ICES Journal of Marine Science, 54: 310–317. 1997

Water fluxes through the Barents Sea

Harald Loeng, Vladimir Ozhigin, and Bjørn Ådlandsvik

Loeng, H., Ozhigin, V., and Ådlandsvik, B. 1997. Water fluxes through the Barents Sea. – ICES Journal of Marine Science, 54: 310–317.

The physical oceanographic conditions in the Barents Sea depend mainly on the variability in the Atlantic inflow from the Norwegian Sea and the inflow of Arctic water from the Kara Sea and the Arctic Ocean. The transport out of the Barents Sea consists of transformed Atlantic water to the Arctic Ocean and also partly to the Norwegian Sea.

To describe the water balance, good estimates of the volume transports between the different seas are needed. By means of available literature, some current measurements and ocean modelling, the present paper describes the water fluxes through the Barents Sea. Russian scientists have calculated the geostrophical transport of the Atlantic current, and found a clear seasonal variation with maximum flow during wintertime. Current measurements, carried out in an array in the north-eastern Barents Sea, confirm the seasonality. The outflow varies from 1 to 3 Sv with maximum during the cold season. The results from a wind-driven numerical model of the Atlantic inflow also show a clear inter-annual variability. Both the seasonal and inter-annual variability seem to be linked to the atmospheric pressure, and the results clearly indicate the highest flow of water when the atmospheric pressure is low.

Based on available literature from all the different in/outflow areas, we try to make a balanced budget for the Barents Sea through-flow. The results indicate an average ingoing and outgoing transport of approximately 4 Sv, of which the throughflow of Atlantic water contributes the half.

Key words: Barents Sea, transport, seasonality, budget.

Received 4 January 1996; accepted 2 May 1996.

H. Loeng and B. Ådlandsvik: Institute of Marine Research, P.O. Box 1870 Nordnes, 5024 Bergen, Norway. V. Ozhigin: PINRO, 6 Knipovich Street, Murmansk 183763, Russia.

Introduction

The main inflow of Atlantic water to the Barents Sea takes place across the south-western boundary. Some of it also leaves through the same border, but most of the Atlantic water passes through the Barents Sea and enters the Arctic Ocean through the strait between Novaya Zemlya and Frans Josef Land (Loeng, 1991). The Atlantic water changes its characteristics on its way through the Barents Sea. This is due to mixing with surrounding water or by transformation caused by cooling and ice formation, a process described in detail by Midttun (1985). The rate of production of dense bottom water may vary from year to year and the outflowing volume may therefore vary considerably. The traditional concept says that the intermediate water masses of the Arctic Ocean are formed by advected Atlantic water from the Norwegian and Greenland Seas through the Fram Strait. However, the flow through the Barents Sea is perhaps more important than earlier believed (Rudels, 1987; Blindheim, 1989; Quadfasel *et al.*, 1992). The Atlantic water from the Barents Sea enters the Arctic Ocean at the depth of the lower halocline or, depending on density, mixes with the deeper water layers (Anderson *et al.*, 1994). The dense bottom water from the Barents Sea probably belongs to the last.

In addition to contributing to the circulation of the Arctic Ocean, the flow of Atlantic water is also important for the Barents Sea itself. It is well documented that the climatic variability in the Barents Sea depends on the amount and properties of the inflowing Atlantic water. Since there is a close relation between temperature variability and fish population parameters of commercially important stocks, as reviewed by Loeng (1989), it is important to have an understanding of the variability of the Atlantic flow. The temperature conditions in the Barents Sea and the importance for the Arctic Ocean water balance is therefore the rationale for studying the Barents Sea through-flux.

1054–3139/97/040301+08 $25.00/0/jm960165

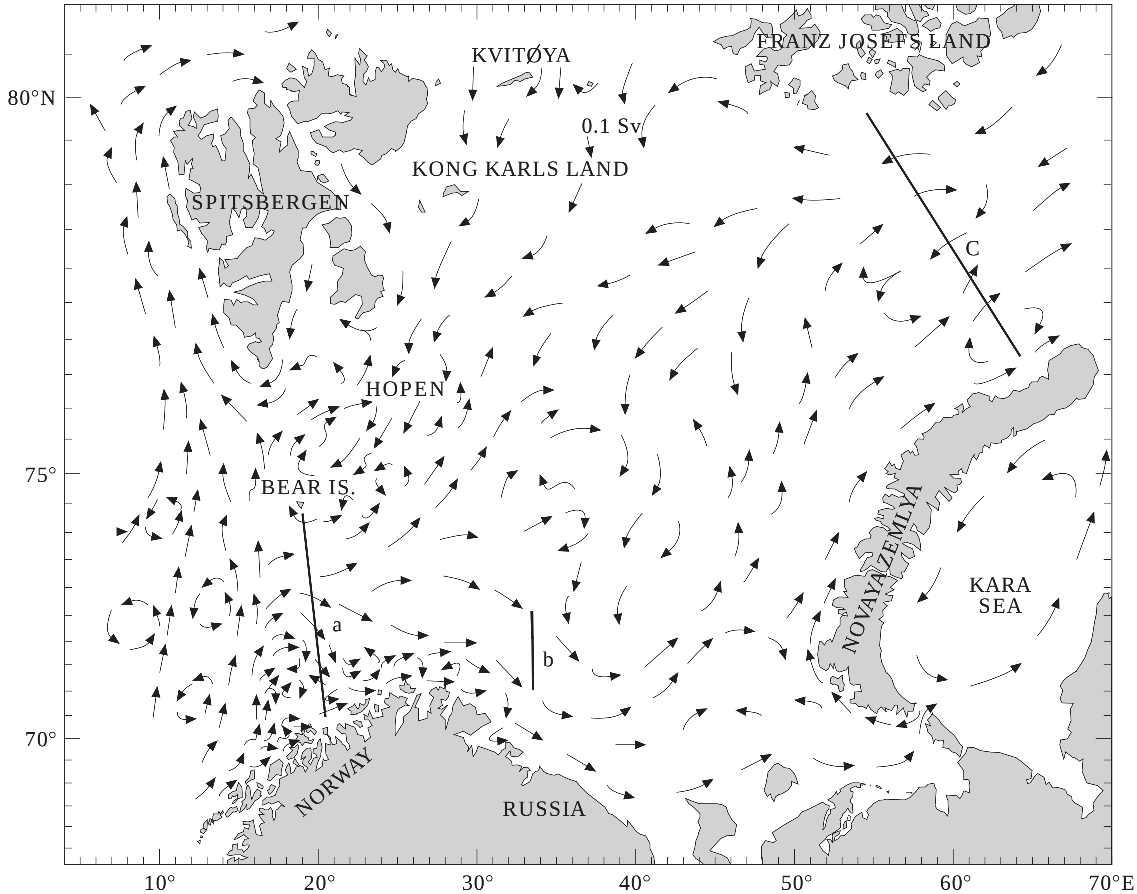

Figure 1. Surface currents in the Barents Sea. The different sections mentioned in the paper are indicated. a, Fugløya-Bear Island; b, Kola-section; c, Novaya Zemlya-Frans Josef Land.

The present paper summarizes the present knowledge of the water flow in and out of the Barents Sea. It focuses on seasonal and inter-annual variability in the Atlantic through-flux, and concludes with an overall budget for the volume fluxes through the different boundaries.

Materials and methods

Most of the data used in this paper are taken from other publications and reports. During the period September–October 1978, current measurements from nine moorings were carried out along the western border of the Barents Sea, between Fugløya (off the Norwegian coast) (70°30′N, 20°00′E) and Bear Island (74°15′N, 19°10′E) (Fig. 1). The results were described by Blindheim (1989). One year with current measurements from the eastern border, between Novaya Zemlya and Frans Josef Land starting in September 1991, is described by Loeng *et al.* (1993a,b). Fluxes through the two mentioned borders are taken from these reports.

Geostrophic calculations of the transport by different currents in the Barents Sea have been carried out by numerous Russian scientists. Seasonal variability of the current system was calculated by Uralov (1960), Timofeev (1963), Moretskiy and Stepanov (1974), Orlov and Poroshin (1988), and Potanin and Korotov (1988).

A wind-driven numerical model has been used to calculate the variability of the inflow through the western boundary of the Barents Sea. The model is documented by Ådlandsvik (1989) and Ådlandsvik and Loeng (1991). The model is barotropic, with atmospheric forcing. The atmospheric data has been taken from the Hindcast Archive of the Norwegian Meteorological Institute (Eide *et al.*, 1985). The output from the model is a time series of wind-driven transport through the same section as used by Blindheim (1989) for current measurements. As the important density driven part of the current is not included in the model, the transport levels are too low. On the other hand, most of the variability of the inflow is captured.

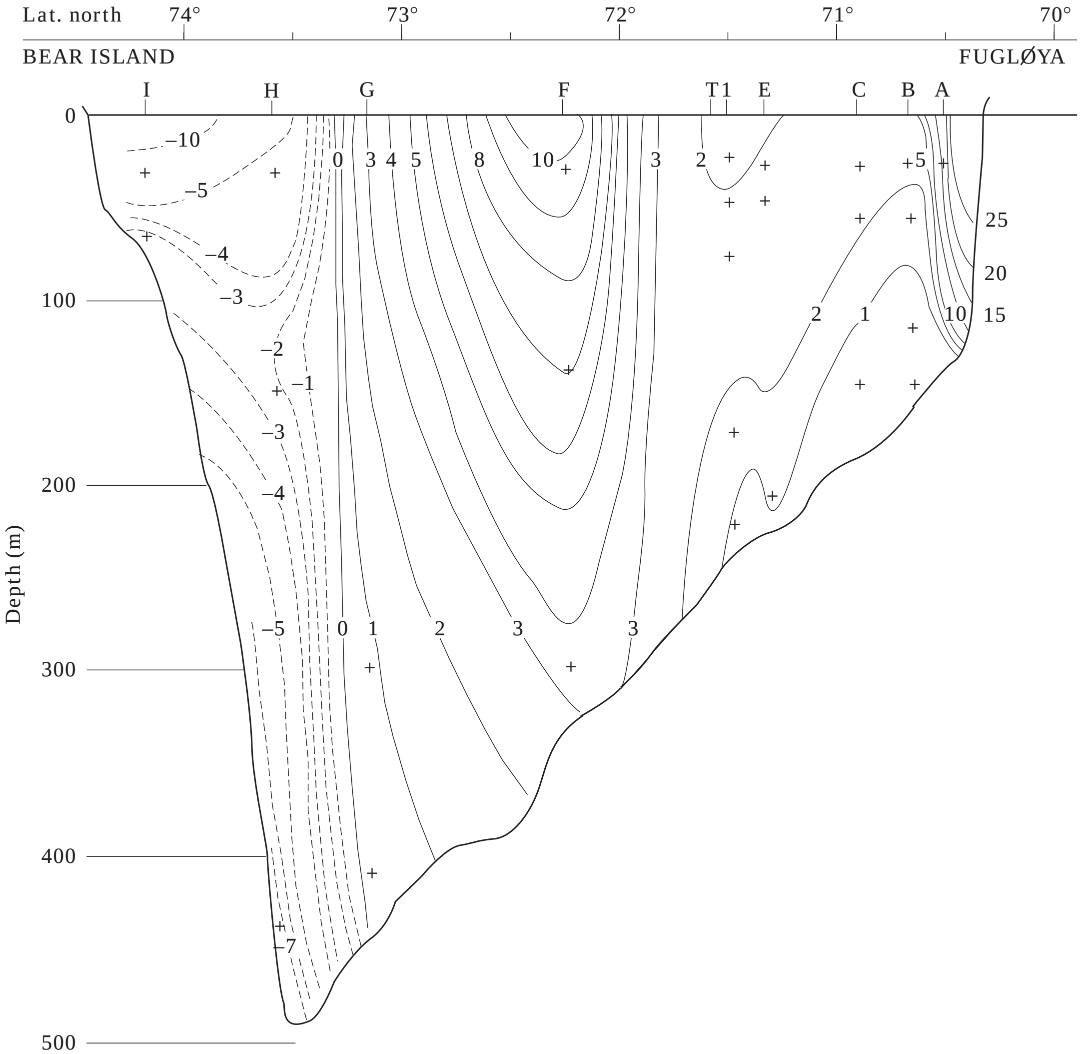

Figure 2. Mean current component (cm s^{-1}) through the Fugløya-Bear Island section in September–October 1978 (Blindheim, 1989).

Results

Blindheim (1989) presented the mean velocity normal to the section from Fugløya to Bear Island based on two months with current measurements (Fig. 2). Close to the Norwegian coast there is a narrow and strong coastal current with average velocity of more than 25 cm s^{-1}. The Atlantic water has a much lower speed, and has its core at N 72°30′. The water which flows out of the Barents Sea over the northern slope of the Bear Island Channel has two components. As indicated in Figure 2 there was a minimum in current velocity around 100 m depth. The upper layer is characterized by cold Arctic water of low salinity carried by the Bear Island Current. In the deeper layers, below the current minimum, the water is denser due to its higher salinity, which may be associated with the high-salinity bottom water. Based on these measurements Blindheim calculated the transport through the section. His calculation gave a flow of 3.1 Sv into the Barents Sea, which includes both the Atlantic and Coastal water. The transport out of the Barents Sea was calculated to be 1.2 Sv, of which bottom water constitute 0.8 Sv (Blindheim, 1989).

One year of current measurements in the strait between Novaya Zemlya and Frans Josef Land revealed a clear seasonality in the current system. The current direction, however, was extreme stable for three of the moorings, while the speed showed a clear seasonal variability (Loeng *et al.*, 1993a,b). The maximum velocity values were observed from November to February, while there was a minimum during summer. The transport through the strait was calculated on the basis of the

Table 1. Mean monthly volume transport (Sv) through the strait between Novaya Zemlya and Frans Josef Land calculated from the mean current velocity observed by the current meters.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Flux out	1.9	2.3	3.3	2.4	2.4	1.7	1.7	1.6	1.2	1.2	1.0*	1.9*
Flux in	0.3	0.1	0.2	0.1	0.0	0.3	0.0	0.4	0.1	0.4	0.7*	1.0*
Net flux	1.6	2.2	3.1	2.3	2.4	1.4	1.7	1.2	1.1	0.8	0.3*	0.9*

*Values based on few observation points, therefore more uncertain than the other values (Loeng *et al.*, 1993b).

monthly mean values of velocity and the results are shown in Table 1. The maximum flow out of the Barents Sea was observed in December with a total flux of 3.3 Sv. However, the whole period from November to February had rather high values. This is also the period with highest net flux out of the Barents Sea. The highest inflow seems to take place in late summer and early autumn when the net outflow was lowest. The average flux out was 1.9 Sv, and annual mean net flux was 1.6 Sv.

Russian scientists have calculated the geostrophic flow of Atlantic current in the Barents Sea (Uralov, 1960; Timofeev, 1963; Moretskiy and Stepanov, 1974; Orlov and Poroshin, 1988; and Potanin and Korotkov, 1988). Even if there are differences in the monthly values, all results show a clear seasonality (Fig. 3) with maximum from September to January and a minimum from April to June. The highest flow is calculated to 2.1 Sv while minimum is 1.2 Sv.

The wind driven model has earlier been run for the period 1970–1986 (Ådlandsvik and Loeng, 1991), but is now extended up to 1994. The output data is the integrated volume flux through the section between Fugløya and Bear Island. The model results should be viewed as fluctuations from the mean Atlantic inflow due to local wind conditions. Positive values represent an increased Atlantic inflow to the Barents Sea and negative values correspond to a decreased inflow. Fig. 4 shows the monthly flux values for the last six years of the investigated period. There is a large variability in the wind induced flow in the section. In January 1992 the wind-driven flux counted for an increased inflow of more than 3.5 Sv. In contrast, the inflow was reduced by almost 1.5 Sv in July 1993. Fig. 4 indicates a seasonal variability in the inflow. Most of the peak inflows are found during winter time, while the lowest values usually are observed during summer. There also seems to be an inter-annual variability in the inflow. For instance, the wind induced inflow in 1989 is lower than the one in 1992.

The mean seasonal flux as calculated from the wind driven model for the 25 year period 1970–1994, is shown in Figure 5. The mean value indicates that the highest inflow occurs during winter with a peak value in December, while the minimum inflow occurs between June and September. Figure 5 also shows that the standard deviation during winter is twice of the summer value.

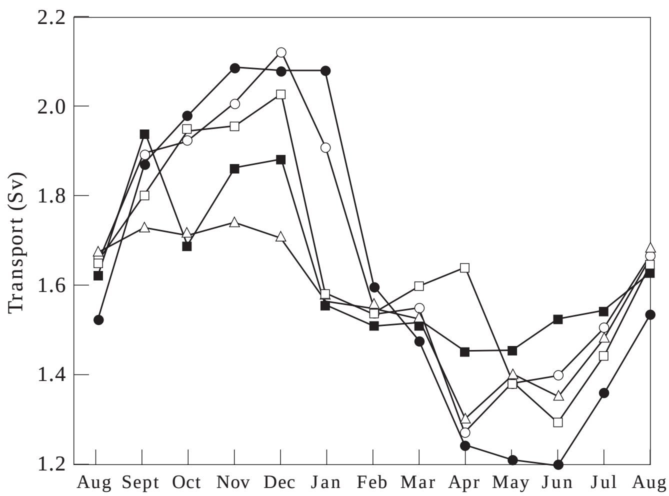

Figure 3. Geostrophic transport in the Atlantic inflow to the Barents Sea as calculated by Uralov (1960) (●), Timofeev (1963) (□), Moretskiy and Stepanov (1974) (△), Orlov and Poroshin (1988) (■), and Potanin and Korotkov (1988) (○).

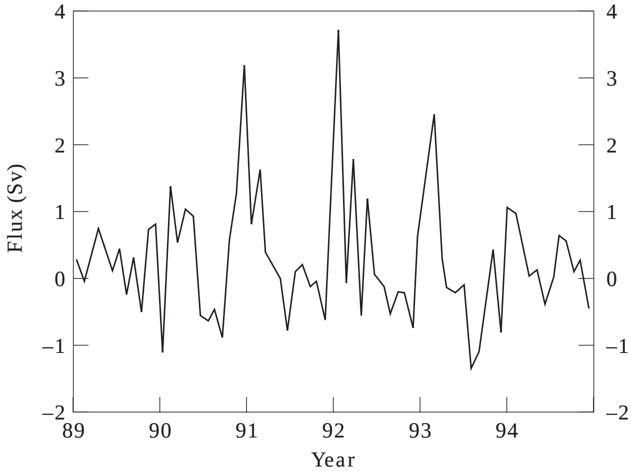

Figure 4. Monthly mean flux (in Sv) through the section Fugløya-Bear Island as calculated by the wind driven model.

In order to look for inter-annual variability, the monthly values have been filtered by a moving one-year average (Fig. 6). The results show an increased inflow in the early 1970s, a decrease from 1977 to 1981, a peak inflow in the period 1982–1983 followed by two years with no net flow before a very low inflow in late 1986 and early 1987. The period after 1988 is characterized by a positive inflow due to the wind effect with peak value from 1990 through 1992. The difference between maximum and minimum in the smoothed curve is more than 1 Sv, which is 50% of the net inflow to the Barents Sea as measured by Blindheim (1989).

Figure 7 summarizes the flow in and out of the Barents Sea. At the south-western and north-eastern boundaries we have used the values from the current measurements, while numbers from Russian literature are used at the other boundaries. The flow to the Kara Sea south of Novaya Zemlya is close to 0.7 Sv based on geostrophic calculations and current measurements (Uralov, 1960; Potanin and Korotov, 1988). Later on, Pavlov and Pfirman (1995) indicated values ranging from 0.05 to 0.6 Sv through the two straits south of Norvaya Zemlya. Fluxes through the northern strait are most uncertain. The inflow varies from 0.4 Sv, as indicated on Figure 7, to double, but in both cases the difference between the inflow and outflow was 0.3 Sv (Agenorov, 1946; Uralov, 1960). The water exchange between Bear Island and Spitsbergen is negligible. As seen from Figure 1 the water recirculates in the area, and the calculated flow is 0.2 Sv (Timofeev, 1963).

Discussion

The results show that the yearly average flux of Atlantic water is approximately 2 Sv through the Barents Sea to

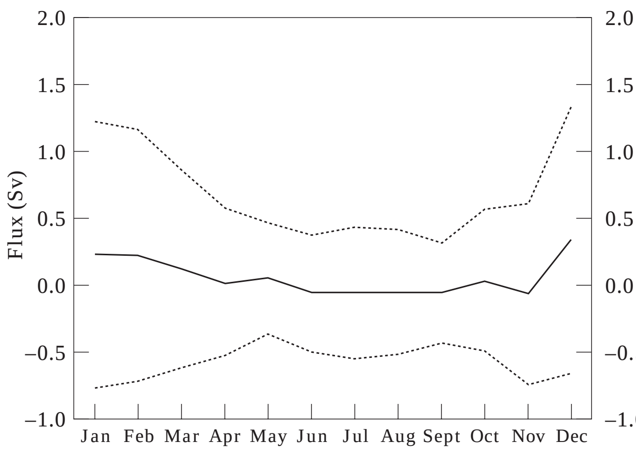

Figure 5. Mean seasonal variation (continuous line) of volume flux through the section Fugløya-Bear Island as calculated by the model. The dotted lines indicate one standard deviation.

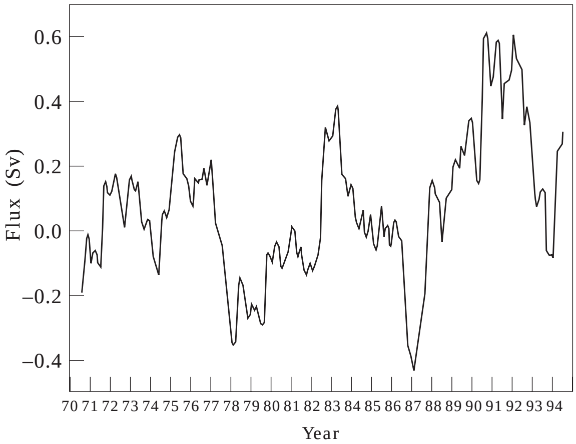

Figure 6. The moving one-year average of monthly values of computed atmospherically driven volume flux through the Fugløya-Bear Island section, 1970–1994.

the Arctic Ocean. However, there is both seasonal and inter-annual variability in this flow. The seasonal variability is clearly demonstrated by the one year of current measurements north of Novaya Zemlya (Table 1). The period of maximum flow is November–February with a peak value in December. This value is twice as high as the minimum flow observed during the summer. Geostrophical calculations of the Atlantic inflow to the Barents Sea (Fig. 3) support the seasonal variations observed by the current measurements. Even if the geostrophical calculations vary in monthly values, they all show a clear seasonality and the ratio between maximum and minimum inflow varies from 1.3 to 1.9. The geostrophic calculation, however, indicates that maximum values occur a bit earlier (September–January) than measured at the north-eastern border. This may either be explained by a delayed outflow compared to the time of inflow, or it may be due to the fact that the only year with current measurement was not quite representative for the annual cycle. The same seasonal variation is observed in the Atlantic inflow to the Nordic Seas (Blindheim, 1993).

The measured fluxes through the western and eastern borders of the Barents Sea seem to fit nicely. However, we should remember that the measurements at the western border were carried out during a cold period

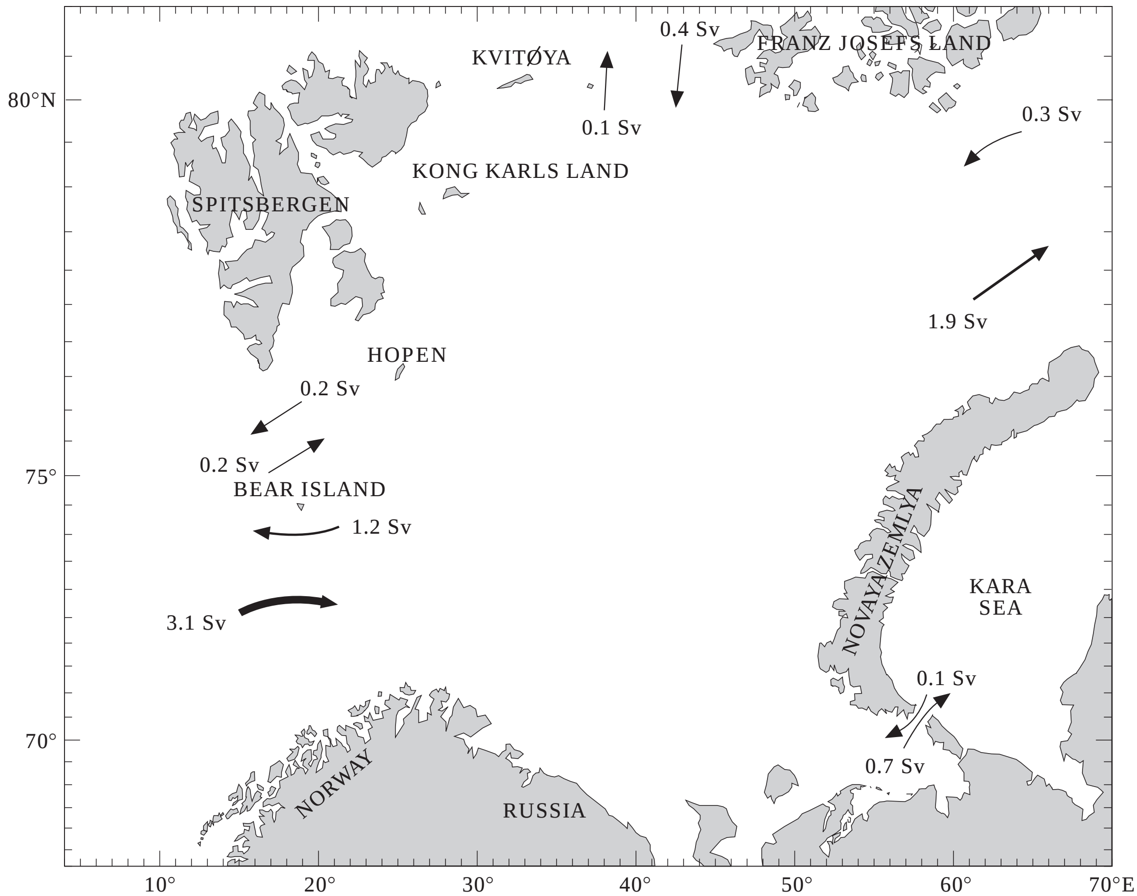

Figure 7. An overview of the waterfluxes in and out of the Barents Sea through the different boundaries.

with relatively low inflow of Atlantic water. The average inflow may therefore be somewhat higher than observed by Blindheim (1989). Figure 6 indicates a difference in the atmospheric driven flux between cold and warm years to range from 0.6 to 1.0 Sv, which means that mean inflow will be close to 4 Sv in warm years. The current measurements at the eastern boundary were carried out in a year with high inflow, so the measured outflow may be higher than the average value. However, an increased inflow in the west may also be compensated by an increased outflow through the western boundary, which means that the net inflow does not change that much. It should also be mentioned that there was almost no outflow of dense bottom water between Novaya Zemlya and Frans Josef Land during the winter of 1992. In some years, such as 1983 and 1989, large volumes of dense bottom water from the eastern Barents Sea left the Barents Sea through the strait north of Novaya Zemlya and was replaced by warm Atlantic water. This is probably a process that take part over a period of at least half a year (Loeng, 1991). During these outflow periods, the volume flux is expected to be much higher than measured by Loeng *et al.* (1993a,b), and during these periods the compensating inflow through the western boundary may exceed the 4 Sv mentioned above.

There are no current measurements that can document the inter-annual variability in the current system. However, there is a close relation between the calculated inflow and the observed temperature anomalies in the Kola-section (Ådlandsvik and Loeng, 1991). This indicates that the model calculated values are realistic and give a good picture of the inter-annual variation. The close relationship also indicates that the variability in the inflowing Atlantic water may be one main cause of the temperature changes. Ådlandsvik and Loeng (1991) also showed that the variability in ice coverage followed the same pattern as the temperature and the inflow. The agreement of the fluctuations in all these climatic variables suggest that the climate of the Barents Sea oscillates between two states, a warm and a cold state (Ådlandsvik and Loeng, 1991). The warm state is characterized by high temperature, low air pressure, increased Atlantic inflow and little ice, while the cold state has the opposite characteristics.

Estimates of the transport through the strait north of Novaya Zemlya based on geostrophical calculation showed much lower values than those based on current measurement. The outflow was estimated to vary between 0.3 and 0.7 Sv while the inflow varied between 0.2 and 0.5 Sv (Agenorov, 1946; Uralov, 1960; Novitskiy, 1961; Loeng *et al.*, 1993a; Pavlov and Pfirman, 1995). This means a very low net outflow of water. The reason for this is probably found in the way the geostrophical calculations were made. The general assumption has been zero velocity at the bottom. However, the current measurements revealed an increasing speed towards the bottom in the strongest outflow area (Loeng *et al.*, 1993a,b). This fact will cause failure in the geostrophic calculations as it will turn the current direction for the whole water column in large areas. By choosing the level of no motion at 60 m, Loeng *et al.* (1993a), obtained a current picture similar to what was observed, but the calculated velocities were much too low. In the inflow area of Atlantic water we do have a decreasing current speed towards bottom, and we expect the geostrophic calculations there to be more realistic (Fig. 3).

The wind driven model revealed large variability, both in the monthly inflow and between years. The monthly mean value has a large range, from +3.7 Sv in January 1992 to −1.3 Sv in March 1979 and July 1993, which creates a large variability in the average inflow to the Barents Sea. The seasonality is not very clear, but Figure 5 indicates maximum in December and lowest wind induced flow during summer. At the same time the standard deviation is twice as high during winter than summer. This may be explained by the general atmospheric circulation that is the driving force. During winter time, the wind field may vary considerably from one year to another. While a winter month one year may have several storms, the same month may not have any storms at all the next year. During summer, however, the wind conditions are rather calm, and do not vary much between years (Steffensen, 1969). Figure 4 supports this conclusion by showing lower variability in the wind induced flow during summer than during winter. The inter-annual variability (Fig. 6) also depends on the atmospheric conditions. Ådlandsvik and Loeng (1991) showed that the highest inflow of Atlantic water occurred in years with low presusre, while a high pressure situation reduced the inflow. Loeng *et al.* (1993b) also showed a close relation between the monthly outflow variability and the air pressure in the area. It may therefore be concluded that there is a close relation between air pressure and current conditions in the Barents Sea.

Acknowledgements

This work has received financial support from the Ministry of Industry and Energy.

References

Ådlandsvik, B. 1989. A wind-driven model of the Barents Sea. Bergen Scientific Centre Report Series 89/14, 20pp.

Ådlandsvik, B., and Loeng, H. 1991. A study of the climatic system in the Barents Sea. Polar Research 10: 45–49.

Agenorov, V. K. 1946. On the Barents Sea water dynamics. Moscow-Leningrad Hydrometeoizdat. 132 pp (in Russian).

Anderson, L. G., Bjørk, G., Holby, O., Jones, E. P., Kattner, G., Kolter-Mann, K. P., Liljeblad, R., Lindgren, R., Rudels, B., and Swift, J. 1994. Water masses and circulation in the Eurasian Basin: Results from the Oden 91 expedition. Journal of Geophysical Research 99: 3273–3283.

Blindheim, J. 1989. Cascading of Barents Sea bottom water into the Norwegian Sea. Rapports et Procès-verbaux des Réunions du Conseil International par l'Exploration de la Mer 188: 49–58.

Blindheim, J. 1993. Seasonal variations in the Atlantic inflow to the Nordic Seas. ICES C.M. 1993/C: 39, 13 pp.

Eide, L. I., Reistad, M., and Guddal, J. 1985. Database av beregnede vind og bølgeparametre for Nordsjøen, Nors= kehavet og Barentshavet hver sjette time for årene 1955 til 1981. DNMI Report. (in Norwegian).

Loeng, H. 1989. The influence of temperature on some fish population parametres in the Barents Sea. Journal of Northwest Atlantic Fisheries Science 9: 103–113.

Loeng, H. 1991. Features of the physical oceanographic conditions of the Barents Sea. Polar Research 10: 5–18.

Loeng, H., Sagen, H., Ådlandsvik, B., and Ozhigin, V. 1993a. Current measurements between Novaya Zemlja and Frans Josef Land. September 1991–September 1992: Data report. Report no. 2—1993. Dept. of Marine Environment, Institute of Marine Research, Bergen. 23 pp + 4 appendices.

Loeng, H., Ozhigin, V., Ådlandsvik, B., and Sagen, H. 1993b. Current measurements in the northeastern Barents Sea. ICES C.M. 1993/C: 40, 22 pp.

Midttun, L. 1985. Formation of dense bottom water in the Barents Sea. Deep-Sea Research 32: 1233–1241.

Moretskiy, V. N., and Stepanov, S. I. 1974. Atmospheric pressure over the Arctic Ocean and the North Atlantic related to water transport in the North Cape Current. Trudy Arctic and Antarctic Research Institute 325: 92–95 (in Russian).

Novitskiy, V. P. 1961. Stable currents in the northern Barents Sea. Trudy Gos. Oceanogr. Inst. 64: 1–32 (in Russian).

Orlov, N. F., and Poroshin, V. V. 1988. Water and heat transport in the North Cape Current in 1961–1980. Nature and Economy of the North, Murmansk, 16: 31–34 (in Russian).

Pavlov, V. K., and Pfirman, S. L. 1995. Hydrographic structure and variability of the Kara Sea: Implications for pollutant distribution. Deep-Sea Research II, 42: 1369–1390.

Potanin, V. A., and Korotkov, S. V. 1988. Seasonal variability of the main currents in the southern Barents Sea and water exchange with the adjacent areas. Geological and Geographical Problems of Natural Resources Exploitation in the Northern Seas, Murmansk, 1988: 81–90 (in Russian).

Quadfasel, D., Rudels, B., and Selchow, S. 1992. The Central Bank vortex in the Barents Sea: watermass transformation and circulation. ICES Marine Science Symposium, 195: 40–51.

Rudels, B. 1987. On the mass balance of the Polar Ocean, with special emphasis on the Fram Strait. Norsk Polarinstitutt Skrifter, 188: 1–53.

Steffensen, E. 1969. The climate and its recent variations at the Norwegian Arctic stations. Meteorologiske annaler, Oslo, 5: 213–349.

Timofeev, V. T. 1963. Water interaction between the Arctic, Atlantic and Pacific oceans. Oceanology, 3: 569–578 (in Russian).

Uralov, N. S. 1960. On the advective component of the heat balance in the southern Barents Sea. Trudȳ Gosudarstvennogo okeanograficheskogo instituta, 55: 3–20 (in Russian).