On large outflows of Arctic sea ice into the Barents Sea

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[1] Winter outflows of Arctic sea ice into the Barents Sea are estimated using a 10-year record of satellite ice motion and thickness. The mean winter volume export through the Svalbard/Franz Josef Land passage is 40 km^3, and ranges from -280 km^3 to 340 km^3. A large outflow in 2003 is preconditioned by an unusually high concentration of thick perennial ice over the Nansen Basin at the end of the 2002 summer. With a deep atmospheric low situated over the eastern Barents Sea in winter, the result is an increased export of Arctic ice. The Oct-Mar ice area flux, at 110×10^3 km^2, is not only unusual in magnitude but also remarkable in that >70% of the area is multiyear ice; the ice volume flux at $\sim$340 km^3 is almost one-fifth of the ice flux through the Fram Strait. Another large outflow of Arctic sea ice through this passage, comparable to that in 2003, is found in 1996. This southward flux of sea ice represents one of two major sources of freshwater in the Barents Sea; the other is the eastward flux of water via the Norwegian Coastal Current. The possible consequences of variable freshwater input on the Barents Sea hydrography and its impact on transformation of Atlantic Water en route to the Arctic Ocean are examined with a 25-year coupled ice-ocean model. **Citation:** Kwok, R., W. Maslowski, and S. W. Laxon (2005), On large outflows of Arctic sea ice into the Barents Sea, *Geophys. Res. Lett.*, *32*, L22503, doi:10.1029/2005GL024485.

1. Introduction

[2] A 10-year record (1994–2003) of satellite ice motion and thickness is used to quantify the outflows of Arctic sea ice through the Svalbard/Franz Josef Land (S-FJL) passage into the Barents Sea. Variability in this outflow is dependent on the wind fields and the mean thickness of the ice cover adjacent to this passage during the winter. Large outflows into the Barents Sea require the co-occurrence of thick ice and northerly winds. The set of satellite observations of 2002/2003 provide not only the thickness and motion estimates at the passage, but also a synoptic scale view of the preconditioning of this winter's large outflow resulting from the location of the perennial ice zone at the end of the preceding summer.

[3] The present note examines the sea ice and atmospheric conditions associated with the outflow of the winter of 2002/03 and the inflow in 1999/00; and, the variability of the outflow over the 10-year record. With a 25-year model simulation, the potential implications of this variable freshwater source on the Barents Sea salinity and its effect on the transformation of the Atlantic Water en route to the Arctic Ocean are discussed.

2. Data Description

[4] The primary datasets include: 1) daily ice motion fields (1992–2003) from satellite passive microwave data; 2) monthly thickness estimates (1993–2003) derived from radar altimeter sea ice freeboard measurements; and, 3) daily maps of perennial ice zone coverage (1999–2003) from QuikSCAT analysis. Ice motion from satellite passive microwave (PMW) observations is derived using the procedure described by *Kwok et al.* [1998]. In the following analyses, only the winter motion estimates from the 85-GHz V-polarization channel are used as ice tracking results are unreliable during the summer and transitional months [*Kwok et al.*, 1998]. Altimetric sea ice freeboard measurements (Oct-Mar) are converted to ice thickness by assuming hydrostatic equilibrium, fixed densities of ice and seawater and a monthly climatology of snow depth and density [*Laxon et al.*, 2003]. The coverage of the perennial ice zone, defined as having >90% multiyear (MY) ice concentration, is from QuikSCAT backscatter fields [*Kwok*, 2004]. The contrast in the radar backscatter between perennial and seasonal ice allows for easy delineation of these two zones.

[5] In addition, output from a coupled ice-ocean model of the pan-Arctic region is analyzed to investigate the effect of sea ice fluxes from the north on the Barents Sea freshwater budget and the potential role of variable freshwater content in the Barents Sea in the transformation of Atlantic Water en route to the Arctic Ocean. The model is configured on a 1/12° and 45-level grid covering all the ice covered oceans of the northern hemisphere. It is forced with daily atmospheric 1979–2002 ECMWF data. Monthly mean model output from a 25-yr simulation is used to examine the oceanic implications. More information about the model setup and integration is given by *Maslowski and Lipscomb* [2003] and *Maslowski et al.* [2004].

3. Results and Discussion

3.1. 10-year (1994–2003) Flux Record

[6] Area and volume flux are computed along a gate that spans the $\sim$300 km passage between Storøya, Svalbard and

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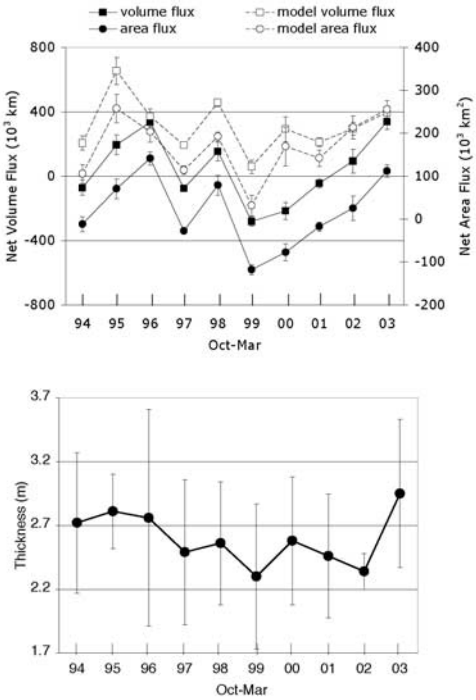

Figure 1. (top) 10-year record of Oct-Mar (estimated and modeled) net sea ice area and volume flux through a gate between Storøya, Svalbard and Zemlya Alekandry, Franz Josef Land. The error bars represent the standard deviation of the monthly means compared to the 6-month net volume flux. (bottom) Mean Oct-Mar sea ice thickness derived from sea ice freeboard measurements. On the plots, the year is associated with the end of the period.

Zemlya Alekandry, Franz Josef Land. The details of the procedures used in constructing these estimates and computing their uncertainties are outlined by *Kwok et al.* [2004]. Briefly, daily motion samples are first summed to form the monthly motion estimates; then, the product of the monthly cross-gate motion and thickness profiles are integrated along the gate to provide the net area and volume flux estimates. To account for open water areas, the area estimates are weighted by passive microwave ice concentration. The Oct-Mar results are shown in Figure 1. Following the procedures by *Kwok et al.* [2004] and using uncertainties in the individual motion vectors and thickness of 5 km/day and 0.5 m, we obtain uncertainties in area and volume flux of $\sim 10 \times 10^3$ km^2 and ~ 40 km^3 over the 6-month period. Over the record, the average Oct-Mar area flux is $20(\pm 80) \times 10^3$ km^2. There are as many years with net inflows as there are with outflows. Average volume flux is 40 km^3 ranging from a net inflow of 281 km^3 in 1998/99 to a high outflow of 340 km^3 in 2002/03; the second highest year is 335 km^3 during the winter of 1995/96. The volume flux into the Barents Sea in 2002/03 is almost one-fifth of the average Oct-May (1978–2003) Fram Strait ice export of 1900 km^3.

3.2. Variability: Oct-Mar of 1999/2000 and 2002/2003

[7] We select two winters, one with net inflow (1999/2000) and another with a large net outflow (2002/2003) to examine the conditions associated with these extremes. 1998/99, an extreme year, is not selected because QuikSCAT data for showing the location of the PIZ are not available until after July of 1999.

[8] In September 2002, the Arctic sea ice extent and area reached their lowest recorded levels since 1978 [*Serreze et al.*, 2003]. Following this record summer minimum, the winter perennial ice zone (PIZ) is unusual in its overall location and spatial coverage of the Arctic Ocean. At the end of the 2002 summer, the boundaries of the PIZ (Figure 2 (bottom)) in the Beaufort, Chukchi, and Laptev Seas are located farther north than usual. In contrast, the PIZ coverage over the Nansen Basin is located as far south as the S-FJL passage into the Barents Sea, and the passage between Franz Josef Land and Severnaya Zemlya into the Kara Sea. The boundaries of the PIZ in the eastern Arctic are typically north of these passages with seasonal ice seen only during the fall and winter. This arrangement is a consequence of a Jun-Aug SLP pattern during the 2002 summer when a closed Arctic low centered far north in the Canada Basin advected the PIZ to their final summer location, with the boundaries displaced from their location compared to the previous three years (not shown here except 1999–2000). Together with a winter SLP pattern, characterized by a deep low in the eastern Barents Sea, a significant area and volume of thick MY ice are exported through the S-FJL passage into the Barents Sea. This

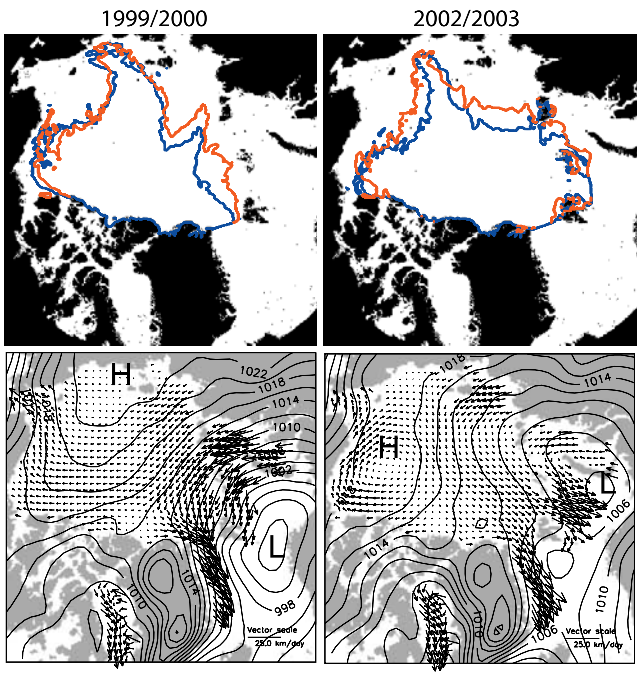

Figure 2. Boundaries of the perennial ice zone (>90% multiyear ice) on December 15 (red) and April 15 (blue) the following year and the associated mean DJFM sea ice drift from satellite observations and sea level pressure fields from NCEP reanalysis products. (left) 1999/2000. (right) 2002/2003. Contour intervals: 2 hPa. Monthly sea-level pressure (SLP) fields are from the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis [*Kalnay et al.*, 1996].

Table 1. Freshwater Flux (mSv; 1 mSV = '10' m/s or 31.5 km/yr, Reference Salinity = 34.8 psu)[a]

Section	25-yr Mean Liquid	25-yr Mean Ice	07/94–12/95 Liquid	07/94–12/95 Ice	07/02–12/03 Liquid	07/02–12/03 Ice
Svalbard-Norway	9.6	−3.9	13.5	−7.4	9.8	−1.0
Kara Gate	−10.6	NA	−14.2	NA	−13.9	NA
FJL-Novaya Zemlya	−12.8	5.5	−14.5	6.3	−12.2	5.0
Svalbard-FJL	0.7	14.9	0.5	25.6	1.8	18.4
Fram Strait	10.1	50.4	14.5	81.7	11.0	29.7

[a]Positive indicates into the Barents Sea, or out of Arctic Ocean at Fram.

combination of high MY ice concentration at the flux gate (~2.9 m; thickest over this short record) and the ice drift associated with northerly winds can be seen in Figure 1 and Figure 2 (bottom). The net area and volume outflows over the six months are 110×10^3 km^2 and 340 km^3. Because of the location of the low pressure cell, this winter also saw the lowest Fram Strait ice area flux over the 25 year ice flux record – the Oct-May ice flux is 480×10^3 km^2 compared to the mean of 750×10^3 km^2 [*Kwok et al.*, 2004]. Comparatively, the Barents Sea ice export represents a significant fraction of the net Arctic Ocean export this winter.

[9] The conditions during Oct-Mar 1999/2000 are quite different. The boundaries and coverage of the PIZ over the Nansen Basin are far north of the passages into the Barents Sea. The center of the mean atmospheric low is situated in the western Barents Sea leading to a net inflow (80×10^3 km^2) of ice into the Arctic Ocean (Figure 2(top)). The net advection of the PIZ boundaries is towards the Arctic interior and the Fram Strait rather than toward the S-FJL passage. With an average thickness of ~2.5 m of mostly seasonal ice, the estimated volume transport into the Arctic Ocean is ~220 km^3.

[10] Over the 10 years, the variability of the ice area and volume export is high. The direction of ice export through the S-FJL passage is controlled by the location of the low in the Barents Sea. The magnitude is determined by two factors: the strength of wind forcing; and, the availability of thick MY ice near the passage. The second factor is connected to the large-scale location of the PIZ within the Arctic Ocean. The location and spatial coverage of the PIZ will become more variable with the decreasing trend in its coverage [*Johannessenen et al.*, 1999; *Comiso*, 2002]. Since the PIZ occupies less of the Arctic Ocean and there is more open ocean in the summer, this zone could presumably be advected to different regions of the Arctic during the summer occasionally preconditioning large winter sea ice outflows such as seen in 2002/2003.

3.3. Oceanographic Implications

[11] One branch of warm and dense Atlantic water that crosses the shelf of the Barents Sea before entering the Polar Basin from the northern Kara Sea is referred to as the Barents Sea Branch Water (BSBW). *Aagaard and Woodgate* [2001] point to the consequences of the sea ice melt in the transformation of this water on the Barents Shelf. Meltwater is entrained into this northward Barents Sea throughflow as the cooling of BSBW allows the meltwater (and runoff or precipitation) to be injected without reducing the initial density of BSBW, since the opposing effect on density of cooling and freshening on the shelf nearly balance. The depth at which this BSBW water resides in the Arctic Ocean is at least in part dependent on the freshwater input and mixing in the Barents Sea in addition to the initial temperature/salinity and advection rate of the BSBW. Prolonged reduction in sea ice and freshwater injection would likely result in a warmer and more saline interior Arctic Ocean below 800 m [*Aagaard and Woodgate*, 2001].

[12] In a year-long (summer 1995–1996) study, *Woodgate et al.* [2001] speculated that the cooling and freshening of the Atlantic layer (AL) observed at three moorings on the slopes of the Eurasian shelf (spanning the junction of the Lomonosov Ridge with the Eurasian continent) could be attributed to changes in the outflow from the Barents Sea in the previous winter, possibly caused by increased outflow of Arctic sea ice into the Barents Sea. They speculated that the observed freshening of the AL could be accomplished by melting ~140 km^3 of sea ice, one-third of their estimated ice flux. This can be compared to our present 6-month (Oct 1994–Mar 1995) outflow estimate of ~195 km^3 of sea ice into the Barents Sea.

[13] We turn to a 25-year model simulation to examine the longer-term implications. The southward flux of sea ice represents one of the two major sources of freshwater in the Barents Sea; the other is the eastward flux of water via the Norwegian Coastal Current (NCC) [*Maslowski and Walczowski*, 2002]. Figure 1 compares the model ice flux into the Barents Sea with the estimates presented above. Except for biases, which can be attributed to both the model parameterization of ice-ocean thermodynamics and the prescribed ECMWF atmospheric forcing, there is general agreement in the variability in volume and area flux. Model freshwater flux estimates averaged over 1979–2002 show (Table 1) a net inflow of sea ice through the S-FJL section into the Barents Sea, equivalent to ~14.9 mSv or 470 km^3/yr (1 mSv = 10^3 m^{3}s^{-1} or 31.5 km^3/yr) compared to a net of ~9.6 mSv freshwater inflow through the Barents Sea Opening via the NCC. Freshwater flux is ~18.4 mSv (ice) and 9.8 mSv (liquid) averaged from July 2002 through December 2003 for the year discussed above.

[14] According to model output the maximum freshwater influx into the Barents Sea (Figure 1 and Table 1) occurred in 1994/1995. Its significance can be seen in the time series of anomalies in freshwater content in the Barents Sea (Figure 3) - the 25-year mean annual cycle signal is removed. The freshwater flux is 25.6 mSv (ice) and 13.54 mSv between July 1994 and December 1995. During that period a maximum excess of ~300 km^3 of freshwater (Figure 3), associated with sea ice inflow during the preceding winter, has accumulated there compared to the 25-year mean of 1657 km^3. This adds to the overall positive freshening trend in the Barents Sea over

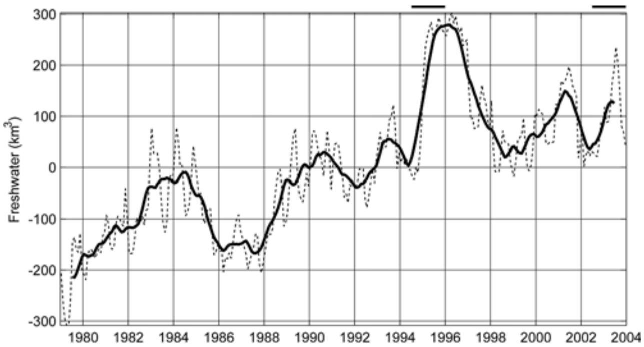

Figure 3. Modeled freshwater content anomaly (km^3) in the Barents Sea. Mean 1979–2002 annual cycle removed. Monthly mean (dashed line) and 13-month running mean (solid) time-series are shown. Two thick black lines above the plot indicate the time periods used in Table 1.

the simulation period; the increased inflow of warmer and more saline Atlantic water in the 1990s can in fact be seen as a dip in the anomalies in freshwater content. Figure 3 also shows additional local maxima in 1983/84 and 1989/1990; illustrating the potential of this region for transformation of BSBW through cooling and mixing en route to the Arctic Ocean. The influx of sea ice into the Barents Sea appears to be a significant if not dominant controlling factor of this process.

[15] Over the same 25 years, the model freshwater outflow through the section between Franz Josef Land and Novaya Zemlya (not shown here) also experiences an overall increasing trend with local maxima in 1989, 1996/1997 and 1999. Combined with the freshwater flux through the Kara Gate, the net input represents the remaining portion of freshwater that does not get mixed with Atlantic Water in the Barents Sea and a source of buoyancy for the upper water column of the Eurasian Basin or regions further downstream in the Makarov or Canada Basins.

[16] In agreement with above observations the export through Fram Strait reached a minimum during the winter of 2002/03 with the averaged flux of $\sim$30 mSv, compared to the 25-year mean of 50 mSv (Table 1). However, during the 1994/1995 period, ice export through Fram Strait was in phase with that through S-FJL passage, reaching a maximum of 81.7 mSv; examination of the ice motion and SLP distribution shows atmospheric forcing favorable to large outflows through both passages in contrast to conditions during the 2002/2003 winter when they are out-of-phase. Area outflows at the two passages are dependent on SLP; volume outflows are preconditioned by the availability of thick ice at these passages.

4. Conclusions

[17] The present note examines the sea ice and atmospheric conditions associated with the outflow of sea ice into the Barents Sea and discusses the impact of this freshwater on the through flow of dense Atlantic Water. Outflow is estimated using available satellite ice motion and thickness. Over the record, the average Oct-Mar area flux is 20(±80) $\times$ 10^3 km^2. Average volume flux is 40 km^3 and ranges from net inflow of 280 km^3 in 1998/99 to a high outflow of 340 km^3 in 2002/03. The direction of ice export is controlled by the location of the mean atmospheric low in the Barents Sea while the magnitude is determined by the strength of the wind and the availability of thick MY ice near the passage. The second factor is connected to the large-scale location or spatial arrangement of the PIZ within the Arctic Ocean. Large variability is expected as the PIZ shrinks and is easily advected to different locations during the summer; location of the PIZ boundaries near passages are conducive to increased loss of thick ice when atmospheric conditions are favorable, as in 2002/03. These considerations are of obvious importance to the development, survival, and future evolution of the PIZ.

[18] Atlantic Water, in its passage through the Barents Sea, is subjected to intense mixing processes that vary from seasonal to interannual time scales. Arctic sea ice is one source of freshwater that affects the transformation of its properties. After the transformation processes in the Barents Sea, the less dense shelf water feeds the upper ocean and the halocline of the Arctic Ocean; the densest water enters the Arctic via the St. Anna Trough. *Aagaard and Woodgate* [2001] suggest that the depth at which this water resides in the Arctic Ocean is dependent on the freshwater input and mixing in the Barents Sea. Prolonged reduction in sea ice and freshwater injection would likely result in a warmer and more saline interior Arctic Ocean below 800 m.

[19] The effects of these large sea ice outflows are evident in the model simulations. The model anomalies in freshwater content (Figure 3) show the potential sensitivity of the Barents Sea to large inflows of sea ice from the Arctic. The sea ice mass balance here is a crucial factor for the final density of the deep water produced on the shelf and its outflow into the Barents Sea can account for a significant portion (up to 18%) of the mean freshwater content. This underscores the need for proper representation of freshwater fluxes into/out of the Arctic Ocean in ocean general circulation models for realistic simulations of variability in the Barents Sea and its role in the transformation of Atlantic Water.

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References

Aagaard, K., and R. A. Woodgate (2001), Some thoughts on the freezing and melting of sea ice and their effects on the ocean, *Ocean Modell.*, *3*, 127–135.

Comiso, J. C. (2002), A rapidly declining perennial sea ice cover in the Arctic, *Geophys. Res. Lett.*, *29*(20), 1956, doi:10.1029/2002GL015650.

Johannessen, O. M., E. V. Shalina, and M. W. Miles (1999), Satellite evidence for an Arctic sea ice cover in transformation, *Science*, *286*, 1937–1939.

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

Kwok, R. (2004), Annual cycles of multiyear sea ice coverage of the Arctic Ocean: 1999–2003, *J. Geophys. Res.*, *109*, C11004, doi:10.1029/2003JC002238.

Kwok, R., A. Schweiger, D. A. Rothrock, S. Pang, and C. Kottmeier (1998), Sea ice motion from satellite passive microwave data assessed with ERS SAR and buoy data, *J. Geophys. Res.*, *103*, 8191–8214.

Kwok, R., G. F. Cunningham, and S. S. Pang (2004), Fram Strait sea ice outflow, *J. Geophys. Res.*, *109*, C01009, doi:10.1029/2003JC001785.
Laxon, S., N. Peacock, and D. Smith (2003), High interannual variability of sea ice in the Arctic region, *Nature*, *425*, 947–950.
Maslowski, W., and W. H. Lipscomb (2003), High-resolution simulations of Arctic sea ice during 1979–1993, *Polar Res.*, *22*, 67–74.
Maslowski, W., and W. Walczowski (2002), Circulation of the Baltic Sea and its connection to the Pan-Arctic region—A large scale and high-resolution modeling approach, *Boreal Environ. Res.*, *7*, 319–325.
Maslowski, W., D. Marble, W. Walczowski, U. Schauer, J. L. Clement, and A. J. Semtner (2004), On climatological mass, heat, and salt transports through the Barents Sea and Fram Strait from a pan-Arctic coupled ice-ocean model simulation, *J. Geophys. Res.*, *109*, C03032, doi:10.1029/2001JC001039.
Serreze, M. C., J. A. Maslanik, T. A. Scambos, F. Fetterer, J. Stroeve, K. Knowles, C. Fowler, S. Drobot, R. G. Barry, and T. M. Haran (2003), A record minimum arctic sea ice extent and area in 2002, *Geophys. Res. Lett.*, *30*(3), 1110, doi:10.1029/2002GL016406.
Woodgate, R. A., et al. (2001), The Arctic Ocean Boundary Current along the Eurasian slope and the adjacent Lomonosov Ridge: Water mass properties, transports and transformations from moored instruments, *Deep Sea Res., Part I*, *48*, 1757–1792.

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