1 and RRx2 is about 3150 km^3/yr. Table 1 summarizes the freshwater transports from the Arctic Ocean to the Nordic Seas. For the calculations a reference sea water salinity of 34.8 psu was assumed as in Aagaard & Carmack (1989). The sea ice salinity in the model is 3.0 psu. Largest freshwater transports appear in experiment RRx2 with a strikingly large water flux east of Spitsbergen. In all experiments the oceanic freshwater transport is lower than the transport of sea ice. However, it grows strongly with increasing runoff.

freshwater transport in km^3/yr	exp. RRx0	exp. RRx1	exp. RRx2
oceanic transport through Fram Strait	51	521	1015
oceanic transport east of Spitsbergen	6	86	1718
sea ice transport through Fram Strait	1413	2574	2599
sea ice transport east of Spitsbergen	525	530	782
total	1995	3711	6114

Table 1: Freshwater transports from the Arctic Ocean to the Nordic Seas.

d. North Atlantic circulation

The salinity distribution in the Nordic Seas and in the northern North Atlantic Ocean is crucial for the formation of North Atlantic Deep Water and, thus, can have a profound effect on the thermohaline circulation of the whole Atlantic Ocean. By means of numerical experiments Gerdes & Köberle (1995) investigated the response of the North Atlantic circulation to an increase in the surface density just north and west of Iceland. They found an enhanced formation rate of DSOW (Denmark Strait Overflow Water), resulting

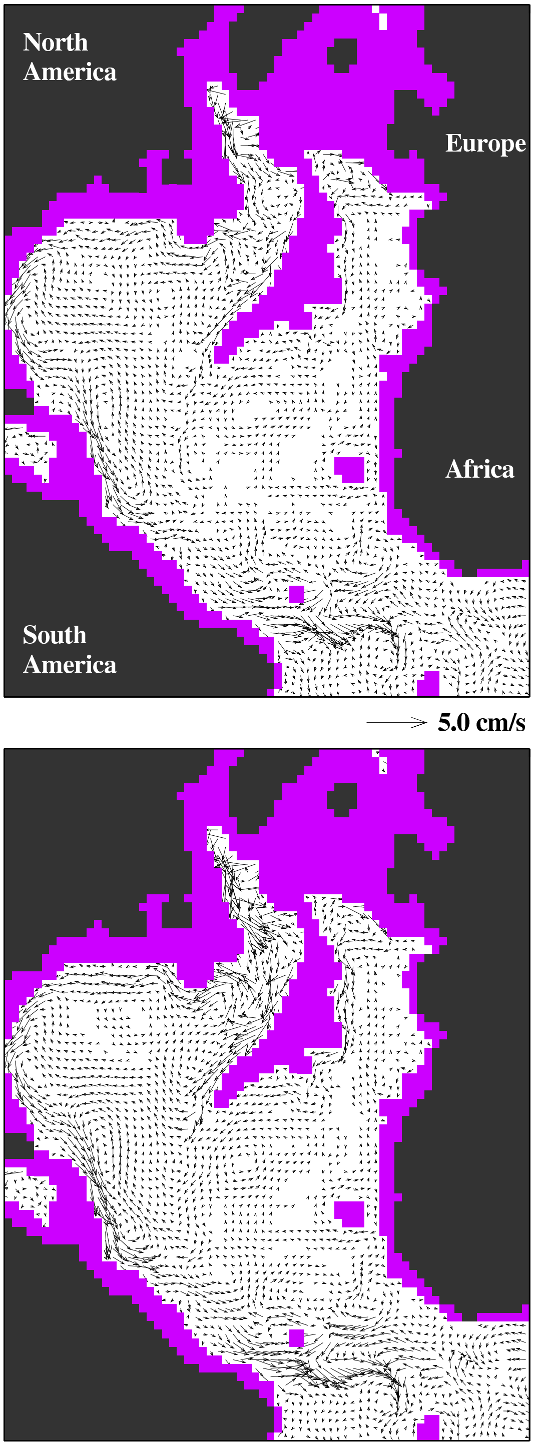

Figure 3: North Atlantic annual mean velocity at 3000 m depth. Top: Experiment RRx1. Bottom: Experiment RRx0.

in intensified meridional overturning and horizontal gyres. In the present study the surface density in Denmark Strait and in the Iceland Sea is affected by freshwater import from the Arctic Ocean, and we observe similar effects on the North Atlantic circulation as Gerdes & Köberle (1995). In experiment RRx0 the surface salinities near Iceland are highest (Figure 1), and we find maximum formation of DSOW. Consequently, the DWBC (Deep Western Boundary Current) is stronger than in RRx1 or RRx2 (Figure 3). The density signal from Denmark Strait is advected southward by the DWBC. Due to JEBAR (Joint Effect of Baroclinicity And Relief) the large-scale barotropic gyres in the three experiments differ in strength. The subtropical gyre in RRx0 is enhanced by approximately 9 Sv compared to RRx1, and by 14 Sv compared to RRx2. The Gulf Stream at around 43^oN transports about 66 Sv in experiment RRx0, 50 Sv in RRx1, and 39 Sv in RRx2.

IV. Conclusion

River runoff is crucial for the maintenance of the Arctic halocline. A weakening of the halocline due to decreased runoff results in stronger vertical mixing and larger ocean-ice heat fluxes. These heat fluxes determine the sea ice volume and, hence, the ice export out of the Arctic Ocean. Melting sea ice and oceanic freshwater import affect the thermohaline forcing in the Nordic Seas. Due to the sensitivity of the large-scale Atlantic circulation to high-latitude thermohaline forcing, Arctic freshwater export in consequence of Arctic river runoff has a global impact.

As a next step to improve the model Pacific water inflow through the Bering Strait shall be included as well as several North Atlantic freshwater sources, in particular runoff from the Norwegian coast and the inflow of Baltic Sea water. Afterwards, the role of Arctic river discharge for interannual high-latitude ocean variability shall be investigated by forcing the model with interannually varying runoff and atmospheric fields.

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