Arctic Ocean change heralds North Atlantic freshening

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[1] A large pool of freshwater formed of ice and runoff is hosted by the Arctic Ocean. It exits through the Canadian Archipelago and Fram Strait to enter the North Atlantic deep water production regions. Using a numerical model and observations we trace a strong freshwater release to subpolar waters in the mid-1990s. In contrast to the ice export driven 1970's 'Great Salinity Anomaly' its source was a large additional liquid freshwater release from the Arctic Ocean. In fact it was a consequence of a change of the Arctic Ocean's thermohaline structure in response to the very intense North Atlantic Oscillation in the early 1990s. Our results show a strong link of large-scale Arctic Ocean changes with the freshwater flux to subpolar waters.
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1. Introduction

[2] While the mechanisms of freshwater storage and release in the northern ocean basins are still under debate [e.g., *Proshutinsky et al.*, 2002; *Dickson et al.*, 2002; *Häkkinen and Proshutinsky*, 2004] it is clear that these freshwater outflows reach sensitive areas of deep water formation in the Greenland, Labrador and Irminger Seas (Figure 1). Model simulations suggest that large freshwater releases into those areas influence the intensity of the northern limb of the global thermohaline circulation [*Häkkinen*, 1999; *Haak et al.*, 2003]. In the late 1960s the 'Great Salinity Anomaly' (GSA) [*Dickson et al.*, 1988] appeared as extraordinarily fresh water passing the Denmark Strait and circulating in the subpolar gyre throughout the 1970s. Its source was a large ice export from the Arctic Ocean [*Häkkinen*, 1993] following several years of large ice storage in the Arctic due to a persistent sea level pressure anomaly [*Köberle and Gerdes*, 2003]. Two further appearances of low salinity water in the Subpolar Gyre were seen in the 1980s and 1990s [*Belkin et al.*, 1998]. These were mostly attributed to local processes in the Labrador Sea [*Belkin*, 2004] or changes in the subpolar gyre transport [*Häkkinen*, 2002].

[3] In contrast to previous investigations we show here that the salinity anomaly of the 1990s is a consequence of a large release of liquid freshwater from the Arctic. This event is the result of a change in the hydrographic structure of the Arctic Ocean, which occurred in response to the high North Atlantic Oscillation (NAO) index period persisting through the early 1990s.

2. Methods

2.1. Model Experiment

[4] The results of the present investigation are derived from a hindcast simulation with the coupled ice-ocean model NAOSIM (North Atlantic/Arctic Ocean Sea Ice Model) [*Karcher et al.*, 2003; *Gerdes et al.*, 2003; *Kauker et al.*, 2003]. It is based on the MOM-2 model of the GFDL. The present version has a horizontal grid spacing of 0.25° and uses a rotated spherical grid. The vertical is resolved with 30 unevenly spaced levels. The ocean model is coupled to a sea ice model with viscous-plastic rheology. It has an open boundary near 50°N where the barotropic transport is prescribed from a coarser resolution version of the model that covers the whole Atlantic [*Köberle and Gerdes*, 2003]. Initial conditions stem from a 50 year spin-up experiment driven by a climatology based on the ECMWF Reanalysis. Forcing (1948–2002) is provided by atmospheric fields taken from the NCEP/NCAR reanalysis. Open boundary hydrography is taken from the PHC climatology from *Steele et al.* [2001], which is also used as reference for a surface restoring of 180 days timescale. Such restoring tends to dampen amplitudes of surface salinity. For a more detailed description of the model experiment analysed here, see *Kauker et al.* [2003]. To highlight the events of interest (with decadal scales), all presented model data are based on running 5-year means.

2.2. Data Analysis

[5] We took observational data from hydrographic archives of the World Ocean Database 2001 (NODC), data from the VEINS (Variability of Exchanges In the Northern Seas) archive at the ICES website (http://octopus.ices.dk/ocean/project/veins/), and from the World Ocean Circulation experiment (WOCE) (http://whpo.ucsd.edu/). We extracted a set of oceanographic stations positioned within a 100 km band across the Denmark Strait. Using the bottom depth and the distance from the coast of Greenland we identified the region which was typically occupied by the southward flowing, relatively fresh water associated with the EGC and selected all hydrographic stations within this region. We calculated and subtracted the seasonal cycle at all depths [*Yashayaev and Zveryaev*, 2001]. Discrepancies in the seasonal amplitudes between the easternmost and westernmost points of the region did not exceed 10%, which is comparable with the overall error in annual and semi-annual harmonics of the seasonal cycle. A spatial bias (salinities tend to increase offshore) was removed from the anomalies by constructing and applying the mean bias as a function of the bottom depth and the distance from the

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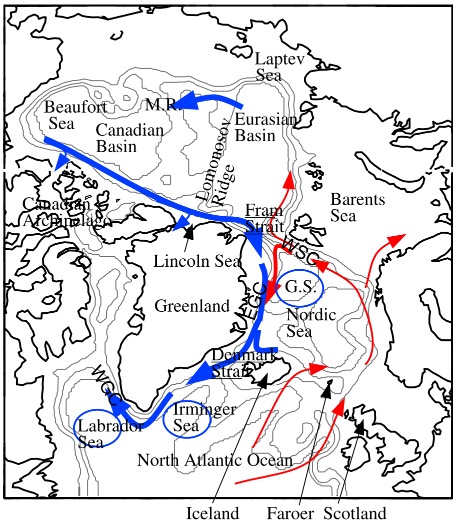

Figure 1. Red arrows show typical inflow pathways of warm and salty Atlantic Water, blue arrows depict the unusual relocation of fresh Arctic Water masses from the Lomonossov Ridge to the Mendeleev Ridge (M.R.) and out of the Arctic Ocean with the East Greenland Current (EGC) during the mid 1990s. Blue circles show areas where the formation of dense water is affected by freshwater influence.

coast. For the final calculations we grouped anomalies and calculated composite values in depth-time bins. The 50% freshest values in each bin to eliminate data with high salinities stemming from the northward flowing Atlantic Water adjacent to the relatively fresh EGC waters will be shown.

3. Results

3.1. Freshwater Exports

[6] Simulated ice export culminating in the late 1960s triggered the GSA in the model (Figure 2). After this peak the export remains higher than in the period before the GSA by ~500 km^3/y for a decade. Another period of high ice export occurs from 1988 to 1995, consistent with the timing in estimates from observations [*Vinje*, 2001]. Model investigations [*Köberle and Gerdes*, 2003] point to anomalies of the local wind in Fram Strait as the primary reason for the large ice export events, leading to a large southward ice drift.

[7] The simulated liquid freshwater export through Fram Strait (Figure 2) is much less variable on interannual time-scales than the ice export, visible even in the 5-year running mean series. A long-term trend culminates in an event of several years duration in the mid 1990s which exceeds the background by 500–1000 km^3/y. After 1998 the liquid export decreases again sharply, lagging the ice export, in contrast to the GSA, which was followed by a period of enhanced ice and liquid freshwater export. Most of the freshwater continues with the East Greenland Current (EGC) to Denmark Strait. A varying fraction, however, is diverted into the interior of the Nordic seas. The ice export through Denmark Strait behaves similar as the export through Fram Strait except for an offset due the melting of ice between the straits.

[8] The liquid freshwater export through Denmark Strait also exhibits a similar temporal behaviour as seen in Fram Strait with a positive offset of ~500 km^3/y. The bulk of the exported freshwater continues with the West Greenland Current into the Labrador Sea, a part recirculates into the Irminger Sea southwest of Iceland.

[9] While the reason for the large ice export of the mid 1990s is well established in literature [*Köberle and Gerdes*, 2003], this is not the case for the liquid export maximum. An analysis of the model simulation shows, however, that the liquid export maximum followed a large-scale change of the hydrographic structure in the Arctic. This involved the entire upper ocean above the halocline, suggesting that the source of the recent freshwater release lies in the Arctic Ocean.

3.2. Displacements of Freshwater Storage

[10] The simulated vertically integrated freshwater content in the beginning of the 1990s (Figure 3) reveals a large freshwater deficit relative to the 1980s extending from the eastern Eurasian Basin to the Mendeleev Ridge. This is consistent with the 'retreat of the cold halocline' [*Steele and Boyd*, 1998], a widespread salinification of the eastern Eurasian Basin observed in the first half of the 1990s. It was attributed to altered river water pathways from the Laptev Sea into the Arctic basin [*Steele and Boyd*, 1998]. The changed conditions of the Arctic sea level pressure patterns after 1989 that were responsible for this switch of river water pathways were associated with changes in the pressure patterns over the northern North Atlantic and the Nordic seas. These patterns are represented by the NAO-index which assumed unprecedented positive values in 1989 [*Hurrell*, 1995]. The intensified westerly winds during this period also forced an increased amount of water from the Atlantic into the Arctic Ocean [*Karcher et al.*, 2003]. In conjunction with the local atmospheric shift in the Arctic, namely a strongly reduced anticyclonic wind stress

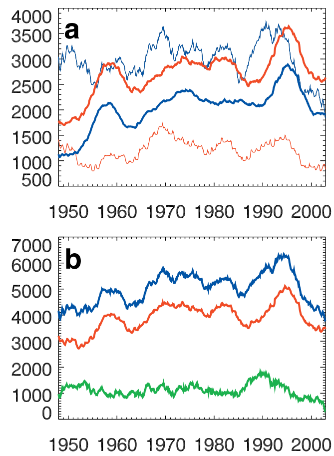

Figure 2. Simulated southward freshwater transports (km^3/yr). (a) Liquid (thick) and ice transport (thin) through Fram (blue) and Denmark Strait (red); (b) total freshwater transport (ice and liquid) and difference between Fram and Denmarkstrait transports (green). Reference salinity is 34.8, negative freshwater is allowed in the integration which covers the entire watercolumn. The graph is based on 5-year running means.

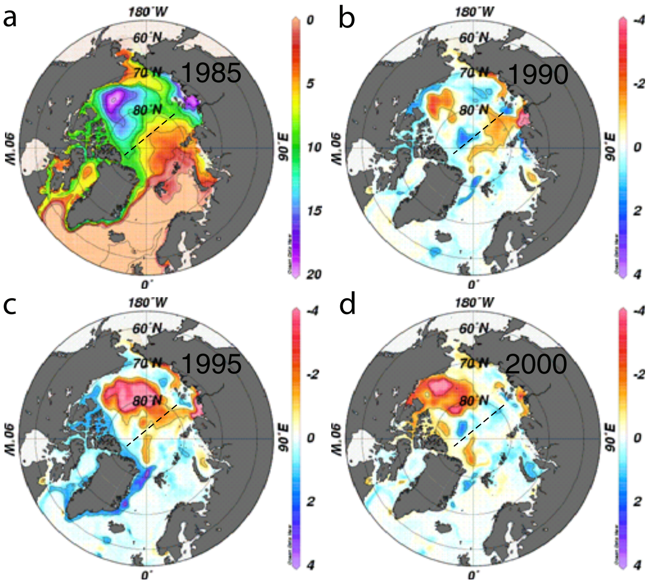

Figure 3. Simulated freshwater content presented as the equivalent freshwater column (m) contained in the upper 250 m relative to a reference salinity of 34.8 (a) in 1985, and anomaly relative to 1985 in the years (b) 1990, (c) 1995, and (d) 2000. Integration down to 250m depth or the bottom, negative freshwater is allowed. Black contours every 2.5 m (Figure 3a) and every 1 m (Figures 3b–3d). The graph is based on 5-year running means, the green line delineates Lomonosov Ridge.

field [*Proshutinsky and Johnson*, 1997], this led to an eastward shift of the Atlantic Water boundary in the lower halocline beyond the Lomonosov Ridge towards the Canadian Basin [*McLaughlin et al.*, 2002]. Our simulation reveals that the salinification in the Eurasian Basin at that time was accompanied by a simultaneous freshening of the eastern parts of the Beaufort and Lincoln Sea. In contrast to the ice which responded instantaneously to the high NAO state after 1989 with increased exports, the oceanic restructuring took several years, delaying the increase of Fram Strait liquid freshwater export. The most pronounced relocation of freshwater along the Canadian and Greenland coast occurred around 1995 (Figure 3c), consistent with observed changes in the Lincoln Sea [*Newton and Sotirin*, 1997]. Observations from the western Fram Strait also support the model result with very fresh EGC water in the mid 1990s [*ICES Oceanography Committee*, 2004]. In the late 1990s the return of atmospheric conditions in the Arctic to anticyclonic circulation [*Polyakov and Johnson*, 2000] together with a reduced Atlantic Water inflow [*Karcher et al.*, 2003] accompanied a partial re-freshening in the eastern Eurasian Basin in our simulation (Figure 3d) as well as in observations [*Boyd et al.*, 2002]. By this time the large simulated freshwater export has decreased to pre 1990s levels (Figure 2).

[11] The difference between ice and liquid freshwater exports for Denmark and Fram Strait is approximately equal to the freshwater diverted into the Nordic seas. After 1988 for about a decade the simulated net freshwater contribution from the EGC to the Nordic seas is higher than in previous periods by ~500 km^3/y. This adds up to an accumulation of several thousands of km^3 of extra freshwater in the Nordic seas during the 1990s compared to previous periods. We submit this accumulation as the cause for the accelerated observed freshening of the Nordic seas [*Blindheim et al.*, 2000]. The simulated net increase in the freshwater content of the Nordic seas, including variable salty inflows of Atlantic Water from the south, amounts roughly to 3000 km^3 between the late 1960s and the late 1990s in the model simulation. Over the same period the simulated loss of freshwater from the Arctic Ocean amounts to roughly 10 000 km^3. The freshwater gain in the Nordic seas is comparable to a recent hydrographic census [*Curry and Mauritzen*, 2005].

3.3. Salinities in the Denmark Strait Outflows

[12] In the simulation freshwater from both release events of the 1990s and the GSA recirculates in the central Nordic seas and north of Iceland. A larger release occurs through Denmark Strait. Both events differ however in the vertical extent of the salinity minima (Figure 4). In the upper 40 m the simulated GSA is less salty than in the 1990s event, especially in the annual minimum values. The 1990s anomaly is more intense at larger depths and distinguishable in yearly minima and maxima as well. It is mixed downward and hence contributes to the low salinities of water below the EGC which feeds the overflow in Denmark Strait. Thus it can contribute to a freshening of the deep subpolar basins, which is described by *Dickson et al.* [2002] from observations.

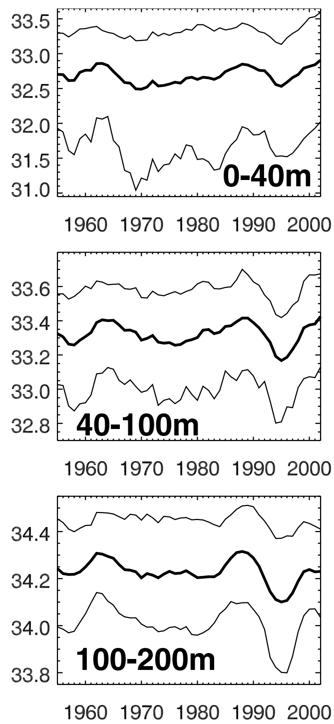

Figure 4. Time series of simulated salinity of the EGC at the southern end of Denmark Strait for different depth intervals. Thick lines represent yearly mean salinities, while light lines stand for minimum and maximum monthly mean salinities occurring in each year. The graph is based on 5-year running means.

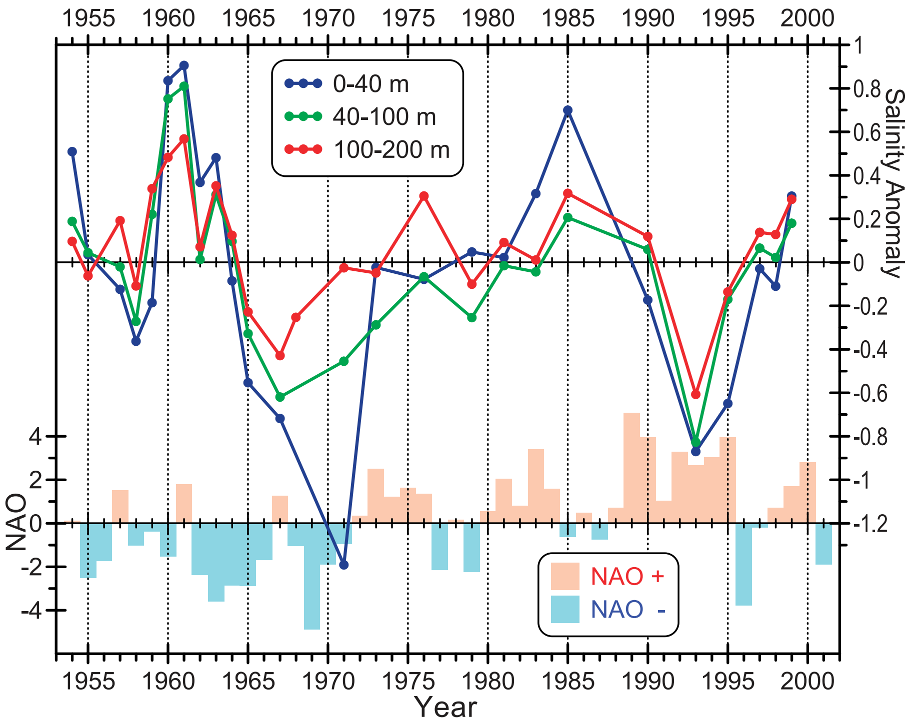

Figure 5. Time series of observed salinity anomalies of the EGC in Denmark Strait for different depth intervals in a 200 km wide region. Vertical colour bars denote the NAO index (December to March).

[13] The simulated low salinities in the EGC passing Denmark Strait southward in the mid 1990s are confirmed by a new compilation of observational data (Figure 5). Despite the sparseness of the observations, our analysis reveals very robust signals in the upper and deeper layers of the EGC. The two periods for which our model simulation suggests higher than normal fresh water transport (lower than normal salinities) are well covered observationally. The occurrences of extremely low salinities in the EGC in the late 1960s/early 1970s and the mid 1990 were the major events in the entire record. Similar to the simulation, the observed GSA exhibits lower salinities than the 1990s anomaly in the upper 40 m. In the deeper part of the EGC down to a depth of 200 m it is the 1990s anomaly which shows the lower salinities. The timing and the depth distribution of the model results are consistent with these observations. Furthermore the simulated downstream propagation of the recent freshwater export event into the Labrador Sea is also consistent with observations of unusually low salinities in the boundary currents west of Greenland and in the Labrador Sea in the mid to late 1990s [*ICES Oceanography Committee*, 2004].

4. Conclusions

[14] Our study reveals that an unusually large outflow of freshwater from the Arctic to the subarctic occurred as an export of ice and fresh water through Fram Strait and Denmark Strait in the mid 1990s. We showed that this export was a consequence of the changes in ice drift and hydrography in the central Arctic Ocean which constitute the large scale response of the Arctic Ocean to the high NAO state 1989–1995. We suggest that this large freshwater release contributed significantly to the observed freshening of the Nordic seas and the subpolar gyre in the 1990s. This confirms a key role of the Arctic Ocean in the mechanisms responsible for the properties of water fed into the Atlantic limb of the global thermohaline circulation. The results stress the importance of a more detailed investigation of the dynamics of the freshwater stored in the Arctic.

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