Cascading of Barents Sea bottom water into the Norwegian Sea

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Introduction

The earliest observations of dense bottom water with high salinity in the eastern Barents Sea were made at the turn of the century. Knipowitsch (1905) concluded that this water was formed in the Barents Sea by rejection of brine during ice formation. Midttun (1985) stated that formation of dense bottom water is a fairly regular phenomenon in the Barents Sea, particularly on the Novaya Zemlya shelf, but in other shallow areas as well. This was also observed by Sarynina (1969), who found dense bottom water of high salinity on the Svalbard Bank. She concluded that this water contributed to the bottom water in the Bear Island Channel. Midttun (1985 and personal communication, 1987) studied the distribution and volume of this water and found considerable year-to-year variation. Midttun and Loeng (1987) further concluded that these fluctuations may depend on the properties and quantity of the inflowing water. After a period with high influx, the transformation requires more than one year of winter cooling before the density of the bottom water is high enough to initiate outflow, which probably takes place mainly through the Novaya Zemlya – Franz Josef Land Channel, the deepest passages to the west of Franz Josef Land and through the Bear Island Channel.

Data

Temperature and salinity data collected in the Bear Island – Fugløy section during the period 1968–1986 are used to classify outflowing water as it leaves the Barents Sea. From 1968 to 1975 this section was observed two or three times per year, mainly from June to October. Since then it has been monitored more regularly, five or six times a year, from January to October. Its position is indicated in Figure 1 together with main features of the bottom topography in the Barents Sea. T–S data from other parts of the Barents Sea are also used to characterize water types. All hydrographic data used here were collected by research vessels from the Institute of Marine Research, Bergen. Before 1970 the observations were from Nansen casts at standard depths. During the period 1970–1974 some observations were made with a Bissett Berman STD system, while after 1975 most observations were made with N. Brown CTD sys-
Figure 1. Main features of the bottom topography in the Barents Sea. The location and moorings of the Bear Island - Fugløy section are indicated.

The accuracy of the data is rather inhomogeneous, in some cases no better than ±0.02 for both temperature and salinity.

An assessment of the transport of water through the Bear Island - Fugløy section is based on current measurements from nine current-meter moorings along the section, mainly during September - October 1978. The positions of the moorings are shown in Figure 1. Although September-October was the period with the most complete coverage of the section, the various moorings do not cover the same period. In the southern part of the section, moorings B to T1 were operated for three to four weeks from the beginning of September. Moorings A, F, G, and I were worked during a 45-day period, also from the beginning of September. In position H the mooring for this period was lost, and observations from the period 19 October 1978 - 11 January 1979 had to be used instead. RCM4 current meters from Aanderaa Instruments were used, and 10-minute averages of speed and an instantaneous direction of the current velocity were recorded at 10-minute intervals. Progressive vector diagrams and average current velocity over the operative period are taken from data reports (Helle, 1979; and Loeng, 1979). The progressive vector diagrams are based on hourly means of the residual current obtained after filtering out the semidiurnal tidal component by calculating 24.8-hour running means from the observed current components.

Results and discussion

Figure 2 shows the density near the bottom, represented by $\sigma_n (\sigma_0)$ as observed in September/October 1986. Ex-
Extremely high densities were found off the west coast of Novaya Zemly a, and from there an area with $\sigma_\circ$-values in excess of 28.15 extended westwards, covering the entire Central Bank area. Water with $\sigma_\circ$ above 28.0 extended farther westwards, following the deeper parts of the Bear Island Channel into the Norwegian Sea.

The heaviest water was observed off the Storfjord at Svalbard, where the highest $\sigma_\circ$-values were above 28.3. The very dense water found in this area is described by Midttun (1985). It sinks into the Norwegian Sea through the Storfjord Channel, a depression extending from the Storfjord area to the shelf edge. This water is formed in small quantities.

Figure 3 shows the T–S relationship at the stations marked I–III in Figure 2. At station I, near Novaya Zemlya, temperatures in the deepest layers were close to −1.8°C and the salinity was about 35.04, indicating water formed by salt rejection when ice was formed during the preceding winter. Station II was worked on the western side of the Central Bank over a bottom depth of 275 m. The salinity minimum indicated in the plot of this station, in Figure 3, was observed at about 190-m depth. The deeper layers were characterized by cold bottom water. As is characteristic of bottom water which may be formed on the Central Bank (Midttun, 1961; Midttun and Loeng, 1987), this water was of somewhat lower salinity than the bottom water at station I. When bottom water flows westwards from these sources, it is subject to mixing with the warmer waters above, which are of Atlantic origin. Hence, in the deeper part of the Bear Island Channel the bottom water at Station III was considerably warmer and slightly fresher than at stations I and II, but still its density was relatively high with a $\sigma_\circ$ of 28.07. This is higher than the density of any inflowing water type, and must therefore be due to the admixture of the Barents Sea bottom water found on stations I and II. Bottom water formed on the Svalbard Bank (Sarynina, 1969) may also contribute, but such water was not observed in the Svalbard Bank area in September–October 1986, excepting the Storfjord area.

The station at 73°30'N 19°20'E on the Bear Island—

Figure 2. Density distribution along the bottom in September–October 1986. (L. Midttun, personal communication, 1987). Positions of the three stations used in Figure 3 are indicated.
Fugløy section has observations to the greatest depths in the Bear Island Channel. The observations closest to the bottom from stations worked in this position are here considered to be characteristic for the water flowing out along the bottom. Temperatures and salinities observed during the period 1968–1986 are plotted in the T–S relationship shown in Figure 4. As illustrated by the figure, the temperature varied between about 0° and 2.5°C and the salinities were in the range 34.9–35.1. Since the values shown are observed in various seasons, the indicated variations include both seasonal and year-to-year fluctuations. This is more clearly illustrated in Figure 5 which shows year-to-year trends in observations from January and August/September. In all years with observations in these months, except for 1975, the temperature near the bottom was higher in January than in August/September, obviously owing to the seasonal temperature cycle. The figure also suggests that the dispersal in the plot in Figure 4 is due more to year-to-year fluctuations than to the seasonal cycle. In Figure 4 there are three observations with density higher than 28.1 in g/c. One of them, from January 1975, is an STD-observation without a calibration, and the possibility of an instrumental error can therefore not be ruled out. A sharp temperature gradient near the bot-

Figure 3. T–S relationship of the three stations indicated in Figure 2.

Figure 4. T–S relationship for observations in the deeper part of the Bear Island Channel during the period 1968–1986.
tom was, however, suggestive of the presence of newly formed bottom water. As described by Sarynina (1969), it may have cascaded into the Bear Island Channel from the Svalbard Bank. The two other $\sigma_t$-values above 28.1 were observed in April and June 1986. These may be due to bottom-water formation on the Svalbard Bank as well, but they are also in agreement with the trend towards generally increasing density during the years immediately preceding (Fig. 5). The main reason for this is the salinity increase since the culmination of the 1970s anomaly period, which is described, for example, by Dickson and Blindheim (1984). Furthermore, while the salinity decrease before the culmination of the anomaly was associated with a cooling trend, the temperature has not risen accordingly after the culmination. The salinity in the inflowing water also increased substantially after the anomaly. In this water mass there was, however, no similar increase in density due to a compensating rise in temperature. This increasing density is suggestive of an intensified production of bottom water after the anomaly.

On leaving the Barents Sea, at least the heaviest bottom water shown in Figures 4 and 5 is dense enough to sink below the Atlantic water in the Norwegian Sea. The extent to which the outflowing water can retain its identity will depend on the intensity of mixing. Indica-
tions of bottom water from the Barents Sea are observed in the slope area north of the Bear Island Channel. For example, the plot in Figure 6 shows a T–S inversion at intermediate depths on a station from 4 October 1986, observed in the position 74°30'N 15°00'E, true west of Bear Island. The maximum salinity in the inversion which was observed at about 650-m depth, was close to 34.96, and the associated temperature was about 0.8 °C. It is likely that this water came from the Bear Island Channel.

Since the Bear Island Channel is a shear zone between outflowing Arctic water to the north, and inflowing water of Atlantic origin to the south, the current in this area is unstable and turbulent. Furthermore, the barotropic field seems to be dominant, and there are relatively high velocities close to the bottom. Geostrophic current computations applied to the hydrographic sections have therefore given confusing results and little information about the transport. This depends not only on the difficulty of establishing a realistic reference level, but also on frequently occurring eddies, in particular near the shear zone in the channel. This is in agreement with tracks of satellite-positioned Argos buoys during the summer of 1986, which show a more turbulent current in the Bear Island Channel than farther south in the Barents Sea and on the Svalbard Bank (H. Loeng and S. Sundby, personal communication, 1987).

This is also supported by the current measurements which confirmed that the current direction may deviate from the average over relatively long periods, possibly also owing to passages of vortices. This is, for example, demonstrated in Figure 7, which shows progressive vector diagrams for the residual current at positions G (73°10'N 19°23'E) and H (73°32'N 19°15'E). All three current meters in position G, at 30-m, 300-m, and 410-m depth, showed low directional stability, and the daily means for direction coincided only seldom with the mean current direction for the 7-week period. The figure indicates that the vertical correlation was good, and further, that the current direction was generally more northeasterly in the upper layers than near the bottom.

On mooring G the current meters were placed at 34-m, 154-m, and 444-m depth. The instrument at 154-m depth was working only from 19 October to 1 December, while the current was recorded from 19 October 1979 to 11 January 1979 at the other two depths. Also in this position the recordings at 34-m and 154-m depth indicated low directional stability, but here the current was somewhat more restricted to direction about SW or NE. Although the series of observations at 154-m depth was shorter than the others, it indicates good vertical correlation between the two upper instruments. This was, however, not valid for the current at 444-m depth. In contrast to the upper layers, the progressive vector diagram for this depth shows a current with high directional stability. The mean direction was, however, the same at all three observation depths, close to 220°.

The direct current measurements from September–October 1978 may be used to obtain some information on the transport during that period. The mooring deployed in position H during this period was, however, lost, and observations made during the period 19 October 1978 – 11 January 1979 were used instead. It may be questioned whether the difference in time of the recording period at this mooring in relation to the others, introduced any considerable difference in the
results. Current recordings in the same position and at the same depths during the period 21 June – 14 July give some information on this. The average current speed was somewhat higher during this period than from October to January, but the mean current direction was practically the same, towards approximately 220° during both periods. This suggests that the measurements from the October–January period may give too low transport figures. The opposite may be concluded from Figure 8, which shows a progressive vector diagram for the recordings at 30-m depth in position G, where the longest continuous series of observations was obtained. The portion of the diagram which covers September–October (also shown in Figure 7), is marked by a rectangle. Together with the summer months this period had a weaker and more turbulent current than the following months. It is therefore concluded that the time difference did not bring about any considerable bias in the volume transport obtained.

The long distances between the current meters may bring about too high a result. This very open grid of observations may have smoothed out permanent features in the current. Particularly between positions F and G, the many hydrographic sections across the Bear Island Channel are suggestive of a semi-permanent countercurrent.

The mean speed of the current component normal to the section is shown in Figure 9. Positions of current-meter moorings and the depth of current recorders which form the basis for the section are indicated in the
Figure 8. Progressive vector diagram showing the residual current, at 30-m depth in position 73°10′N 19°23′E, during the period 19 June 1978 – 7 March 1979. Beginning of months is indicated.

Figure 9. Mean current component (cm s⁻¹) through the Bear Island – Fugløy section in September–October 1978.
South of a position between moorings G and H there was a current component into the Barents Sea. As shown in the figure, the highest velocities were recorded in the coastal water close to the Norwegian coast, and between 72° and 73°N where mooring F indicated the main Atlantic inflow. High velocities out of the Barents Sea were recorded on the Svalbard shelf at mooring I near Bear Island. At mooring H the highest velocities were recorded near the bottom in the deepest part of the section, where there was an almost uninterrupted flow out of the Barents Sea, as shown in Figure 7.

Computation of the transport through the section resulted in a flow of $3.1 \times 10^6$ m$^3$ s$^{-1}$ into the Barents Sea and $1.2 \times 10^6$ m$^3$ s$^{-1}$ out of it.

The water which flows out of the Barents Sea over the northern slope of the Bear Island Channel and the Svalbard shelf has two components. As indicated in Figure 9, there was a minimum in current velocity around 100-m depth. The section from 1 November 1978, shown in Figure 10, indicates that the upper layer was characterized by cold Arctic water of low salinity, carried by the Bear Island Current. In the deeper layers, below the current minimum, the water was denser due to its higher salinity, which may be associated with the high-salinity bottom water farther to the east. According to the volume indicated in Figure 9, the transport of this bottom water was $0.8 \times 10^6$ m$^3$ s$^{-1}$.

As mentioned above, due to the 50-year low in the
salinity of the inflowing water (Dickson and Blindheim, 1984), the density of the water close to the bottom in the Bear Island Channel was also relatively low in 1978 (Fig. 5). According to the density distribution in the Norwegian Sea, off the Bear Island Channel, in 1978, it could not sink to depths greater than 500 m at the most. As shown in Figure 6, there were indications of water from the Barents Sea at about 650-m depth in 1986, and similar indications were observed between 650- and 750-m depth in 1985. These observations suggest that the water flowing into the Norwegian Sea through the Bear Island Channel may sink to varying depths depending on its density and the density distribution in the Norwegian Sea.

In the Norwegian Sea this water most likely represents a substantial contribution to the intermediate water. With \( \sigma_T \)-values about 28.0 it will spread at about the same density level as the intermediate water which advects into the Norwegian Sea from the Iceland/Greenland Sea (Blindheim, 1986). Of these two, the water originating from the Barents Sea is normally the saltiest. It therefore contributes to a rise in the salinity of the intermediate water which flows towards the Fram Strait.

The recordings along the Bear Island – Fugløya section may be too short to give a reasonably realistic indication of the mean transport through the section. Nevertheless, this is the most extensive set of current measurements available from this area. Moreover, the recordings from position G (Fig. 8), which covered almost nine months, did not indicate stronger currents in September–October than the average for the whole period.

The estimated net transport into the Barents Sea of approximately \( 2 \times 10^6 \text{ m}^3 \text{ s}^{-1} \) must continue into the Arctic Ocean. The transport between Bear Island and West Spitsbergen is not important in this connection since it recirculates into the Arctic Ocean with the West Spitsbergen Current. Compared with estimates of the transport through, for example, the Fram Strait, the volume arrived at above is perhaps surprisingly large. Based on year-long current recordings at about 79°N, Foldvik et al. (in press) recently estimated the mean southward transport in the upper 700 m between 1°W and 8°W at \( 3.0 \times 10^6 \text{ m}^3 \text{ s}^{-1} \). In relation to these results the present estimate of the transport through the Barents Sea seems too large, while it compares more reasonably with unpublished transport estimates for the West Spitsbergen Current of \( 5.6 \times 10^6 \text{ m}^3 \text{ s}^{-1} \) (Hańczik), referred to by Foldvik et al. (in press). Such a large transport of salt into the Barents Sea may also be suggestive of a larger supply of deep water to the Arctic Ocean than that postulated by Rudels (1986).

References