The Northern Barents Sea: Water Mass Distribution and Modification

S.L. Pfirman[1], D. Bauch[2], and T. Gammelsrød[3]

[1]*Barnard College, Columbia University, New York City, New York*
[2]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York*
[3]*Geophysical Institute, University of Bergen, Bergen, Norway*

The main water masses in the northern Barents Sea are surface water, Arctic water, transformed Atlantic water, and cold bottom water. Using summer data from 1981 and 1982, the formation, distribution, modification and circulation of these water masses are discussed. Recent estimates show that about 2 Sv of Atlantic water enters the Barents Sea by the North Cape Current, balanced by a similar outflow through the strait between Novaya Zemlya and Frans Josef Land. Passing through the Barents Sea, Atlantic-derived water is modified by interaction with other water masses as well as with the atmosphere, and the end products are believed to be important contributors to the hydrographic structure of the Arctic Ocean.

INTRODUCTION

The main sources of deep waters which fill the deep basins of the global oceans are known to be located in polar regions. Here, water masses are transformed by processes that increase their density, usually by cooling and/or increasing salinity. Because deep water formation governs global oceanic circulation, it is important to determine the actual locations and processes involved, as well as to determine their sensitivity to environmental changes.

The Barents Sea is a key region for modification of water masses in the Arctic. It is one of several continental shelf seas marginal to the Arctic Ocean which influence its hydrographic structure. Water flowing over shallow regions is transformed when heat loss and brine rejection during sea-ice formation increase density in winter, while warming and addition of sea-ice meltwater and river runoff decrease surface water density during summer [e.g. *Nansen*, 1906; *Redfield and Friedman*, 1969; *Hanzlick and Aagaard*, 1980; *Midttun*, 1985; *Quadfasel et al.*, 1988; *Aagaard and Carmack*, 1989].

The Barents Sea is different from other Arctic shelves because it has close connections to the Norwegian Sea as well as to the Arctic Ocean. The amount of Atlantic water passing through this sea from a branch of the Norwegian Atlantic Current may equal that supplied through Fram Strait in the West Spitsbergen Current [Fig. 1; *Rudels*, 1987]. Atlantic water inflow into the Barents Sea between Norway and Bear Island appears to be about 1.6 Sv, varying between 2.1 Sv in winter and 1.4 Sv in summer (see compilation by Loeng et al., 1993). Blindheim (1989) estimates the total inflow (coastal water plus Atlantic water) through this passage to be about 3 Sv, with about 1 Sv outflow. The average mass transport leaving the Barents Sea through the strait between Novaya Zemlya and Frans Josef Land is of order 2 Sv (varying between 0.7 to 3.2 Sv; Loeng et al., 1993). Meanwhile, estimates of Atlantic water entering the Arctic Ocean via the West Spitsbergen Current vary between about 2 and 3.7 Sv [*Hanzlick*, 1983; *Rudels*, 1987].

Because of Atlantic water inflow and the very limited contribution of freshwater from river runoff [*Novitsky*, 1961; *Rudels*, 1987], the Barents Sea is also more saline

The Polar Oceans and Their Role in Shaping the Global Environment
Geophysical Monograph 85

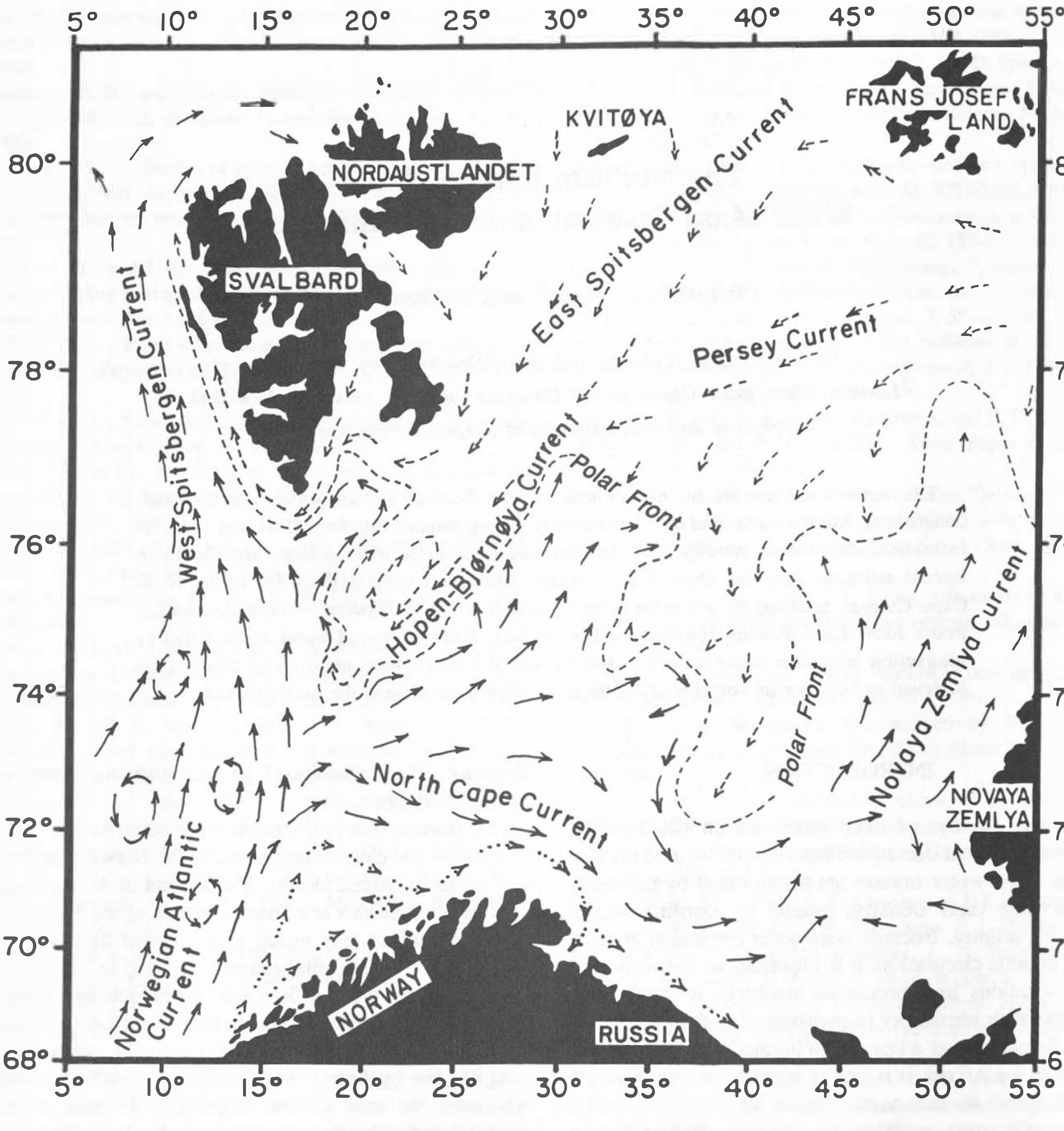

Fig. 1 Circulation of surface waters (adapted from *Tantsiura*, 1959; *Novitsky*, 1961; *Midttun and Loeng*, 1987) showing main warm currents (Atlantic water: solid arrows), cold currents (Arctic water: dashed arrows), Norwegian/Murmansk Coastal Current (dotted arrows) and location of the oceanic polar front (also called the Arctic front: dashed line).

than the other shelf seas. This means that winter cooling and additional salt contributed from sea-ice formation can easily result in formation of cold, saline water that is denser than the Atlantic layer. When such dense waters flow off the shelf, they are thought to contribute a cold, saline signal to deep waters of the Arctic Ocean [*Nansen*, 1906; *Gordienko and Laktionov*, 1969; *Aagaard et al.*, 1981; *Swift et al.*, 1983; *Midttun*, 1985; *Rudels*, 1987; *Quadfasel et al.*, 1988; *Blindheim*, 1989; *Midttun*, 1989]. Recent $\partial^{18}O$ profiles indicating that deep and bottom waters of the Arctic do not show river-runoff influence, also point to the Barents Sea as a possible source region [*Schlosser et al.*, 1994].

This paper examines the major water masses in the northern Barents Sea, using temperature and salinity data collected during summer expeditions in 1981 and 1982, to trace their distribution and modification [see also *Tantsiura*, 1959, 1973; *Novitsky*, 1961; *Pfirman*, 1985; *Midttun and Loeng*, 1987; *Loeng*, 1991].

BATHYMETRY AND HYDROGRAPHY

The main hydrographic feature of the near-surface waters of the Barents Sea is the oceanic polar front (also called the Arctic front), which divides relatively warm and saline water of Atlantic origin in the south from colder and fresher Arctic water in the north (Fig. 1). It is not as distinct in the eastern Barents Sea where a mixed water mass extends over large areas [*Midttun and Loeng*, 1987]. The polar front divides the Barents Sea roughly in half and is located in the southern portion of our study area.

Because the Barents Sea is shallow with many banks and troughs (Fig. 2), bathymetric relief guides water mass transport and exchange. Atlantic water found south of the polar front is derived from the Norwegian Atlantic Current, which flows north along the Norwegian continental slope and then east up Bjørnøyrenna (also known as the Bear Island Channel) as the North Cape Current (Fig. 1). Atlantic water transport in this current appears to be about 1.6 Sv [see compilation in Loeng et al., 1993].

The North Cape Current branches in the Barents Sea, flowing through depressions between banks. The branch to the south of Sentralbanken (also called Central Bank) continues toward Novaya Zemlya and the Kara Sea and is known as the Novaya Zemlya Current [Tantsiura, 1959; Novitsky, 1961]. Here, modified Atlantic water which has mixed with Arctic water has been called Atlantic water [e.g. Pfirman, 1985], or Barents Sea water [Loeng, 1991]. In order to clarify the origin of this water mass, we call it Barents Atlantic-derived water (BAW) in this contribution. In the Arctic Ocean and the Norwegian-Greenland Sea the modified, Atlantic-derived water is often called Arctic intermediate water [e.g. *Swift*, 1986].

Part of the Norwegian Atlantic Current also continues west and north of Bjørnøyrenna along the western flank of Spitsbergenbanken, becoming the West Spitsbergen Current. North of Spitsbergen, an easterly branch of this current flows along the northern slope of the Barents Sea. Nansen (1906) and Mosby (1938) found that Atlantic water submerges beneath Arctic water in this region and becomes an intermediate water mass. Some branches of Atlantic water enter the Barents Sea between Nordaustlandet and Frans Josef Land from the north as a near-bottom water mass [*Mosby*, 1938].

Arctic water, also called polar water or winter water, is a water mass with temperatures near the freezing point which dominates the upper part of the water column north of the polar front. It originates from convection during sea-ice formation in fall and winter [*Mosby*, 1938]. In summer, a remnant of this layer is found in the Barents Sea. Arctic water forms locally or is advected into the Barents Sea from the northern Kara Sea and the Arctic Ocean [*Novitsky*, 1961; *Tantsiura*, 1973]. There are three main currents transporting this cold water and sea ice within the Barents Sea (Fig. 1): the Persey Current flowing west across the Barents Sea towards Spitsbergenbanken; the ill-defined East Spitsbergen Current, flowing out of the Arctic Ocean into the Barents Sea between Nordaustlandet and Frans Josef Land; and the high-velocity Hopen-Bjørnøya Current flowing south along the eastern flank of Spitsbergenbanken [*Tantsiura*, 1959; *Novitsky*, 1961; *Midttun and Loeng*, 1987].

From fall to early summer, sea-ice covers the region north of the polar front. As summer progresses, the ice melts and the marginal ice zone retreats towards the north. A thin layer of surface water is formed that overlies Arctic water during mid- to late summer. This layer has a lower salinity and is warmed due to exposure to solar radiation [*Mosby*, 1938; *Loeng*, 1980; *Loeng*, 1991].

Near the sea floor, a cold, saline water mass is frequently observed. The distribution of this dense bottom water shows large seasonal and annual variations [*Tantsiura*, 1973]. It forms both by cooling of Atlantic water and by addition of salt to the water column by brine rejection during sea-ice formation [*Nansen*, 1906; *Midttun*, 1985]. Where the salinity of the cold bottom water is greater than that of Atlantic water, this is a good indication that sea ice formation contributed to development of the water mass. Following Nansen (1906), we refer to water with colder temperatures near the sea floor as cold bottom water (CBW, also called bottom water by Loeng (1991) and cold deep water by Pfirman (1985)).

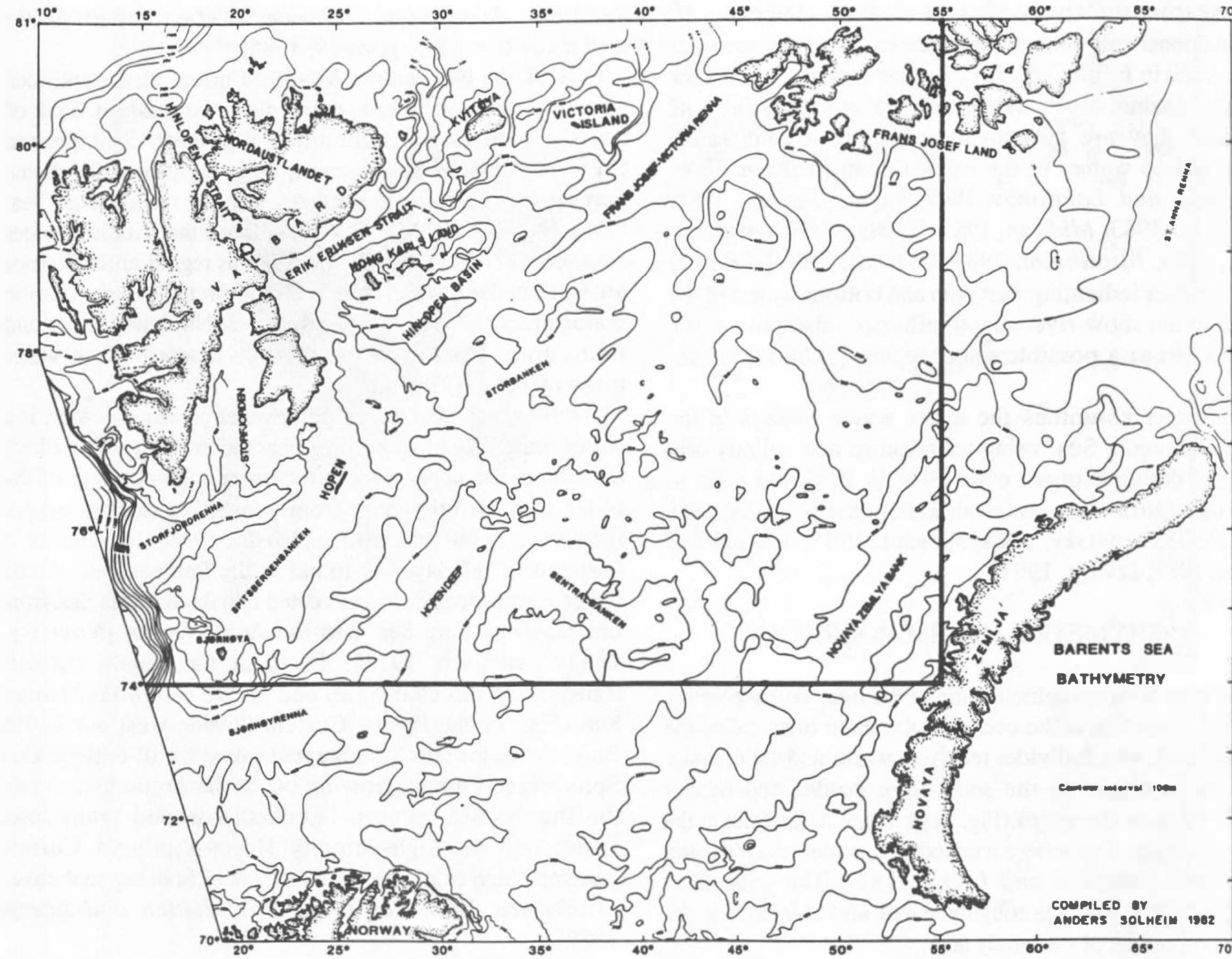

Fig. 2 Overview of Barents Sea geography and bathymetry. The study area is boxed in over the northwestern portion of the map.

During winter, sea ice formation causes vertical mixing to take place throughout the Barents Sea. Convection commonly extends down to 150 to 200m, reaching the sea floor over some banks [*Novitsky*, 1961; *Tantsiura*, 1973; *Midttun*, 1989]. Convection forms very saline and cold CBW near Novaya Zemlya Bank [Fig. 2: *Knipowitsch*, 1905; *Nansen*, 1906; *Tantsiura*, 1959; *Midttun*, 1985]. Similar cold brines form in Storfjorden [*Novitsky*, 1961; *Midttun*, 1985; *Anderson et al.*, 1988; *Quadfasel et al.*, 1988]. Less saline dense water forms over Sentralbanken [*Tantsiura*, 1959; *Midttun*, 1961; *Midttun and Loeng*, 1987; *Midttun*, 1989]. Convection over the banks also forms secondary circulation patterns, which aid in modifying adjacent Atlantic-derived water [*Tantsiura*, 1959]. For example, winter cooling of Atlantic water results in dense, but fairly warm bottom water near Spitsbergenbanken [*Tantsiura*, 1959; *Sarynina*, 1969; *Midttun and Loeng*, 1987]. Once formed, CBW seeks depressions and channels, flowing out of the Barents Sea and contributing to the intermediate, deep and bottom water characteristics of the Norwegian Sea and the Arctic Ocean [*Nansen*, 1906; *Swift et al.*, 1983; *Midttun*, 1985; *Midttun and Loeng*, 1987; *Quadfasel et al.*, 1988; *Midttun*, 1989; *Blindheim*, 1989; *Schlosser et al.*, 1994].

DATA AND METHODS

The data used in this study were obtained in the summers (July, August, September) of 1981 [*Midttun*, 1985; *Pfirman*, 1985; *Elverhøi et al.*, 1989] and 1982 (Fig. 3A). The more complete data set collected in 1981 is used as a basis of discussion. Even with this fairly extensive data set

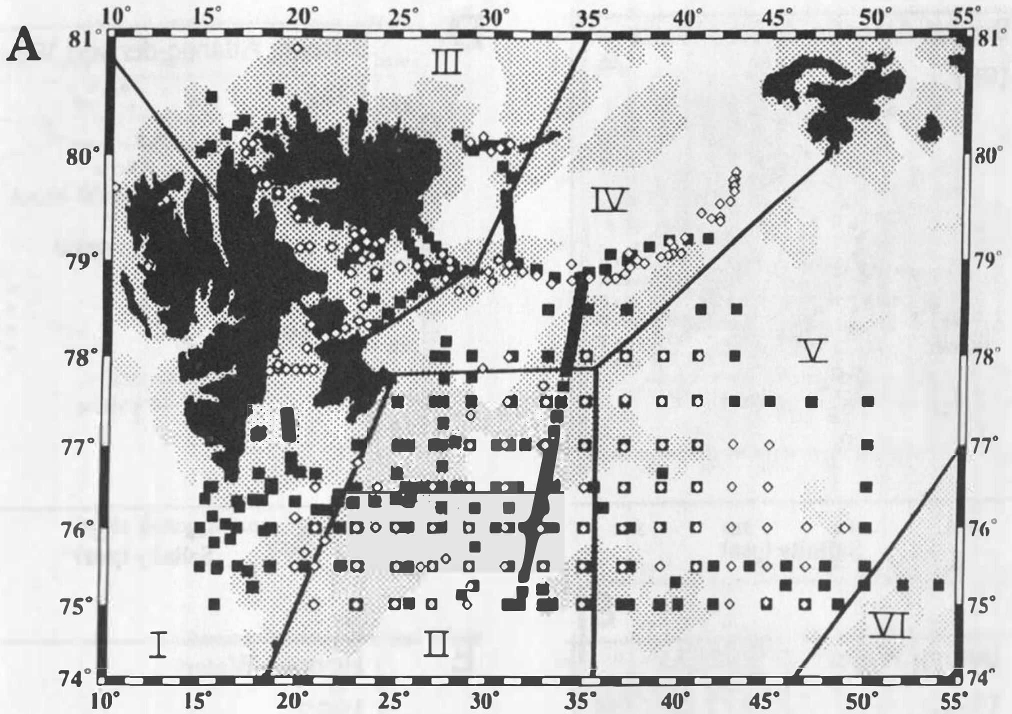

Fig. 3 A) Locations of hydrographic stations sampled in July, August, and September 1981 (squares) and 1982 (diamonds). Roman numerals indicate areas used in water mass analysis depicted in Fig. 3B, C, D, E. Stippling indicates regions where water depths are less than 200m. Potential temperature-salinity plots of: B) the temperature maximum representing Atlantic-derived water sampled in 1981, C) bottom water with salinities > 34.5°/oo sampled in 1981 (note cold, saline water in areas I (*Midttun*, 1985) and VI), D) the temperature maximum representing Atlantic-derived water sampled in 1982 (note: in area IV some stations had two Atlantic-derived water maxima. A "+" symbol is used to designate the deeper maximum, and the area is called IV*), and E) bottom water with salinities > 34.5°/oo sampled in 1982. The box labelled "EBDW" indicates the water mass characteristics of Eurasian Basin deep water of the Arctic Ocean.

it is difficult to describe the details of the water mass distribution patterns due to low sampling density, lack of synopticity, and lack of additional tracer data.

Hydrographic data were obtained from two sources: the University of Bergen and the Institute for Marine Research in Bergen (Havforskningsinstitutt). Both data sets were collected using a Neil Brown CTD calibrated by bottle data. The r.m.s. error in salinity of the University of Bergen data was ±0.008 in 1981 and ±0.004 in 1982. The precision of the temperature data was +/- 0.005°C and that of the pressure sensor was +/- 0.1%. The original CTD data was reduced to two decibar averages and the salinities were calculated from the average values. The Institute for Marine Research data was compiled from a variety of cruises and may have a slightly higher salinity error. These data were reported at standard depths (0, 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 200, 250, 300, 350, 400m).

Identification of Arctic water, Atlantic-derived water and cold bottom water is based on temperature, and to a lesser degree, salinity extrema. This method, called the core method [*Wuest*, 1935] and used in the northern Barents Sea by Mosby (1938), aids in following a water mass while it is transformed.

WATER MASS DISTRIBUTION

In late summer, north of the polar front, a typical station obtained in one of the deeper regions of the Barents Sea generally has: a relatively warm surface water layer; underlain by a temperature minimum corresponding with the Arctic water layer; underlain by a temperature and salinity maximum, which is related to the Barents Atlantic-derived water; and colder water near the bottom, here called cold bottom water (see Table 1, Fig. 4).

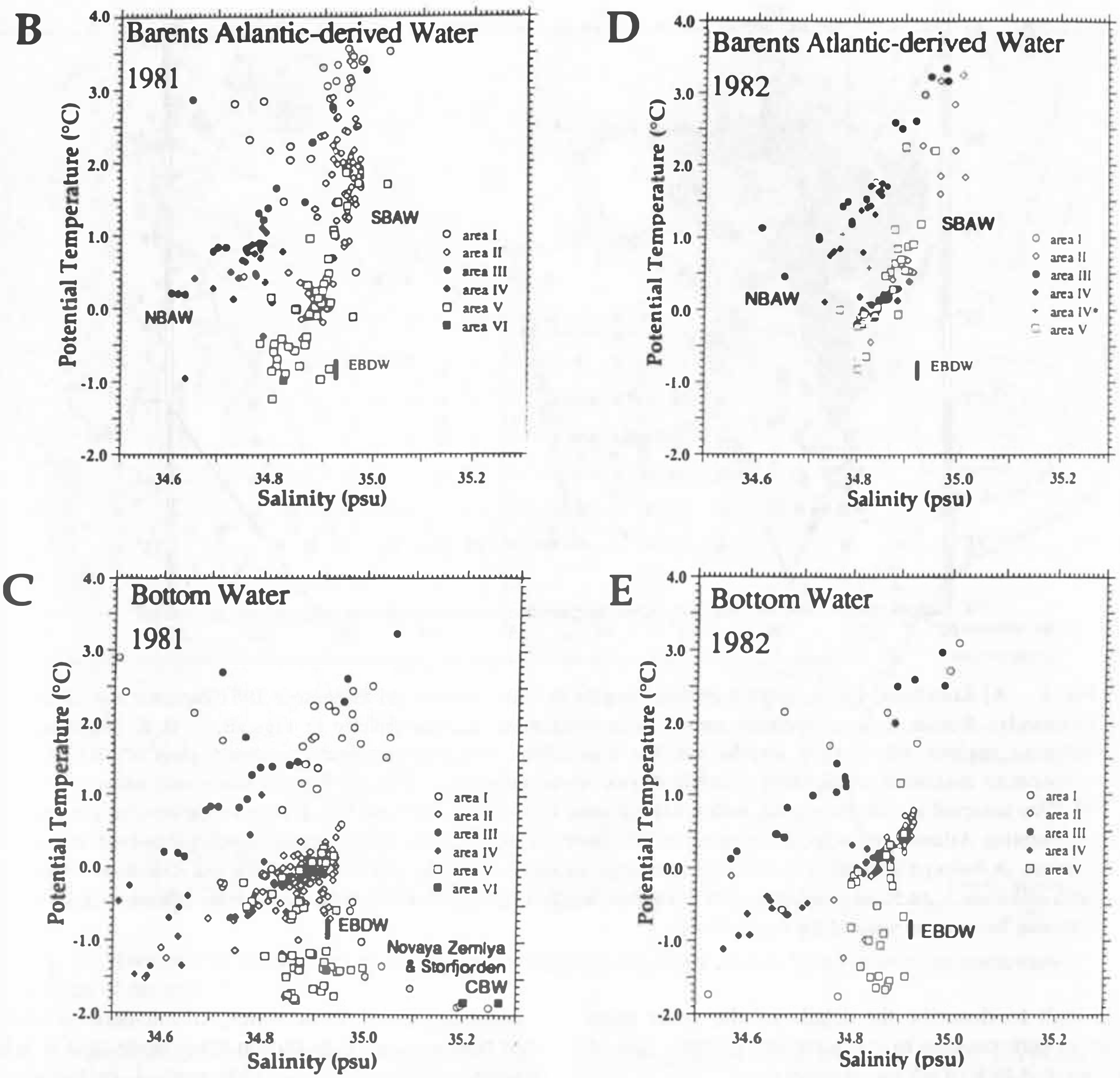

TABLE 1. Core Characteristics of Water Masses in the Northern Barents Sea in Late Summer

Water Mass	Depth [m]	Potential Temperature [°C]	Salinity [psu]	Density [σ_0]
Surface water	0 - 20	-1 to 3	32.0 - 34.0	25.0 - 27.0
Arctic water [a]	30 - 80	-1.8 to -1.0	34.3 - 34.7	27.5 - 27.8
Atlantic-derived water [b]	75 - 250	0 to - 2.0	34.75 - 34.95	27.8 - 28.0
cold bottom water		-1.8 to 0.0	34.9 - 35.2	28.0 - 28.4

[a] correlated with a temperature minimum; [b] correlated with a temperature and salinity maximum

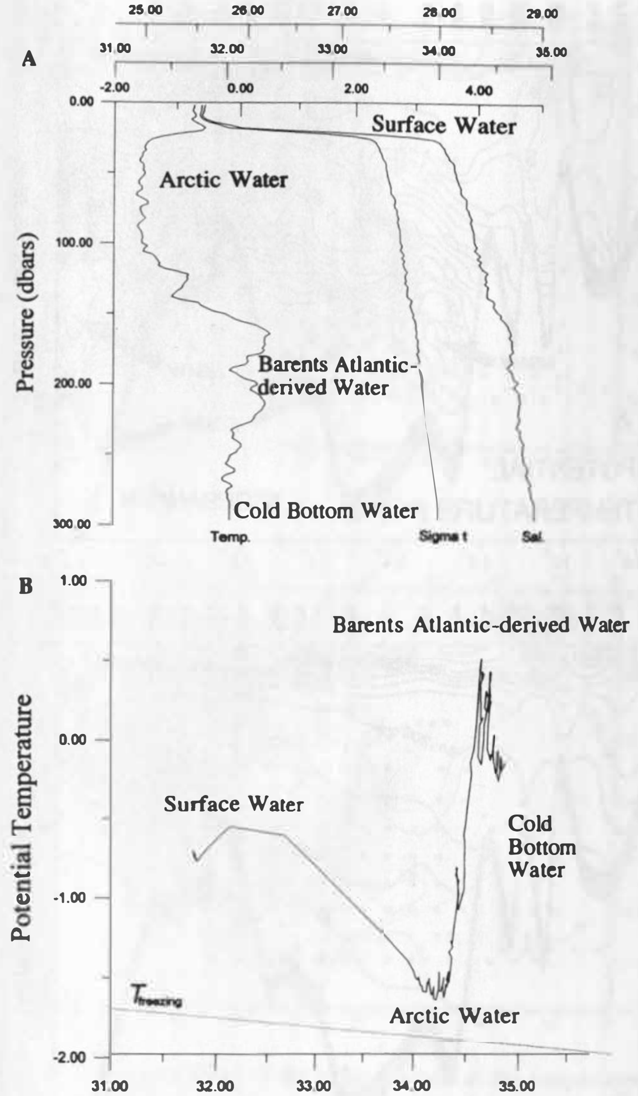

Fig. 4 A) Profile of a station north of the polar front (78°30'N and 33°11'E) in summer showing the surface water layer, the cold Arctic water, the warmer and more saline Barents Atlantic-derived water and the underlying cold bottom water. B) Potential temperature-salinity profile of the same station showing the well-defined Arctic water and Barents Atlantic-derived water masses, and the cold bottom water.

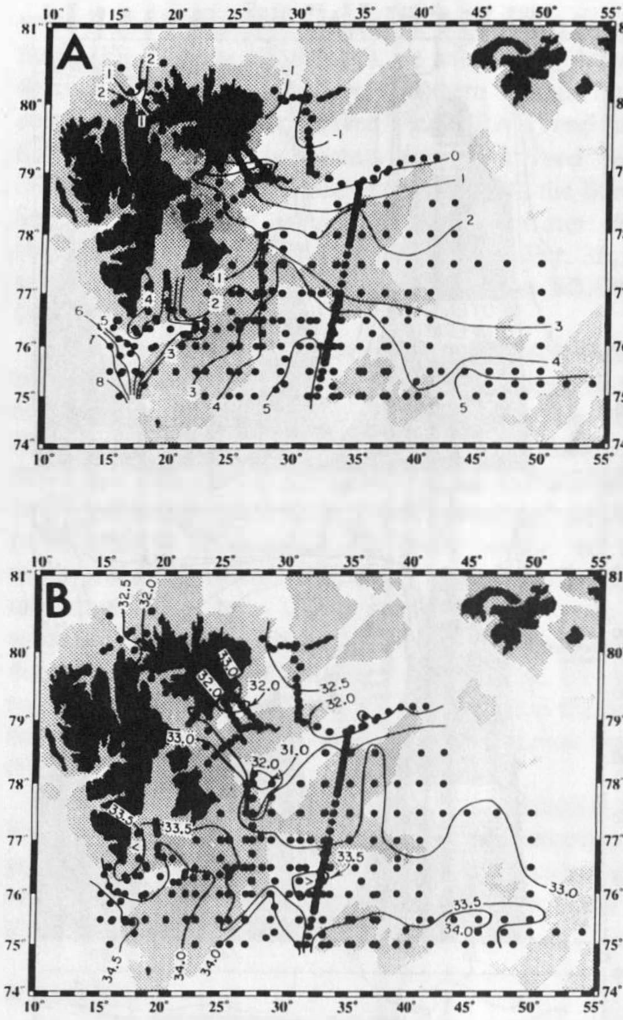

Fig. 5 Surface water characteristics: A) temperature, B) salinity. Data are from summer 1981. Stippling indicates regions with water depths less than 200m.

Surface Water

In general, during summer the surface water temperature decreases toward the north (Fig. 5A). This is due to progressive retreat of the sea ice cover by melting, with a northward decrease in the duration of exposure to solar radiation [*Mosby*, 1938; *Loeng*, 1980; *Loeng*, 1991]. Salinities also decrease toward the north, caused by admixtures of sea ice meltwater (Fig. 5B).

Along a hydrographic transect at 75.5°N (Fig. 6A) the surface layer is about 40m thick and there are lenses of low-salinity water centered over the banks (Fig. 6B). A northern hydrographic transect, from Kong Karls Land to the eastern side of Storbanken (also called the Great Bank or Persey Elevation) at 79°N (Fig. 7A), shows a thinner surface layer, less than 30m thick. Here again there is a lower salinity lens over Storbanken (Fig. 7B).

Arctic Water

The Arctic water layer typically is found between 20 to 150m [*Midttun and Loeng*, 1987], with a temperature

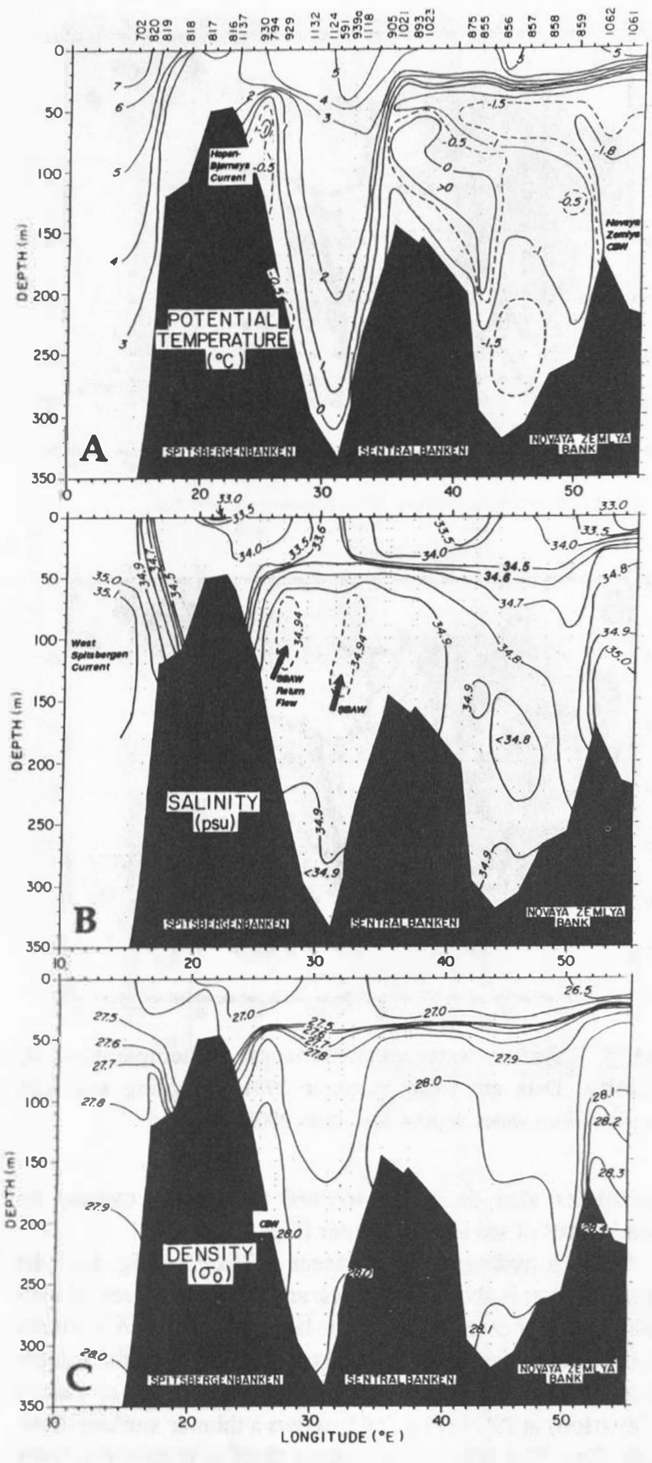

Fig. 6 Hydrographic transect along 75.5°N obtained in 1981: A) potential temperature, B) salinity, C) density.

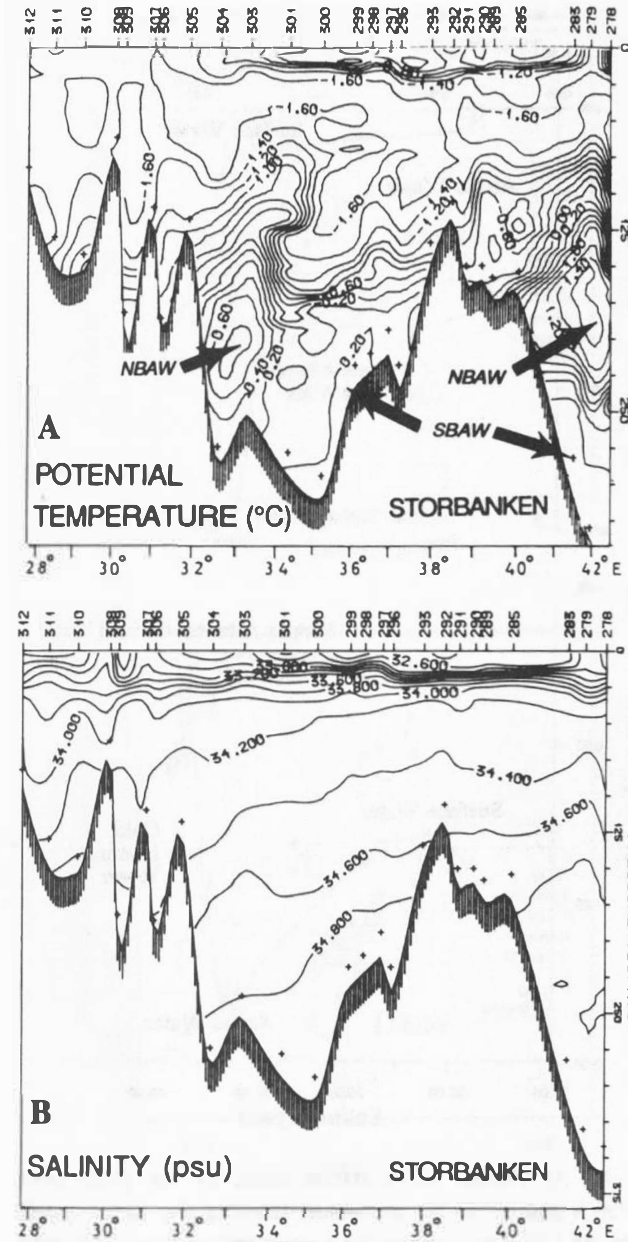

Fig. 7 Hydrographic transect along 79°N obtained in 1982: A) potential temperature, B) salinity.

minimum between 50 and 75m [Fig. 4A; *Novitsky*, 1961]. North of the polar front, there is very little variation in temperature and the water mass is between -1.6 and -1.8°C (Fig. 8A). Only over Storbanken is it below -1.8°C. Temperatures are higher in the vicinity of the polar front

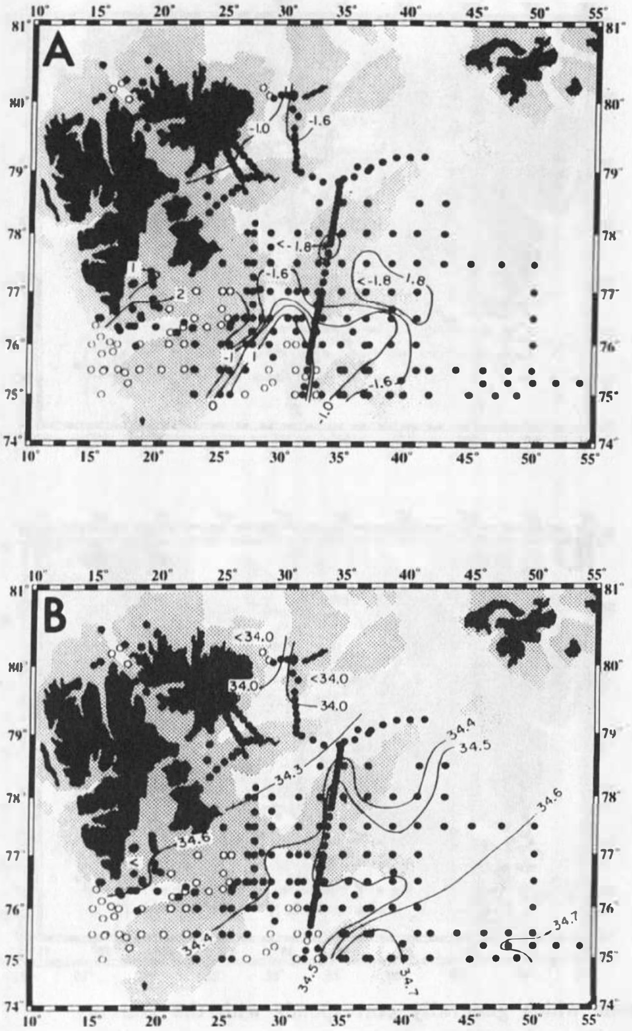

Fig. 8 Characteristics of the water column at the temperature minimum which generally corresponds with the characteristics of Arctic water: A) potential temperature, B) salinity. Data are from summer 1981. Stippling indicates regions with water depths less than 200m, open circles indicate stations where a temperature minimum was not observed.

(Fig. 1) showing the influence of nearby Atlantic-derived water. Salinity increases in this water mass from 34.0°/oo in the northwest to 34.7°/oo in the southeast (Fig. 8B, see also Fig. 6B, 7B). Corresponding to changes in the salinity distribution, the density increases from 27.6 in the north to over 27.9 σ_0 in the south (Fig. 6C).

Atlantic-derived Water

In order to distinguish Atlantic-derived water entering the Barents Sea via the North Cape Current (Fig. 1; Fig. 3, areas II and V) from that entering the Barents Sea from the north (Fig. 3, areas III and IV), we refer to the Atlantic-derived water with origin in the southern Barents Sea as southern Barents Atlantic-derived Water (SBAW) and that to the north as northern Barents Atlantic-derived Water (NBAW). These water masses are modified in the Barents Sea by cooling and mixing with Arctic water. Core characteristics fall on different mixing lines (Fig. 3B, D), with NBAW generally being less saline than SBAW in 1981 and 1982.

In Hopen Deep, south of the polar front, SBAW fills the entire water column (Fig. 3A: central part of area II; Fig. 6A, B). The salinity maximum is at about 75m depth (Figs. 6B, 9D). In northern Hopen Deep, Atlantic water flows over sills, crosses the polar front and is transformed into a submerged water mass. North and east of the polar front, SBAW is overlain by Arctic water. In this transformation region, the depth to the temperature maximum drops to > 200m (Figs. 7, 9D), while its salinity decreases by about 1.5°/oo, and its temperature decreases to 0°C (see Figs. 3B, D, area II; 8A, B). As a submerged water mass, SBAW is also observed to the north and east, following depressions between shallower banks (Fig. 3: areas IV and V).

NBAW occurs in the strait between Nordaustlandet and Kvitøya (Fig. 3: area III), with a maximum temperature greater than 1°C (Fig. 9A). Similar temperatures are also observed in: Erik Eriksen Strait, the passage south of Kvitøya and just to the northeast of Storbanken.

Bottom Water

The water overlying the sea floor has a large range in temperature and salinity (Fig. 3C, E) which is strongly dependent on the water depth (compare Figs. 2 and 10). Usually, either cold bottom water or Barents Atlantic-derived water are found at the bottom in topographic depressions, while Arctic water occurs as the bottom water mass on Spitsbergenbanken and Storbanken (Fig. 10A, B).

Densest bottom waters (Fig. 10C) are found on Novaya Zemlya Bank (Fig. 3, area VI) and in Storfjorden (Fig. 3, area I; selected stations were previously published by Midttun, 1985). Both areas are known as regions where very dense cold bottom water (CBW) with salinities > 35°/oo is formed [Figs. 3C, E, 10B; *Knipowitsch*, 1905; *Nansen*, 1906; *Novitsky*, 1961; *Midttun*, 1985; *Anderson et al.*, 1988; *Quadfasel, et al.*, 1988; *Blindheim*, 1989; *Midttun*, 1989; *Loeng*, 1991]. CBW in both of these regions is definitely more saline and colder than the deep water and bottom water of the Eurasian Basin of the Arctic Ocean (Fig. 3C). The densest water in Storfjorden is found

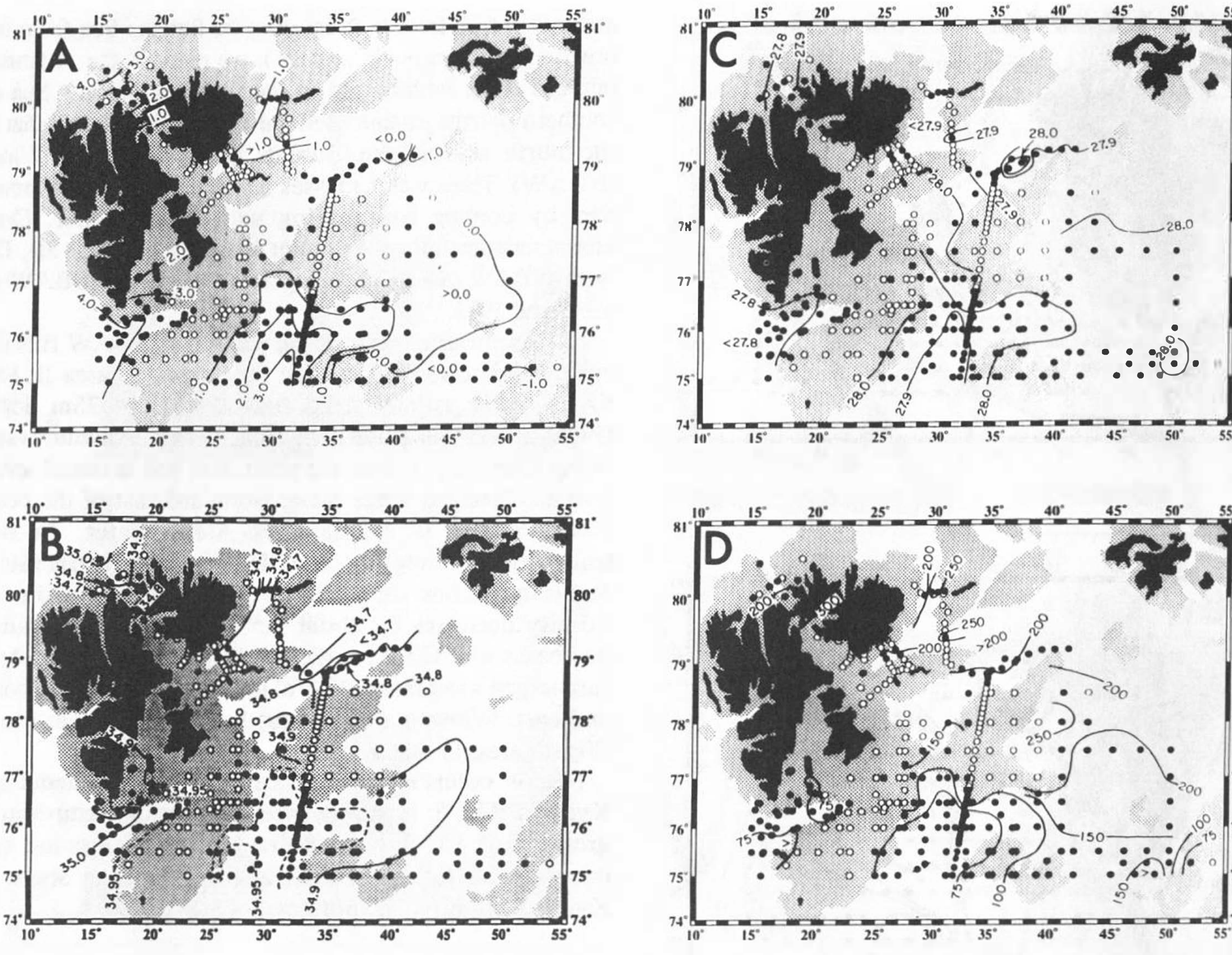

Fig. 9 Characteristics of the saline temperature maximum which generally corresponds with the Barents Atlantic-derived water: A) potential temperature, B) salinity, C) density, D) depth. Data are from summer 1981. Stippling indicates regions with water depths less than 200m, open circles indicate stations where a saline temperature maximum was not observed.

in the very north of the fjord which is separated from the southern part by a sill that is between 50 and 100m deep. The bottom water becomes continuously fresher and warmer towards the southern part of the fjord (Fig. 10). In 1982, our hydrographic stations were located north of the basin where dense water was observed in 1981 and do not show this feature (Fig. 3E).

Bottom water throughout the rest of the Barents Sea is generally less saline although it does reach 34.94°/oo in area V in 1981. Density is less than or equal to 28.1 σ_0.

CIRCULATION AND MIXING PATTERNS

Using the water mass distribution and temperature-salinity relationships observed in this investigation and analyses of hydrographic and current data by Tantsiura (1959, 1973), Novitsky (1961), Eide and Loeng (1983), Midttun (1985), Pfirman (1985), Midttun and Loeng (1987), and Loeng et al. (1993) we discuss circulation and mixing patterns in the northern Barents Sea (Figs. 1 and 11). Due to variations in winds, water exchange with adjacent seas, and continental runoff there are large seasonal and annual variations in current velocity, location and hydrographic characteristics [*Tantsiura*, 1959; *Novitsky*, 1961; *Midttun and Loeng*, 1987; *Ådlandsvik and Loeng*, 1991].

Surface Water

Although the characteristics of summer surface water is

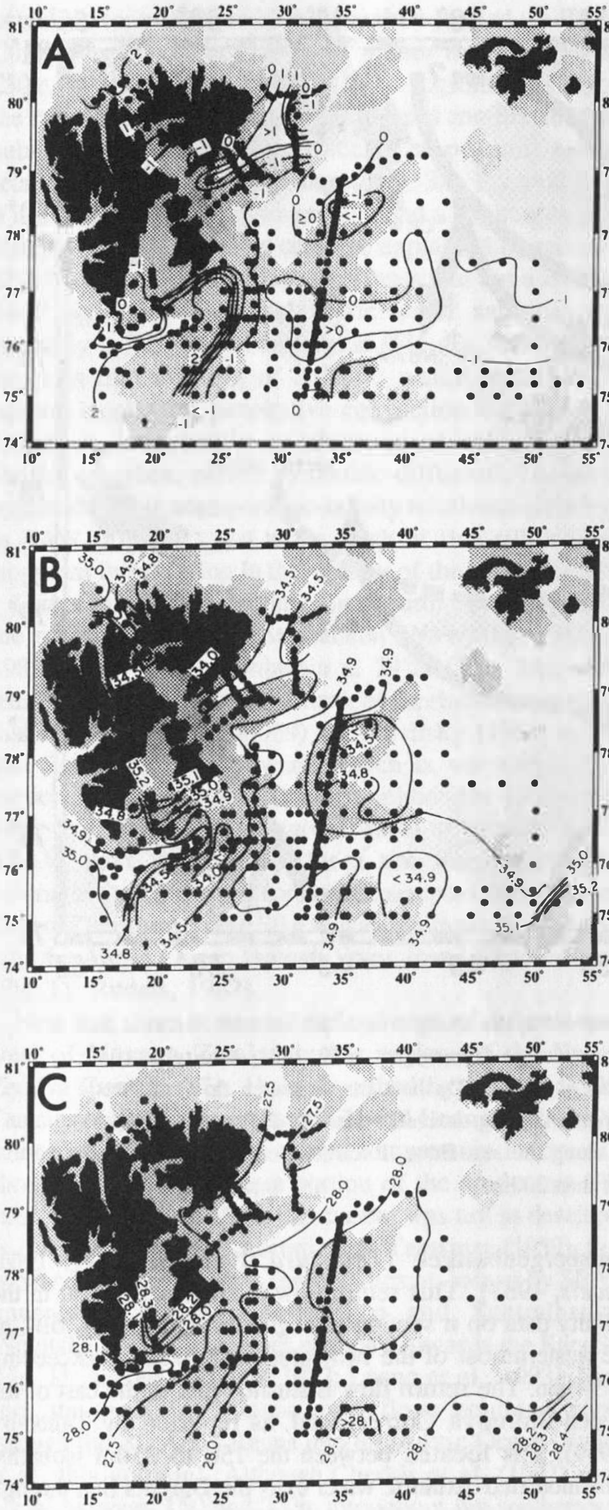

Fig. 10 Bottom water characteristics: A) potential temperature, B) salinity, C) density. Data are from summer 1981. Stippling indicates regions with water depths less than 200m.

governed by sea-ice melting and retreat, deviation from this pattern is seen along the eastern flank of Spitsbergenbanken where there is a region that is colder than that to either side (Fig. 5). This cold tongue corresponds to the southward-flowing Hopen-Bjørnøya Current (Figs. 1 and 11). Another anomaly is observed over Hopen Deep, where the surface water is warmer and more saline due to Atlantic water inflow. Similar Atlantic water influence is also observed in Storfjorden where a branch of the West Spitsbergen Current flows eastward up the trough.

The low salinity lenses observed over the banks (Figs. 5B, 6B, 7B), may represent water trapped by anticyclonic vortexes [*Midttun and Loeng*, 1987; *Midttun*, 1989].

Arctic Water

A portion of the Arctic water in the Barents Sea forms in the previous winter as a result of convection during development of the sea ice cover. The lower temperature and higher salinity Arctic water near Storbanken (Figs. 7 and 8) may represent winter water trapped by an anticyclonic vortex [*Midttun and Loeng*, 1987; *Midttun*, 1989]. However, it could also indicate advection of Arctic water into the Barents Sea from the northern Kara Sea and the region near Frans Josef Land via the westward-flowing Persey Current previously described by Tantsiura (1959) and Novitsky (1961) (Figs. 1 and 11). The Persey Current continues across the Barents Sea to the west, where it merges with the well-defined, southward-flowing Hopen-Bjørnøya Current [*Tantsiura*, 1959; *Novitsky*, 1961]. Comprised of Arctic water, with low temperatures extending from 50 down to 200m water depth [*Novitsky*, 1961], the Hopen-Bjørnøya Current, clearly observed in our data set, has a core at about 70m water depth (26°E; Figs. 7A, 8A). It has high velocities [up to 1 knot: *Tantsiura*, 1959], and generally is located over the 100 to 200m isobaths along the eastern flank of Spitsbergenbanken [*Tantsiura*, 1959]. Some Arctic water from the Arctic Ocean also contributes to this flow via the East Spitsbergen Current [*Tantsiura*, 1959; *Novitsky*, 1961].

Atlantic-derived Water

The section along 75.5°N (Fig. 6) shows Atlantic water of the West Spitsbergen Current flowing north along the western flank of Spitsbergenbanken. Maximum salinities here exceed 35.1°/oo (Fig. 3, area I). A tongue of Atlantic water enters Storfjorden with a core depth of about 75m (Fig. 9). Note that this water does not appear to continue eastward into the Barents Sea, probably because of the shallow depth of Spitsbergenbanken [*Tantsiura*, 1959: depth

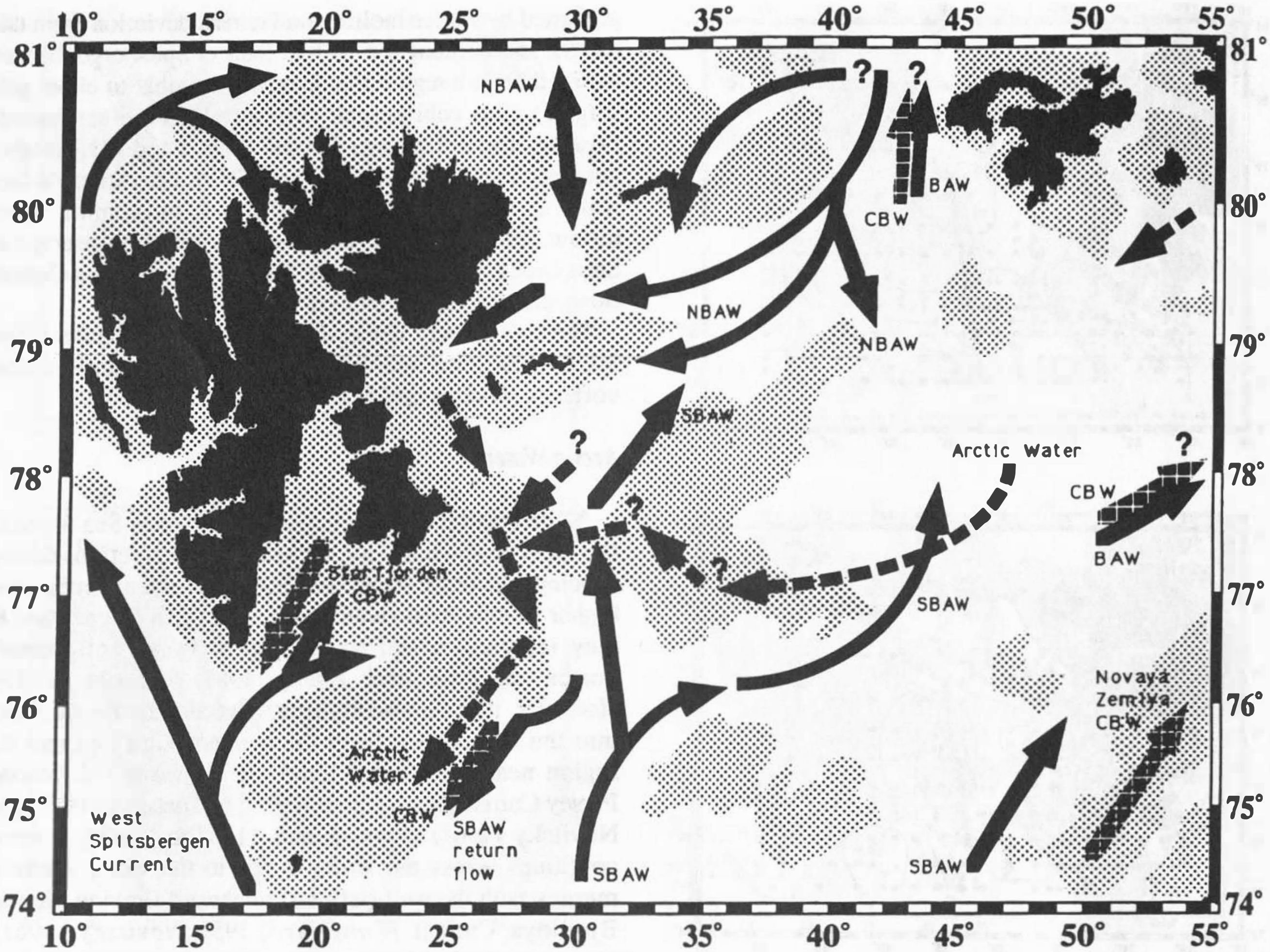

Fig. 11 Schematic of subsurface circulation of water masses observed in the study area of the northern Barents Sea using summer data from this study and information from various sources (*Tantsiura*, 1959, 1973; *Novitsky*, 1961; *Midttun*, 1985; *Pfirman*, 1985; *Quadfasel et al.*, 1988; *Loeng et al.*, 1993). Dashed arrows sketch flow of Arctic water (20-150m water depth); solid arrows sketch flow of Barents Atlantic-derived water (75-250m water depth), and cross-hatched arrows sketch flow of cold bottom water along the sea floor. Recirculation in basins is not shown. Stippling indicates regions where water depths are less than 200m.

between 60 and 80m, *Kristoffersen et al.*, 1988], which is close to the core depth in this region.

Atlantic water does enter the Barents Sea south of Spitsbergenbanken via the North Cape Current (Fig. 1). Atlantic water inflow through this passage may be about 1.6 Sv [see summary by *Loeng*, 1993]. A branch of the North Cape Current extends north along the western flank of Sentralbanken [Figs. 1 and 11; *Nansen*, 1906; *Novitsky*, 1961], forming a current of SBAW that is up to 60 miles wide [*Tantsiura*, 1959]. Current meters deployed in this region in the summer indicate surface to bottom flow to the north [*Eide and Loeng*, 1983]. A portion of this flow turns back to the south along the eastern flank of Spitsbergenbanken [*Tantsiura*, 1959; *Novitsky*, 1961; *Rudels*, 1987]. This return flow is apparently seen in the salinity data on a section through this region (Fig. 6B), as the westernmost of the two cores with salinities exceeding 34.94°/oo. The return flow is situated just to the east of the Hopen-Bjørnøya Current, and, as reported by Tantsiura (1959), it is located between the 150 to 350m isobaths. This modified Atlantic water exits the Barents Sea through Bjørnøyrenna, and returns to the Norwegian Sea [*Novitsky*, 1961].

Tongues of SBAW (Fig. 11) also extend over the sill between Storbanken and Spitsbergenbanken [sill depth between 150 and 200m, *Cherkis et al.*, 1991], as well as between Storbanken and Sentralbanken [called the Eastern Current by *Novitsky* (1961), sill depth between 200 and 250m, Cherkis et al., 1991]. In these regions, just beyond the polar front, SBAW undergoes rapid modification and submerges below the surface. Temperature-salinity relationships lie on a steep slope (Fig. 3B, D, areas II and V), indicating a drop in temperature and a slight decrease in salinity. This relationship could be explained by mixing of SBAW with a near-freezing water mass that has a salinity < 34.8°/oo. In 1981, actual Arctic water salinities were generally < 34.7°/oo in this region (Fig. 8). Rudels (1987) suggests that cooling of Atlantic water in this region occurs: locally by penetrative convection during sea ice formation, isopycnally by advection of cold water with similar densities, and/or by double diffusion. The jagged appearance of the temperature-salinity relationship observed in BAW (Fig. 4A) just to the north of this sill, indicates isopycnal interleaving in the vicinity of the polar front.

Part of the SBAW continues as a warm bottom current to the north and west of Storbanken [*Novitsky*, 1961]. In 1982, SBAW was seen again at 79°N (Fig. 7A), where temperatures along the west flank of Storbanken are greater than 0.2°C. Tantsiura (1959) and Novitsky (1961) indicate that flow in this northward branch is variable and not particularly substantial. Although neither the 1981 nor the 1982 data sets extend far enough north to trace the path of SBAW past Storbanken, there are no bathymetrical hindrances to continued northward transport into the Arctic Ocean. Therefore, some SBAW may continue flowing north into the Arctic Ocean through Frans Josef-Victoria Renna [Fig. 11: Rudels, 1987].

Note that there is no well-defined core of Atlantic water west of Novaya Zemlya in the region of the Novaya Zemlya Current (Fig. 1), as described by Nansen (1906), Tantsiura (1959), Novitsky (1961) and Loeng et al. (1993), among others. Depth to a modest temperature maximum is about 200m in the eastern portion of the study area (Fig. 9D). Apparently, in 1981, this current was not as developed as it is in other years. According to Tantsiura (1959), flow of SBAW in the Novaya Zemlya Current, joined by SBAW transported between Storbanken and Sentralbanken [Novitsky, 1961], continues eastward towards the Kara Sea [Fig. 11: see also Rudels, 1987; Loeng et al., 1993]. From here, the modified Atlantic water flows continues north, through the St. Anna Renna into the Arctic Ocean [*Rudels et al.*, this volume]. Although Cherkis et al. (1991) show depths between 150 and 200m throughout the southern part of the passage between Frans Josef Land and Novaya Zemlya which would divert flow of water deeper than that to the north, Loeng et al. (1993) indicate a passage with water depths between 200 and 300m -- sufficiently deep to allow flow of Barents Atlantic-derived water. Loeng et al. (1993) found that outflow of water through the passage between Frans Josef Land and Novaya Zemlya increases towards the bottom, and the average total outflow is about 2 Sv, with a maximum in early winter.

Turning now to the northern reaches of the Barents Sea, NBAW enters Hinlopen Strait (Figs. 2 and 11), but does not extend all the way into the Barents Sea because of the shallow water depths in the southern portion of the strait [less than 100m, *Cherkis et al.*, 1991]. NBAW does enter the Barents Sea further east through various straits between Nordaustlandet and Frans Josef Land [*Mosby*, 1938]. NBAW decreases markedly in salinity (by more than 0.3°/oo), as well as temperature, as it penetrates southward into the northern basins (Figs. 3B, D, 9). Because CBW is absent, NBAW is the bottom water mass in the northern basins (Fig. 10A), and it mixes primarily with the overlying cold and less saline Arctic water.

Both Mosby (1938) and Novitsky (1961) suggest a modest southward flow of NBAW through the strait between Nordaustlandet and Kvitøya [sill depth between 250 and 300m, *Cherkis et al.*, 1991]. However, a year of current meter measurements in the NBAW core (255m), indicate an average velocity here to the *northeast* of 0.5 cm sec^{-1} [*Aagaard et al.*, 1983]. In 1981, the maximum temperature in the strait was > 1°C and the salinity was > 34.8°/oo (Fig. 9A, B). Continuing southward, into Erik Eriksen Strait east of Svalbard (Fig. 3: area III), this branch of NBAW appears to mix with Arctic water that a salinity of about 34.4°/oo. Actual salinities at the temperature minimum of the Arctic water are generally < 34.3°/oo (Fig. 8). Because the Arctic water here is so fresh, the mixing relationship for western NBAW (Fig. 3: area III) is less steep than that for NBAW entering the Barents Sea to the east (Fig 3: area IV) where the salinity of Arctic water is greater. Novitsky (1961) indicates that this northwestern branch of NBAW is separated in some way from the main mass of NBAW that enters the Barents Sea east of Kvitøya.

According to previous analyses, some NBAW enters the Barents Sea between Kvitøya and Victoria Island, with a temperature maximum at about 200m [*Mosby*, 1938; *Pfirman*, 1985; apparent sill depth between 200 and 250m, *Cherkis et al.*, 1991], but the majority of the flow is along the eastern margin of Victoria Island through Frans Josef-Victoria Renna [Fig. 11: *Mosby*, 1938; *Novitsky*, 1961]. The sill depth of this passage appears to be between 300 and 350m [*Cherkis et al.*, 1991], making this strait the deepest, as well as the widest conduit into the northern Barents Sea from the Arctic Ocean. NBAW occurs as a bottom water mass along the western slope, influencing the sea floor from about 150 to 400m water depth [*Mosby*, 1938]. South of Victoria Island, NBAW spreads to the southwest (Fig. 11), filling the deepest part of Frans Josef-Victoria Renna, and continuing into the depression south of Kong Karls Land [*Novitsky*, 1961: see Fig. 7; the 0.8°C core with a salinity of about 34.76°/oo at 33°E]. Although some water also passes to the east of Storbanken (see Fig. 7; the 1.4°C core with a salinity of about 34.87°/oo at 42°E), according to Novitsky (1961) it does not flow far to the south because it encounters northward-flowing SBAW. NBAW mixes with overlying Arctic water during transport, with core properties falling along a mixing line that extends to Arctic water with a salinity of about 34.5°/oo (Fig. 3B, D, area IV). Actual salinities at the temperature minimum of the Arctic water in this region were between 34.3 and 34.4°/oo in 1981 (Fig. 8).

In the 1982 data set, SBAW is detected on both sides of Storbanken in this region (Fig. 3; area IV). SBAW is the bottom water mass, while NBAW, less saline and warmer (in 1981 as well as 1982 data, also noted by Rudels, 1987), is observed at shallower depths (Fig. 7A: 200m at 33°E and 175m at 42°E). Along the western flank of Storbanken, SBAW with 0.2°C and 34.86°/oo salinity is found. Another branch of SBAW, about 0.1°C colder but with the same salinity, is also observed at the very bottom on the eastern side of Storbanken. This water mass is apparently a northern extension of SBAW that passed along the east side of Storbanken, or it has circulated around Storbanken.

The depths at which NBAW and SBAW occur depend on their relative density. In 1981 and 1982, NBAW was warmer than SBAW and its maximum salinity within the confines of the Barents Sea was lower than that of SBAW (NBAW 1981: 34.8°/oo between Nordaustlandet and Kvitøya; NBAW 1982: 34.9°/oo east of Storbanken; SBAW: 34.95 to 35°/oo in Hopen Deep). In 1931, Mosby (1938) found NBAW with temperatures greater than 2°C and salinities greater than 34.9°/oo entering the Barents Sea between Kvitøya and Frans Josef Land. There could be several reasons for differences between SBAW and NBAW. One reason could be that there are variations in the currents which feed NBAW into the Barents Sea, and that sometimes the inflow is not as great [e.g. *Midttun and Loeng*, 1987]. Also, although both SBAW and NBAW originate from the Norwegian Atlantic Current, it takes longer for Atlantic water to flow around Svalbard and enter the Barents Sea from the north. Starting from the Norwegian Atlantic Current (73°N 15°E), the distance to Storbanken (79°N 40°E) is about 1650km for NBAW and about 1050km for SBAW. Assuming an average advection velocity of 1 cm/s, NBAW would take about 2 years longer than SBAW to reach Storbanken (NBAW = 5.2 years; SBAW = 3.3 years). Different travel times mean that NBAW originates from an older 'vintage' of Atlantic water than SBAW sampled during any one year. It could be that in 1981 and 1982 this vintage was less saline than that which entered the Barents Sea more recently from the south. This compares with the occurrence of the "Great Salinity Anomaly" (when the salinity of the Atlantic water was about 0.1°/oo less than average: *Dickson et al.*, 1988), which passed the North Cape and West Spitsbergen currents in 1978-1979. More generally, Atlantic water temperature and salinity characteristics are known to vary by more than ±0.5°C and ±0.06°/oo [*Mosby*, 1938; *Blindheim and Loeng*, 1981; *Midttun*, 1989]. If these were the only two reasons for the variations, then one could expect that NBAW would sometimes be denser than SBAW.

However, according to Anderson et al. (1989), along the northern slope of the Barents Sea, just north of Kvitøya, the NBAW temperature maximum lies between 200 and 250m, while the salinity maximum lies between 300 and 500m. These depths are close to the sill depths of the northern channels (250 to 300m between Nordaustlandet and Kvitøya, 200 to 250m between Kvitøya and Victoria Island, and 300 to 350m between Victoria Island and Frans Josef Land, *Cherkis et al.*, 1991). Therefore, differences in the core extrema could also be due to skimming off of the less saline fraction during entry into the northern Barents Sea. In addition, NBAW sampled in our study has had more opportunities to mix with Arctic water due to its longer travel time as a submerged water mass, and the Arctic water with which it mixes is fresher than the Arctic water with which the SBAW mixes. As a result of these processes, NBAW may generally be less dense than SBAW and be found above it when the two water masses meet in the northern Barents Sea.

Moving further east, Tantsiura (1959) and Loeng et al. (1993) indicate inflow of modified Atlantic water as a submerged water mass from the Arctic Ocean into the Kara Sea through the St. Anna Renna and then on into the northeastern Barents Sea south of Frans Josef Land. Cherkis et al. (1991), locate the deepest part of the passage between Frans Josef Land and Novaya Zemlya just south of Frans Josef Land, with a sill depth between 200 and 250m. Loeng et al. (1993) indicate another passage further south with sill depth between 200 and 300m. In warm years, this flow of Atlantic-derived water in from the Kara Sea may join the eastward-flowing SBAW of the Novaya Zemlya Current [*Novitsky*, 1961]. Our stations are located too far to the west to resolve this water mass in the present study.

Cold Bottom Water

Because data used in this study are summer values, and

CBW forms primarily in fall and winter, the distribution of CBW shown here represents only a remnant of this water mass [*Novitsky*, 1961]. CBW is modified by summer mixing and thus is probably also less dense than it originally was.

Even in mid-summer, very dense CBW is observed to accumulate over Novaya Zemlya Bank in 1981 (Fig. 6). Nansen (1906) noted that the same kind of dense, cold water is found almost everywhere on Novaya Zemlya Bank, comprising a layer more than 100m thick. Because this water is so saline, it has to have added salt from brine rejection during sea ice formation (Fig. 3, area VI). The process of dense water formation starts here in the fall, when the water column is cooled, and continues when salt is added from sea ice formation [*Loeng*, 1991]. Novaya Zemlya CBW apparently flows east into the Kara Sea (Fig. 11), and may continue on through the St. Anna Renna into the Arctic Ocean [*Nansen*, 1906; *Midttun*, 1985; *Blindheim*, 1989]. Temperature and salinity properties of this water mass are more extreme than that of Eurasian Basin deep and bottom water (Fig. 3C) and Novaya Zemlya CBW is thought to contribute to formation of these Arctic water masses [*Nansen*, 1906; *Midttun*, 1985]. Although bottom water in the trough west of the bank has slightly elevated salinity and density in proximity to the sea floor, it is much less dense and saline than the water on Novaya Zemlya Bank (Fig. 6). In 1981, a sharp front separated the two water masses and they do not appear to have been connected (also observed by *Nansen*, 1906). In Midttun's (1985) report on dense water near Novaya Zemlya Bank, CBW appeared to spread toward the west along the sea floor into the adjacent trough.

Water mass characteristics of Novaya Zemlya CBW are similar to those observed in Storfjorden [Fig. 3C, area I, *Midttun*, 1985). Dense CBW flows out of Storfjorden to the west (Fig. 11) and then spreads along the west Spitsbergen margin to the north [*Quadfasel et al.*, 1988]. During summer, the volume of cold water pooled in Storfjorden decreases, and by late fall it has disappeared or is found in only minor amounts in the deepest part of the trough [*Novitsky*, 1961]. As with Novaya Zemlya CBW, temperature and salinity properties of this water mass are more extreme than that of Eurasian Basin deep and bottom water (Fig. 3C, E), and water formed here could contribute to development of these Arctic water masses [*Midttun*, 1985; *Quadfasel et al.*, 1988].

Less extreme cold bottom water observed in Hopen Deep may contribute to waters of intermediate depth in the Norwegian Sea [*Blindheim*, 1989]. The hydrographic structure observed at 75.5°N suggests flow of such cold bottom water (Fig. 6: temperature < -0.5°C, salinity about 34.92°/oo, and density > 28.0 σ_0) southward along the eastern flank of Spitsbergenbanken at about 225m water depth (Fig. 11). This water most likely continues flowing southwestward and exits the Barents Sea through Bjørnøyrenna. Blindheim (1989) estimated about 0.8 Sv of outflowing bottom water through this passage.

CBW occurring in most of the other depressions in the Barents Sea generally is slightly warmer (Fig. 10: temperature between -0.2 and +0.2°C, salinities between 34.90 to 34.94°/oo, and densities between 28.0 and 28.1 σ_0). The highest salinities are observed east of Sentralbanken (in a region sometimes called the Central Depression; Fig. 3, area V), an area also discussed by Nansen (1906). In 1981, CBW sampled here was slightly less saline than in 1982 (Fig. 3C, E; compare salinity range in area V).

Throughout the Barents Sea there are large annual--as well as seasonal--variations in the regional accumulation and discharge of CBW [*Nansen*, 1906; *Midttun and Loeng*, 1987; *Blindheim*, 1989; *Midttun*, 1989]. For example, Midttun (1989) displays sections along 45°E collected in September of 1982 and 1983 which show a large amount of cold < -1.5°C bottom water south of 75°N in 1982 compared with only a small amount in 1983 (note: this feature is not observed in our 1982 data set, because our study area cuts off at 75°N). Also, the distribution of bottom density in September-October 1986 [*Blindheim*, 1989] showed a much larger region with densities > 28.1 σ_0 than that observed in this study (compare our Fig. 10C with Blindheim's (1989) Fig. 2). Midttun and Loeng (1987) found that the rate of dense water formation and accumulation is related to variations in its outflow, as well as variations in the salinity of the inflowing water. According to these authors, following a period of high Atlantic water influx, it takes more than a year for winter cooling to accumulate CBW with a density great enough to initiate a new outflow, which may occur as a massive discharge [*Loeng*, 1991].

Outflow of CBW could take place [*Nansen*, 1906; *Swift et al.*, 1983; *Midttun*, 1985; *Midttun and Loeng*, 1987; *Quadfasel et al.*, 1988; *Midttun*, 1989; *Blindheim*, 1989; *Loeng*, 1991]: to the west of Frans Josef Land where there is a deep conduit between this region and the Arctic Ocean (with depths between 250 and 300m, *Cherkis et al.*, 1991), between Frans Josef Land and Novaya Zemlya [the primary avenue according to *Loeng*, 1991; *Loeng et al.*, 1993], and/or to the southwest through Bjørnøyrenna.

CONCLUSIONS

Under summer conditions, the water column in the

Barents Sea, north of the polar front, is stratified: a warm, fresh surface layer is underlain by cold, relatively fresh Arctic water, which in turn is underlain by a warm, saline Atlantic-derived layer. Cold bottom water, which is colder and usually slightly more saline than the Barents Atlantic-derived layer, is found near the sea floor mostly in bathymetric depressions, but also over Novaya Zemlya Bank.

Arctic water may develop in place during sea ice formation in fall and winter. It may also be advected into the Barents Sea, primarily from the northern Kara Sea via the Persey Current and to a lesser degree from the Arctic Ocean via the East Spitsbergen Current. Arctic water is freshest in the northwestern portion of the Barents Sea, less than 34.3°/oo, and ranges up to 34.7°/oo in the southeastern portion of the study area.

Atlantic water enters the Barents Sea both from the south, as southern Barents Atlantic-derived water (SBAW) and the north as northern Barents Atlantic-derived water (NBAW). SBAW cools abruptly when it penetrates north and east of the polar front, and becomes an intermediate or bottom water mass overlain by cold Arctic water. Salinity decreases only slightly in this process (from 34.95 to 34.8°/oo). In contrast, while penetrating southward into troughs in the Barents Sea, NBAW is cooled and diluted significantly (up to 0.3°/oo) by mixing with the fresher, overlying Arctic water. North of about 79°N, during 1981 and 1982, SBAW was denser than NBAW and occurred beneath it. Some SBAW may continue flowing northward into the Arctic Ocean through the Frans-Victorica Renna west of Frans Josef Land [*Rudels*, 1987]. Here it would be located in the eastern portion of the passage, to the east of the core of NBAW which flows southward in this region. The greater volume of SBAW flows eastward into the Kara Sea south of Frans Josef Land [*Rudels*, 1987; *Loeng et al.*, 1993]. Total outflow (modified Atlantic and other water) through this passage is about 2 Sv [Loeng et al., 1993], apparently comparable to the inflow of Atlantic water through Bjørnøyrenna (1.6 Sv). This flow continues north, through the St. Anna Renna into the Arctic Ocean [*Rudels et al.*, this volume]. Therefore, while some modified Barents Atlantic-derived water is contributed directly to Arctic Ocean from the Barents Sea, most appears to be contributed indirectly through the Kara Sea.

Remnants of cold, saline water formed by brine rejection during sea ice formation are observed near the sea floor. In 1981, extremely dense water (> 28.3 σ_0) was observed both in Storfjorden and on Novaya Zemlya Bank (described earlier by *Midttun*, 1985). These waters are the densest observed in the Barents Sea. Less cold and saline dense bottom waters also occur in other regions. Following bathymetric depressions, this dense bottom water flows out of the Barents Sea and, depending on its density, influences the intermediate, deep and bottom water characteristics of the adjacent Norwegian Sea and the Arctic Ocean. Outflow occurs along the bottom and takes place:

1) into the Norwegian Sea along the northern flank of Bjørnøyrenna [*Sarynina*, 1969; *Swift*, 1986; *Midttun and Loeng*, 1987; *Blindheim*, 1989; *Midttun*, 1989],

2) from Storfjorden to the western Spitsbergen margin of the Norwegian Sea where it continues north into the Arctic Ocean [e.g. *Quadfasel et al.*, 1988],

3) directly into the Arctic Ocean west of Frans Josef Land [*Blindheim*, 1989], and

4) into the Kara Sea along the southern portion of the passage between Frans Josef Land and Novaya Zemlya, where it probably exits to the Arctic Ocean through St. Anna Renna. This is the main passageway for the extremely cold and dense Novaya Zemlya cold bottom water [*Nansen*, 1906; *Midttun*, 1985; *Midttun*, 1989; *Loeng*, 1991].

Acknowledgments. Hydrographic data from the Institute for Marine Research (Havforskningsinstitutt), in Bergen, Norway, was provided by Harald Loeng. The research was funded under U.S. Office of Naval Research contracts N00014-81-C-009 (directed by John D. Milliman) and N00014-90-J-1362, with some travel funding from the Norwegian Marshall Fund. Ship time on the M/S Lance and logistical assistance was provided by the Norwegian Polar Research Institute. Lamont-Doherty Earth Observatory contribution #5169.

REFERENCES

Aagaard, K. and Carmack, E. C., 1989, The role of sea ice and other fresh water in the Arctic circulation, *Jour. Geophys.Res.*, 94(C10), 14487-14498.

Aagaard, K., Coachman, L. K. and Carmack, E. C., 1981, On the halocline of the Arctic Ocean, *Deep-Sea Res.*, 28, 529-545.

Aagaard, K., Foldvik, A., Gammelsrød, T. and Vinje, T. (1983) One-year records of current and bottom pressure in the strait between Nordaustlandet and Kvitøya, Svalbard, 1980-81, *Polar Research 1n.s.*, 107-113.

Ådlandsvik, B. and Loeng, H. (1991) A study of the climate system in the Barents Sea, *Polar Res.*, 10(1), 45-49.

Anderson, L.G., Jones, E.P., Koltermann, K.P., Schlosser, P., Swift, J., and Wallace, D.W.R., 1989, The first oceanographic section across the Nansen Basin of the Arctic Ocean, *Deep-Sea Res.* 36, 475-482.

Anderson, L.G., Jones, E.P., Lindegren, R., Rudels, B., and

Sehlstedt, P.-J., 1988, Nutrient regeneration in cold, high salinity bottom water of the Arctic shelves, *Continental Shelf Res.*, 8(12), 1345-1355.

Blindheim, J., 1989, Cascading of Barents Sea bottom water into the Norwegian Sea, *Rapp.P.-v.Reun.Cons.int.Explor. Mer*, 188, 49-58.

Blindheim, J. and Loeng, H., 1981, On the variability of Atlantic influence in the Norwegian and Barents Sea, *Fisk. Dir. Skr. Ser. Hav.Unders.*, 17, 61-189.

Cherkis, N.Z., Fleming, H.S., Max, M.D., Vogt, P.R., and Czarnecki, M.F. (1991) *Bathymetry of the Barents and Kara Seas*, Geological Society of America, Inc., Boulder, Colorado.

Dickson, R.R., Meincke, J., Malmberg, S.-A. and Lee, A.J. (1988) The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982, *Prog.Oceanog.*, 20, 103-151.

Eide, L.I. and Loeng, H., 1983, Environmental conditions in the Barents Sea and near Jan Mayan, *Det Norske Meteorologiske Institutt*, Oslo, August, 1983.

Gordienko, P.A. and Laktionov, A.F., 1969, Circulation and physics of the Arctic Basin waters, in Annals of the International Geophysical Year, *Oceanography*, 46, Pergamon, New York, p. 94-112.

Hanzlick, D.J., 1983, *The West Spitsbergen Current: transport, forcing, and variability*, Ph.D. thesis, University of Washington, 127 pp.

Hanzlick, D. and Aagaard, K., 1980, Freshwater and Atlantic water in the Kara Sea, *Jour.Geophys.Res.*, 85(C9), 4937-4942.

Knipowitsch, N., 1905, Hydrologische Untersuchungen in Europaeischen Eismeer, *Annalen der Hydrographie und Maritimen Meteorologie*, 33, 289-308.

Kristoffersen, Y., Sand, M., Beskow, B., and Ohta, Y., 1988, *Western Barents Sea bathymetry*, Norsk Polarinstitutt, Oslo.

Loeng, H., 1980, Physical oceanographic investigations in central parts of the Barents Sea, *Fisken Hav.*, 3, 29-60.

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

Loeng, H., Ozhigin, V., Ådlandsvik, B. and Sagen, H. (1993) Current measurements in the northeastern Barents Sea, *ICES Statutory Meeting*, 22 p.

Midttun, L. 1961, Norwegian hydrographical investigations in the Barents Sea during the international geophysical year, *Rapp.P.-v.Reun.Cons.int.Explor.Mer*, 149, 25-30.

Midttun, L., 1985, Formation of dense bottom water in the Barents Sea, *Deep-Sea Res.*, 32(10), 1233-1241.

Midttun, L., 1989, Climatic fluctuations in the Barents Sea, *Rapp.P.-v.Reun.Cons.int.Explor.Mer*, 188, 23-35.

Midttun, L. and Loeng, H., 1987, Climatic variations in the Barents Sea, in The effect of oceanographic conditions on distribution and population dynamics of commercial fish stocks in the Barents Sea, H. Loeng, ed., *Proc. Third Soviet-Norwegian Symposium*, Murmansk, May, 1986, pp. 13-28.

Mosby, H., 1938, Svalbard Waters, *Geofysiske Publikasjoner*, 12(4), 1-85.

Nansen, F., 1906, Northern waters: Captain Roald Amundsen's oceanographic observations in the Arctic seas in 1901, *Vitenskabs-Selskapets Skrifter* 1, Mathematisk-Naturv. Klasse., 3, 145 pp.

Novitsky, V.P., 1961, Permanent currents of the Northern Barents Sea, *Trudy Gosudarstvennogo Okeanografiches-kogo Instituda*, 64, 1-32, Translated by U.S.N.O. 1967, Leningrad.

Pfirman, S.L., 1985, *Modern sedimentation in the northern Barents Sea: Input, dispersal and deposition of suspended sediments from glacial meltwater*, Ph.D. Thesis, Mass. Inst.Tech./Woods Hole Oceanogr. Inst., Woods Hole Oceanogr.Inst., Tech.Rept. WHOI-85-4, 382 p.

Quadfasel, D., Rudels, B., and Kurz, K., 1988, Outflow of dense water from a Svalbard fjord into the Fram Strait, *Deep-Sea Res.*, 35(7), 1143-1150.

Redfield, A.C. and Friedman, I., 1969, The effect of meteoric water, melt water and brine on the composition of Polar Sea water and of the deep waters of the ocean, *Deep-Sea Res.*, 16, 197-214.

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

Rudels, B., Jones, E.P., Anderson, L.G. and Kattner, G., On the intermediate depth waters of the Arctic Ocean, in *Geophysical Monograph Series*, edited by O. Johannessen, R.D. Muench, and J.E. Overland, AGU, Washington, D.C., in press, 1994.

Sarynina, R.N., 1969, Conditions of origin of cold deep-sea waters in the Bear Island Channel, *Symposium on Physical Variability in the North Atlantic*, Dublin, 23-27 September 1969.

Schlosser, P., Bauch, D., Rairbanks, R. and G. Boenisch, Arctic river-runoff: mean residence time on the shelves and in the halocline, *Deep-Sea Research*, in press, 1994.

Swift, J.H., Takahashi, T. and Livingston, H. D., 1983, The contribution of the Greenland and Barents seas to the deep water of the Arctic Ocean, *Jour.Geophys.Res.*, 88(C10), 5981-5986.

Swift, J.H., 1986, Arctic Waters, in: *The Nordic Seas*, ed. B.G. Hurdle, Springer-Verlag, New York, 129-153.

Tantsiura, A.I., 1959, On the currents of the Barents Sea, *Transactions of the Polar Scientific Research Institute of Marine Fisheries and Oceanography* - N.M. Knipovic (PINRO), 11, 35-53, in Russian, translated to English by the Norwegian Polar Research Institute, Oslo, 1983.

Tantsiura, A.I., 1973, On Seasonal changes in currents in the Barents Sea, *Transactions of the Polar Scientific Research Institute of Marine Fisheries and Oceanography* - N.M. Knipovic (PINRO), in Russian, translated to English by the Norwegian Polar Research Institute, Oslo.

Wuest, G., 1935, Die Stratosphaere. Deutsche Atlantische Expedition, Meteor 1925-1927, *Wiss. Erg.*, 6(1), 288 pp.