North Atlantic Water in the Barents Sea Opening, 1997 to 1999

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North Atlantic Water (NAW) is an important source of heat and salt to the Nordic seas and the Arctic Ocean. To measure the transport and variability of one branch of NAW entering the Arctic, a transect across the entrance to the Barents Sea was occupied 13 times between July 1997 and November 1999, and hydrography and currents were measured. There is large variability between the cruises, but the mean currents and the hydrography show that the main inflow takes place in Bjørnøyrenna, with a transport of 1.6 Sv of NAW into the Barents Sea. Combining the flow field with measurements of temperature and salinity, this results in mean heat and salt transports by NAW into the Barents Sea of 3.9×10^{13} W and 5.7×10^{7} kg s^{-1}, respectively. The NAW core increased in temperature and salinity by 0.7 °C yr^{-1} and 0.04 yr^{-1}, respectively, over the observation period. Variations in the transports of heat and salt are, however, dominated by the flow field, which did not exhibit a significant change.

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The influence of the flow of warm and saline North Atlantic Water (NAW) into the Nordic seas and the Arctic Ocean has long been recognized (Helland-Hansen & Nansen 1909; Hansen & Østerhus 2000). The strong interactions between the ocean, ice and atmosphere at high latitudes lead to large transfers of heat from the NAW to the atmosphere, making the region warm for its latitude, and the inflow of NAW to the Arctic through the Barents Sea is important in the formation of the dense waters that form the deep limb of the thermohaline circulation. Anomalies of heat and freshwater, such as the Great Salinity Anomaly (Dickson et al. 1988), that are advected through the Arctic, including the Barents Sea, appear to be an important link in the feedback loops controlling Arctic climate (Mysak 1998). To understand the climate of the region and the role it plays in the larger scale climate system that includes the North Atlantic and Arctic oceans, it is necessary to understand the exchanges between the Barents and Norwegian seas, and the variability of these exchanges. This is the motivation for the VEINS (Variability of Exchanges in Northern Seas) project, which had the objective of measuring and modelling the variability of fluxes between the Atlantic and Arctic oceans to understand the role of the high latitude oceans in the climate system. As part of VEINS, the Norwegian Polar Institute carried out a series of cruises along the Barents Sea Opening (BSO). Here we focus on the variability of the branch of NAW flowing into the Barents Sea and attempt to identify some of the mechanisms contributing to the observed variability. The results described here are based on temperature, salinity and velocity measured on a section along the BSO that was repeated every three to four months between July 1997 and November 1999.

As shown in Fig. 1, NAW is transported northward along the Norwegian coast by the Norwegian Atlantic Current. The current splits at the

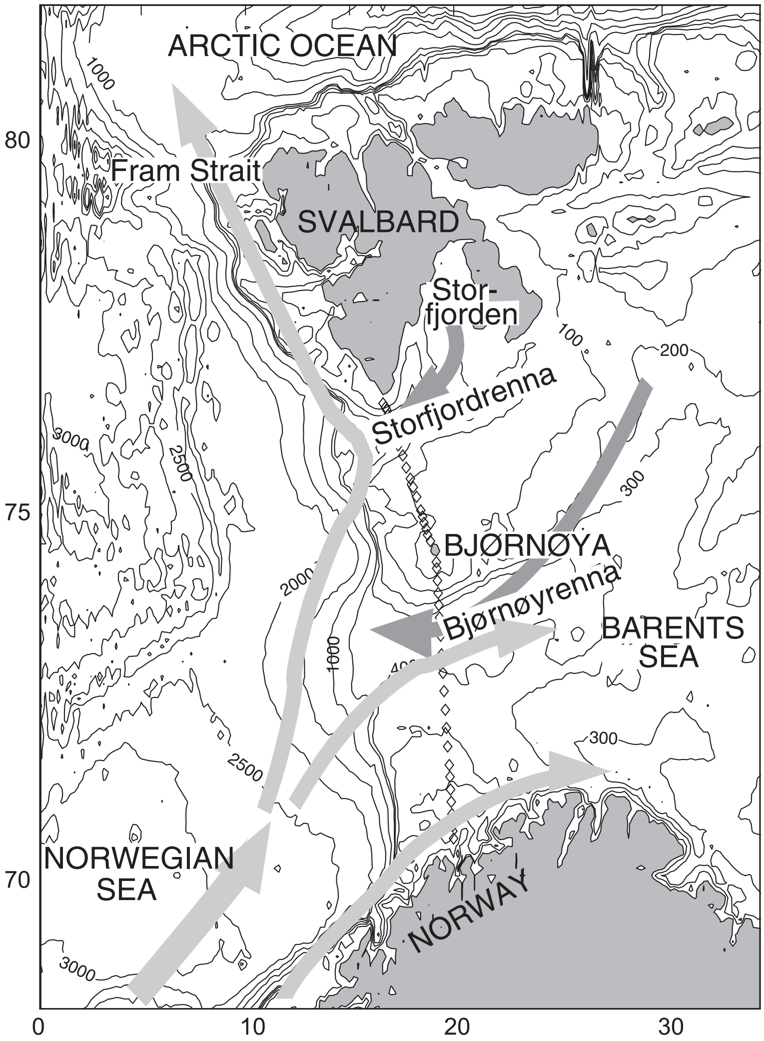

Fig. 1. The main features of the topography and circulation in the BSO. CTD stations are marked ◇.

BSO and one branch flows eastward into the Barents Sea, whilst the remainder continues northward to Fram Strait and directly into the Arctic Ocean (Hansen & Østerhus 2000). Flow through the BSO occurs in the channels on either side of the island of Bjørnøya. The deepest is Bjørnøyrenna, in the south, with a maximum depth of nearly 500 m. The water entering Bjørnøyrenna can flow across the entire Barents Sea without encountering topography shallower than 200 m; this is the main inflow path for NAW. Storfjordrenna to the north is 300 m deep, but it shoals to the east, and is blocked by Spitsbergenbanken at about 23° E. NAW is not observed in Storfjorden to the north either (Haarpaintner et al. unpubl. ms), so the NAW in Storfjordrenna must recirculate within Storfjordrenna and return west, with properties that have been modified by cooling and mixing. However, Storfjordrenna does provide a path to the west for the cold and saline deep water that is formed in Storfjorden (Schauer 1995).

The Barents Sea is a key region for water mass modification in the Arctic (Swift et al. 1983). Interactions with ice and atmosphere, and mixing in the Barents Sea, significantly modify the water masses before they enter the Arctic Basin, in contrast to the NAW that enters relatively unchanged through Fram Strait. There are large seasonal variations in conditions in the Barents Sea. In winter the northern Barents Sea is ice-covered. Cooling and brine-rejection increases the density of the surface layer and, combined with mechanical mixing by the wind, this leads to vertical homogenization of the water column. The dense water that is formed fills the northern Barents Sea. Some flows northwards into the Arctic Ocean and some southwards through the BSO into the Norwegian Sea (Pfirman et al. 1994). In spring and summer the sea ice melts, creating a fresh surface layer; warming of the surface layer during the summer further increases the stability of the water column. This inhibits vertical mixing, and tends to isolate the deeper water from atmospheric contact, conserving the properties of the water masses created in the winter in the deep water.

Observations

The section along the BSO shown in Fig. 1 was repeated 13 times between July 1997 and November 1999. The section consisted of temperature and salinity measurements at 38 CTD stations, and continuous measurements of velocity by ship-mounted ADCP (details are given in Table 1).

CTD salinities were calibrated using water samples collected at each station. On most stations water samples were collected at the surface and the bottom, except in the shallow water near Bjørnøya, where only the bottom sample was collected. During VEINS01, salinities were analysed on board and for the other cruises salinities were analysed after the cruise (Table 1). Samples for which the difference between the bottle and CTD values was greater than two standard deviations from the mean were not used for calibration. A linear fit between the remaining sample salinities and CTD salinities was used to correct the CTD salinities. The CTD data were checked for density inversions and points were removed if the vertical gradient of potential density was greater than $0.1\ \mathrm{kg\ m^{-3}\ m^{-1}}$.

The ADCP measurements cover the top 200 m. They thus miss the flow in the deepest parts of Bjørnøyrenna and Storfjordrenna. Profiles of northward and eastward velocities were averaged over ten minutes and processed using the GfICODAS package. The tidal velocities were subtracted from the processed data using results from a barotropic tidal model (Gjevik et al. 1994). There are several possible sources of uncertainty in the transports determined from the ADCP measurements, including: 1) The ADCP measurements are subject to errors due to the ship's motion. Velocities measured along the ship's track are most strongly affected, and in this case, where the ship's track lies nearly north—south, errors are minimized by only considering the east—west flow. 2) The instantaneous flow field is dominated by the tides, therefore a relatively small error of around 10 % in the tidal component obtained from the model could lead to an error with a magnitude similar to the mean flow. 3) There are large short timescale (from days to months) variations in the flow. Because these timescales are not properly resolved by the ADCP measurements, there could be aliassing of this short timescale variability. Therefore, although these data are a useful supplement to the hydrographic data, they should be treated with a certain amount of caution.

The mean conditions are described below. To study the variability, the NAW cores in Bjørnøyrenna and Storfjordrenna are identified for each cruise from the CTD data as the salinity maximum where $T > 2$ °C. To determine the transport of NAW, CTD and ADCP measurements are combined as follows: for each cruise the vertically averaged velocity is interpolated onto 0.1° latitude intervals, and for each interval the CTD data within 0.2° latitude are averaged to give temperature and salinity profiles. Points where $S > 34.95$ and $T > 2$ °C are identified as being NAW. The commonly used definition in the Nordic seas is $S > 35$ (Helland-Hansen & Nansen 1909), but

Table 1. Details of the thirteen VEINS cruises, giving the number of CTD stations occupied, the CTD used (Neil Brown, NB, or Seabird, SB). Crosses in the final two columns indicate whether water samples were taken and whether ADCP measurements were made.

Cruise	Date	No. of CTD stations	Type of CTD	Water samples	ADCP
VEINS01	July 1997	38	NB	×	×
VEINS02	Nov. 1997	37	NB		×
VEINS03	Feb. 1998	10	NB		
VEINS04	Mar. 1998	29	NB	×	×
VEINS05	May 1998	30	NB	×	×
VEINS06	July 1998	38	NB	×	×
VEINS07	Sept. 1998	35	NB	×	×
VEINS08	Nov. 1998	38	NB	×	
VEINS09	Feb. 1999	22	NB/SB		×
VEINS10	May 1999	32	SB	×	×
VEINS11	July 1999	38	SB	×	×
VEINS12	Sept. 1999	26	SB	×	
VEINS13	Nov. 1999	38	SB	×	×

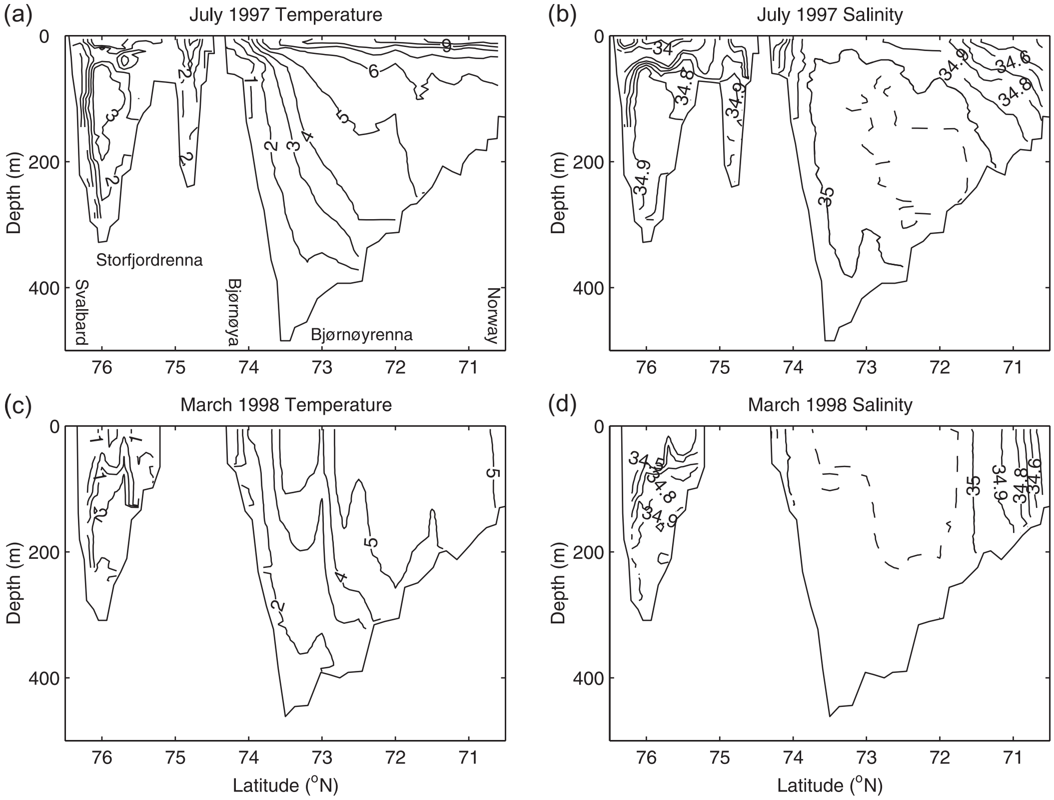

Fig. 2. Conditions in the BSO in July 1997: (a) temperature and (b) salinity; and in March 1998: (c) temperature and (d) salinity. Note that the section is looking eastward, into the Barents Sea.

the fresher definition is often used in the Barents Sea since the temperature and salinity of NAW decrease northwards (Loeng 1991). Temperature, salinity and velocity at the points identified as NAW are used to calculate transports of volume, heat and salt. Heat transport is determined relative to 0 °C and salt transport relative to 0. The seasonal and interannual variability of the core values is described in later sections.

Mean conditions

CTD sections from July 1997 and March 1998 (Fig. 2) show conditions typical for the BSO. In the summer there is a warm, fresh layer of meltwater at the surface (Fig. 2a, b) and this leads to strong stratification. In winter increased vertical mixing means that the water column becomes more homogeneous (Fig. 2c, d). NAW is present throughout the year as a warm salinity maximum, with its main core on the southern slope of Bjørnøyrenna at a depth between 150 and 250 m. The NAW in Storfjordrenna is cooler and fresher than that in Bjørnøyrenna, and NAW as we have defined it here is not always present in Storfjordrenna. This probably reflects the fact that Storfjordrenna lies further along the flow path of NAW than Bjørnøyrenna does, and the NAW in Storfjorden has undergone more mixing with the surrounding cold, fresh Arctic water masses. The cold, dense water mass at the bottoms of the channels in the BSO is formed in winter in the northern Barents Sea (Pfirman et al. 1994) and in Storfjorden (Schauer 1995).

The instantaneous velocity field is dominated by barotropic tidal currents. In the shallow water surrounding Bjørnøya, there is flow of up to 40 cm s^{-1}, and in the deeper channels the flow reaches about 10 cm s^{-1}. The detided currents remain strongly barotropic, and the following analysis uses the vertically averaged currents. Transports vary greatly between cruises, but the

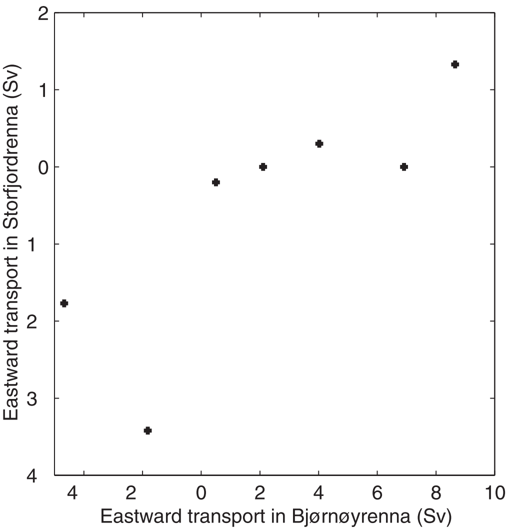

Fig. 3. Transport in Storfjordrenna plotted against transport in Bjørnøyrenna.

positive correlation between the transports in Storfjordrenna and Bjørnøyrenna (Fig. 3) indicates that they share a common forcing agent. This is probably the wind, as suggested by Loeng et al. (1997) and Ådlandsvik & Hansen (1998).

The mean circulation over the top 200 m, determined from all the cruises (Fig. 4) appears to be topographically controlled. The circulation in each hollow is cyclonic, with eastward flow to the south and westward flow to the north. This implies either recirculation within the hollow, or two separate water masses flowing in opposite directions on each bank of the hollow. The main inflow, on the southern slope of Bjørnøyrenna between about 72° and 73° N, has a velocity of about 10 cm s^{-1}, coinciding with the core of the NAW (Fig. 2). The flow in Bjørnøyrenna resembles that observed using current meters by Blindheim (1989). Haugan (1999) and Furevik (2001) report two cores of NAW in Bjørnøyrenna, and there is an indication of two inflows on the Bjørnøyrenna slope, although they do not seem to be associated with separate cores in the CTD data (Fig. 2). On the northern slope of Bjørnøyrenna, a current of a similar magnitude flows in the opposite direction, associated with the colder, fresher outflow from the Barents Sea. There are strong currents near Bjørnøya, but this area is shallow and the associated transports are small. On average 1.6 Sv of NAW flows into the Barents Sea through Bjørnøyrenna, carrying heat and salt amounting to 3.9×10^{13} W and 5.7×10^{7} kg s^{-1}, respectively. North of Bjørnøya, in Storfjordrenna, the transports are, respectively, -0.4 Sv, -0.7×10^{13} W and -1.5×10^{7} kg s^{-1}. This appears puzzling, since it implies a flow of NAW out of the Barents Sea through Storfjordrenna; however, the magnitude of this transport is similar to the standard error of the mean transport and it is therefore also consistent with there being no net flow of NAW through Storfjordrenna.

Seasonal variability

The plots of temperature and salinity by month in Fig. 5 (a, b) show that NAW tends to be cooler and fresher in winter than summer. In Bjørnøyrenna the temperature varies between 4.6 °C and 7.3 °C and salinity between 35.07 and 35.24 during the observational period. The seasonal cycle in Storfjordrenna is more pronounced: temperature varies between 2.7 °C and 5.6 °C and salinity between 34.97 and 35.13. However, in the 29 months during which the observations were carried out, the variation between summers could be as large as the variation between summer and

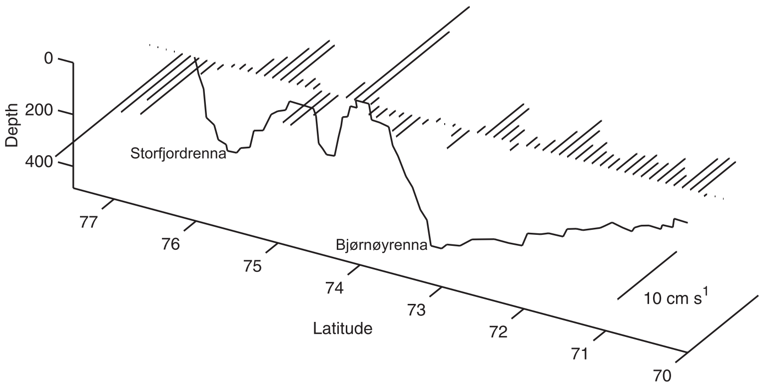

Fig. 4. The mean vertically averaged velocities, shown in relation to the BSO topography.

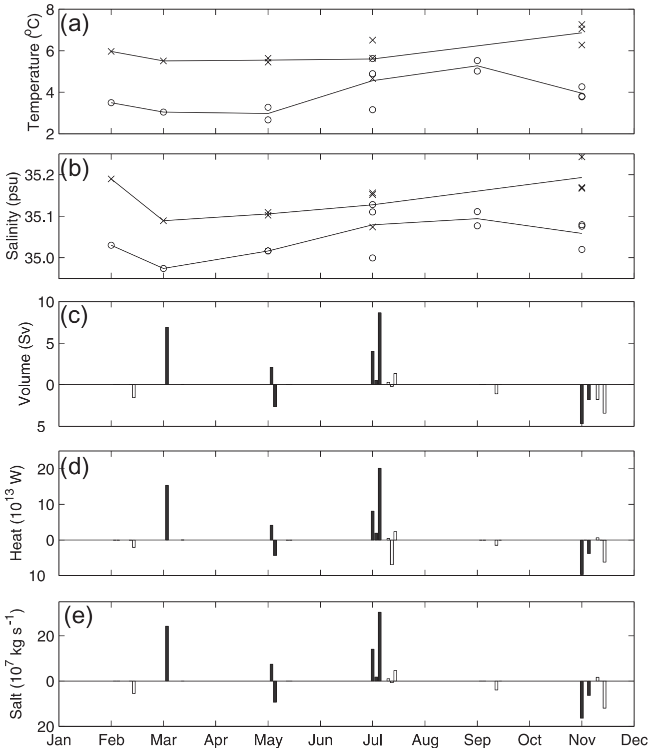

Fig. 5. (a) Temperature and (b) salinity of the NAW, and transports of (c) volume, (d) heat and (e) salt by NAW, plotted against month to show seasonal variability. In (a) and (b) crosses represent Bjørnøyrenna and circles Storfjordrenna. In (c)–(e) black bars represent Bjørnøyrenna and white bars Storfjordrenna.

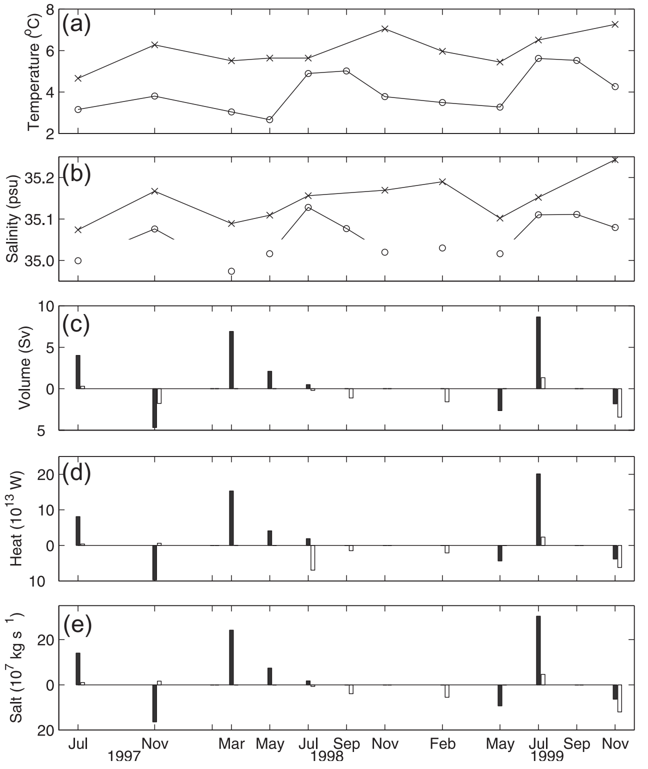

Fig. 6. (a) Temperature and (b) salinity of the NAW core, and transports of (c) volume, (d) heat and (e) salt by NAW, plotted against time to show interannual variability. Symbols in the plots are as for Fig. 4.

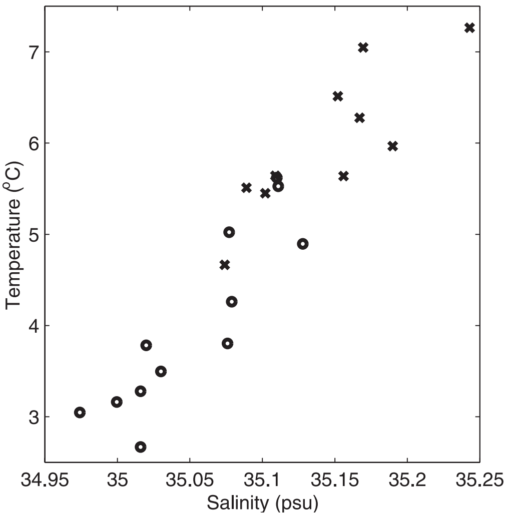

Fig. 7. T-S diagram of the core properties in Bjørnøyrenna and Storfjordrenna. There is a correlation of 0.93 between T and S.

winter, as illustrated by the large differences in July temperatures (1 °C) and salinities (0.08) in Bjørnøyrenna over the three years of observations (Fig. 5a, b). Midttun (1990) noted similar large interannual variability for the years 1977 to 1987.

Figure 5c shows the large variability of the volume transport through the BSO. The variation of heat and salt transports through the BSO (Fig. 5d, e) are mainly determined by the flow field, and the effects of temperature and salinity variations are relatively small. There appear to be generally higher transports in July, and low transports in November, suggesting a possible seasonal cycle, although the single transport measurement in March is also large.

Interannual variability

Figure 6 (a, b) shows that the temperature and salinity of the NAW cores in both Bjørnøyrenna and Storfjordrenna increase steadily between 1997 and 1999. In Bjørnøyrenna, temperature and salinity increase by 0.7 °C yr^{-1} and 0.04 yr^{-1}, respectively. In Storfjordrenna the increases are 0.7 °C yr^{-1} and 0.02 yr^{-1}, respectively. The T-S diagram in Fig. 7 shows that temperature and salinity from Bjørnøyrenna and Storfjordrenna lie on a straight mixing line, with a correlation coefficient of 0.93. The various NAW cores could therefore be created by mixing between two source water masses with constant properties, for example, the most extreme NAW observed, with T = 7.3 °C and S = 35.24, and a cold, fresh water mass with T = 0 °C and S = 34.80.

There is no significant trend in NAW transport during the short observation period (Fig. 6c). Any interannual signal is dominated by the large short timescale variability. Therefore, despite the increasing trends of temperature and salinity, no significant increases in the transports of heat and salt through the BSO are observed (Fig. 6d, e).

Discussion

ADCP measurements over the top 200 m of the BSO show currents that are dominated by barotropic tides. The mean flow calculated over all the cruises is topographically controlled, with cyclonic circulations in both Bjørnøyrenna and Storfjordrenna (Fig. 4). The main flow of NAW occurs in Bjørnøyrenna, where (from the velocities measured over the top 200 m) an average transport of 1.6 Sv of NAW into the Barents Sea imports heat and salt at rates of 3.9×10^{13} W and 5.7×10^{7} kg s^{-1}, respectively. The mean transport and circulation in Bjørnøyrenna agree with those observed by Blindheim (1989). The mean transport in Storfjordrenna indicates a westward flow of 0.4 Sv of NAW, out of the Barents Sea. Considering the uncertainties in the ADCP measurements, this result is consistent with there being no net transport of NAW through Storfjordrenna. The transport in Bjørnøyrenna appears to be higher in summer and low in winter. This does not agree with earlier geostrophic calculations and modelling results (Loeng et al. 1997), which show a winter maximum, and our result may be caused by aliassing of the large short timescale wind-driven variability. Whilst mean transport values appear to be robust, the large variability of the flow means that a longer timeseries of observations would be necessary to properly measure variability on seasonal and interannual timescales. Current meter moorings may offer the best method of observing this flow, since they give good time-resolution, and a relatively coarse spatial resolution may be sufficient to observe the main features of the flow of NAW in Bjørnøyrenna.

The hydrographic fields are less subject to short timescale variability than the velocity fields, and the patterns of variability of temperature and salinity on seasonal and interannual timescales are clearer than those of the transport variability. On a seasonal timescale, NAW is colder and fresher in the winter than the summer. On an interannual timescale, during the period of observation there are increases of 0.7 °C yr^{-1} in the temperature and 0.04 yr^{-1} in the salinity of the NAW entering the Barents Sea. Trends of this magnitude that continue for three or four years are normal for the Barents Sea, as can be seen in the temperature record from the Kola section shown by Ådlandsvik & Loeng (1991). Despite the changes in temperature and salinity, no significant increase is observed in the imports of heat and salt to the Barents Sea by NAW, due to the large variability of the transport discussed above.

The T-S diagram in Fig. 7 includes NAW core properties for both Bjørnøyrenna and Storfjordrenna, from different times of year, and different years. There is a straight line through the points, which suggests that a common mechanism, involving mixing between two sources with constant properties, is responsible for creating all the different varieties of NAW observed between 1997 and 1999. Thus cooler and fresher NAW is formed by increased mixing in winter, and the NAW in Storfjorden is cooler and fresher than in Bjørnøyrenna, also due to mixing along its path. Analagously, the longer-term warming and salinification of NAW may be due to a reduction in mixing. Furevik (2001) suggests two possible causes of long timescale variability in the NAW entering the Barents Sea: an anomaly may either be advected from the North Atlantic, or be created within the Nordic seas by changes in the rates of heat loss and mixing along the path of the NAW. Our observation corresponds to the second mechanism, where reduced mixing rates along the path of the NAW in the Nordic seas could lead to increasing temperature and salinity of the NAW in the BSO.

In conclusion, the CTD data from the series of cruises in the BSO show the seasonal cycles in temperature and salinity, and show evidence of variability on a longer timescale. However, the large short timescale variability of the flow field means that the seasonal cycle and longer-term variability of the transport are not properly resolved by the ADCP data.

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