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The quantitative definition of the Barents Sea Atlantic Water: mapping of the annual climatic cycle and interannual variability

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The Barents Sea Atlantic Water (AW) is defined in eight different ways in the literature. These definitions can be consolidated into one statement (decision rule) that allows the separation of the AW of the Barents Sea from the rest of the water masses there. The decision rule defines AW as a straight-line function of temperature and salinity and non-Atlantic Water and Mixed Water by their proximity to AW on a temperature–salinity diagram. This rule is used to map the monthly-mean distribution of AW in the Barents Sea at 0, 30, 50 and 100 m depths. These maps demonstrate two stable seasons (winter and summer) of AW intrusion into the Barents Sea. The average duration of the AW-winter season is five months (January to May), whilst that of the AW-summer season is four months (July to October). During the winter, the area coverage of the AW at the surface equals 23% and varies slightly with depth. During summer, there is zero areal coverage of the AW at the surface, and with depth it varies considerably. The decision rule was used to map the monthly distribution of AW along latitude 74°30′N in the Barents Sea for the period 1975–1989. The maximum inflow of AW into the Barents Sea along 74°30′N occurs during March. The minimum inflow of AW occurs in August. The March/August inflow ratio is 1.55.

Keywords: Barents Sea, Atlantic water, quantitative definition, annual cycle, interannual variability.

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Introduction

The Barents Sea is the only Arctic region that remains unfrozen throughout the year. During some years, the ice boundary in winter reaches 75°N. The inflow of warm Atlantic Water (AW) makes the climate of the Kola Peninsula and adjacent regions relatively warm and rainy during winter (January–February). The anomalous oceanographic characteristics of the Barents Sea and the availability of oceanographic data (Matishov *et al.*, 1998; Matishov *et al.*, 2000) make it an ideal site for studying oceanographic and marine–biological phenomena.

The key element of the Barents Sea climatic system is the inflow of AW. It is well known that this impedes ice formation (Helland-Hansen and Nansen, 1909), ameliorates the winter climate of polar latitudes (Stommel, 1979) and affects the distribution of the marine biota (Helle and Pennington, 1999). Therefore, it is important to document the characteristics of the AW in the area. The thermohaline variability of the North Atlantic (Aagard *et al.*, 1985; Furnes *et al.*, 1986; Levitus, 1989; Read and Gould, 1992), and of the Barents Sea, in particular (Kislyakov, 1964; Swift *et al.*, 1983; Midttun and Loeng, 1990; Pfirman *et al.*, 1994), is well documented, but the variability of the boundaries of AW in the Barents Sea has not been investigated.

Mapping of the AW's boundaries in the Barents Sea depends on the definition of the water mass. The commonly accepted definition of "relatively high temperature and salinity" is not useful for quantification, because the notion

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of "high temperature and salinity" is a function of the sub-region, depth and time (Hopkins, 1991; Pfirman *et al.*, 1994).

The first aim of this study was to determine quantitative criteria that can be used to define the AW and its penetration into the Barents Sea. The second was to use these criteria to suggest the variability of the boundaries of the AW in the Barents Sea over different time domains.

Materials

The temperature and salinity data used in this work are taken from the World Ocean Atlas (1994) CD-ROM and data, which the World Data Center for Oceanography, Silver Spring, has received for the period 1994–1997 from ICES and various Russian institutes. Criteria described by Boyer and Levitus (1994) have been used to exclude erroneous data. The Barents Sea is defined as the area between Novaya Zemlia, in the east and the line Norway–Bear Island–South Spitsbergen, in the west. The data comprises 25 810 temperature (T)–salinity (S) profile stations inside this area (Figure 1). All these stations are included on the Climatic Atlas of the Barents Sea CD-ROM (Matishov *et al.*, 1998).

Method

Because the aim of the present work is to separate AW from other water masses, two categories of water masses have been considered: (a) AW, originating from the North Atlantic Drift and (b) the remaining water masses i.e. non-AW.

Temperature and salinity ranges of AW

Table 1 lists the temperature–salinity ranges used to define AW to date in the literature. Figure 2 displays these ranges on the T–S plane. When the definition of AW is expressed in terms of "more" or "less", i.e. $T < 1°C$, $S > 35.00$ (Hopkins, 1991), arrows show the start point and direction of the temperature and salinity ranges. Figure 2 raises the question of whether or not T–S ranges of AW, as defined by different authors, are in conflict. The following two possibilities are considered.

(1) The definitions of the AW, cited in Table 1, contradict each other. The validity of this statement is based on the commonly accepted concept of a water mass (Mamaev, 1975, van Aken and de Boer, 1995) viz.,

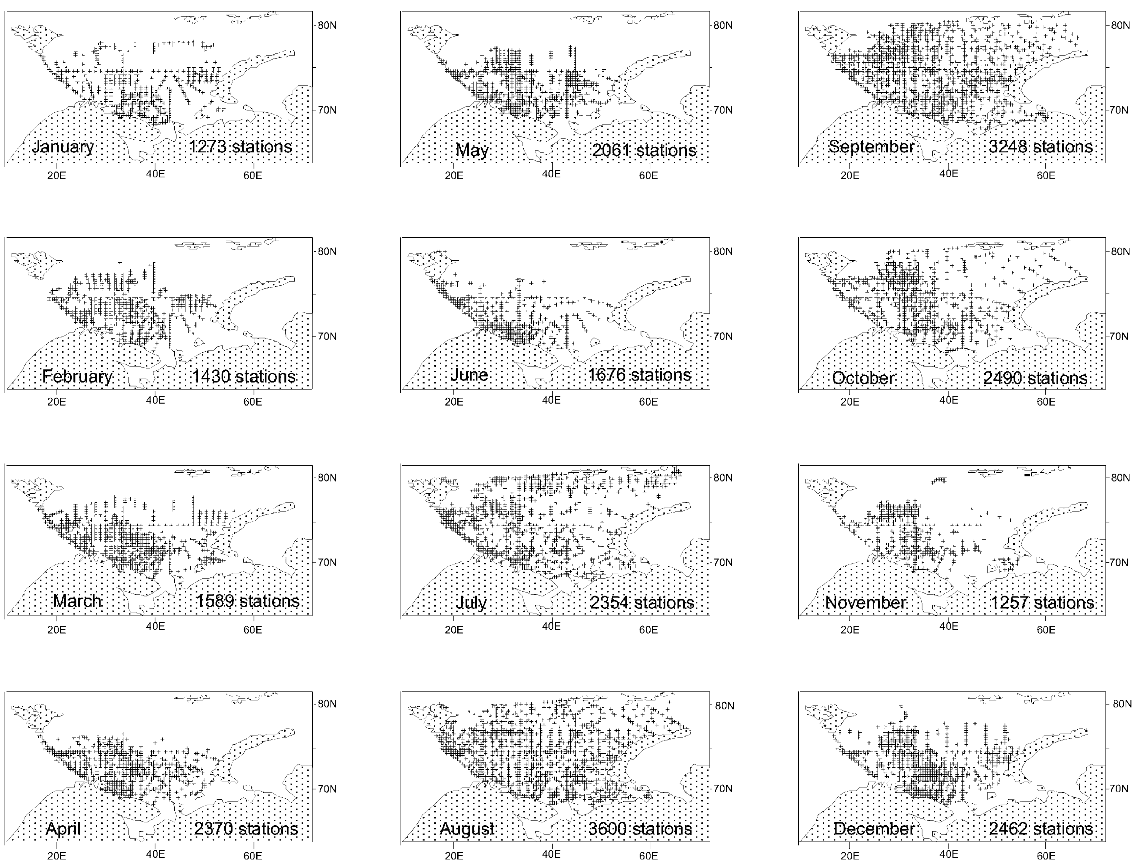

Figure 1. Oceanographic-station locations in the Barents Sea from 1900 to 1990.

A water mass is generally taken to be a set of water-parcels that form a quasi-compact group (i.e. having their intergroup variability much less than the intragroup variability) in T–S space.

Statement 1

From this point of view, the core characteristics of the AW listed in Table 1 do not form a compact group in T–S space, since the water-parcels cited have temperature values ranging from −2 to +6°C.

(2) The definitions of AW cited in Table 1 do not contradict each other. To confirm this statement, it is necessary to find a common function for the T–S ranges that are reported.

To investigate these alternatives, we consider how the T–S ranges of the AW (Table 1) are related to the actual T–S properties of Barents Sea waters.

Basic concept

Because measurements of temperature and salinity in the Barents Sea are distributed unevenly as a function of depth, we plotted a T–S diagram using linear interpolation to define the values of temperature T_i and salinity S_i at 10-m depth intervals. We denote water-parcel b_i with temperature T_i and salinity S_i as $b_i = (T_i, S_i)$. Figure 3a shows the distribution of the resulting parcels in a T–S diagram for the area. The Z-axis in Figure 3a is the number of water-parcels with temperature T_i and salinity S_i per 0.05°C per 0.01‰ interval.

The historical definitions of AW (Figure 2) are distributed along the ridge (line AB) of the T–S diagram in Figure 3b. Indeed, this ridge is the common T–S characteristics of the AW definitions. Thus, line AB is the equation for the transformation of AW during its flows through the Barents Sea. Based on this concept, the historical definitions of AW (Figure 2) can be combined into a new definition

If the water-parcel $b_i = (T_i, S_i)$ *falls on the straight line AB (Figure 3b), then* b_i *belongs to AW. As* b_i *moves away from the line AB, it loses the AW characteristics.*

Statement 2

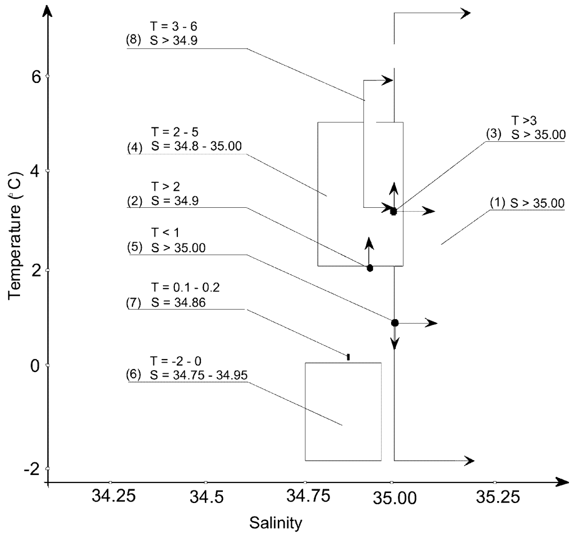

Figure 2. The temperature–salinity characteristics of the Barents Sea Atlantic Water (AW).

In order to use statement 2 for mapping the distribution of AW in the Barents Sea, the deviation (distance) between water-parcel $b_i = (T_i, S_i)$ and straight line AB must be quantified.

Distance in T–S space

The deviation of the water-parcel $b = (T, S)$ from the line AB, is the perpendicular distance (line bd in Figure 4) between the point of interest $b = (T, S)$ and the line AB. Our approach to the definition of the bd distance in T–S space is based on specific features of the distribution of the temperature and salinity in the Barents Sea. Some of these features are subsequently described.

Table 1. The definitions of the Barents Sea Atlantic Water (AW).

Parameters of the AW			
Temperature (°C)	Salinity	Comments	References
	S > 35.00		Helland-Hansen and Nansen, 1909
T > 2	S > 34.90	North Barents Sea AW	Mosby, 1938
T > 3	S > 35.00		Loeng, 1991
T = 2–5	S = 34.8–35.00		Hopkins, 1991
T < 1	S > 35.00	This water is the result of local cooling of the Barents Sea AW	Hopkins, 1991
T = −2–0	S = 34.75–34.95	Core characteristic of the AW on depth 75–250 m	Pfirman *et al.*, 1994
T = 0.1–0.2	S = 34.86	South Barents Sea AW	Pfirman *et al.*, 1994
T = 3–6	S > 34.90	South Barents Sea AW at surface	Sakshaug, 1997

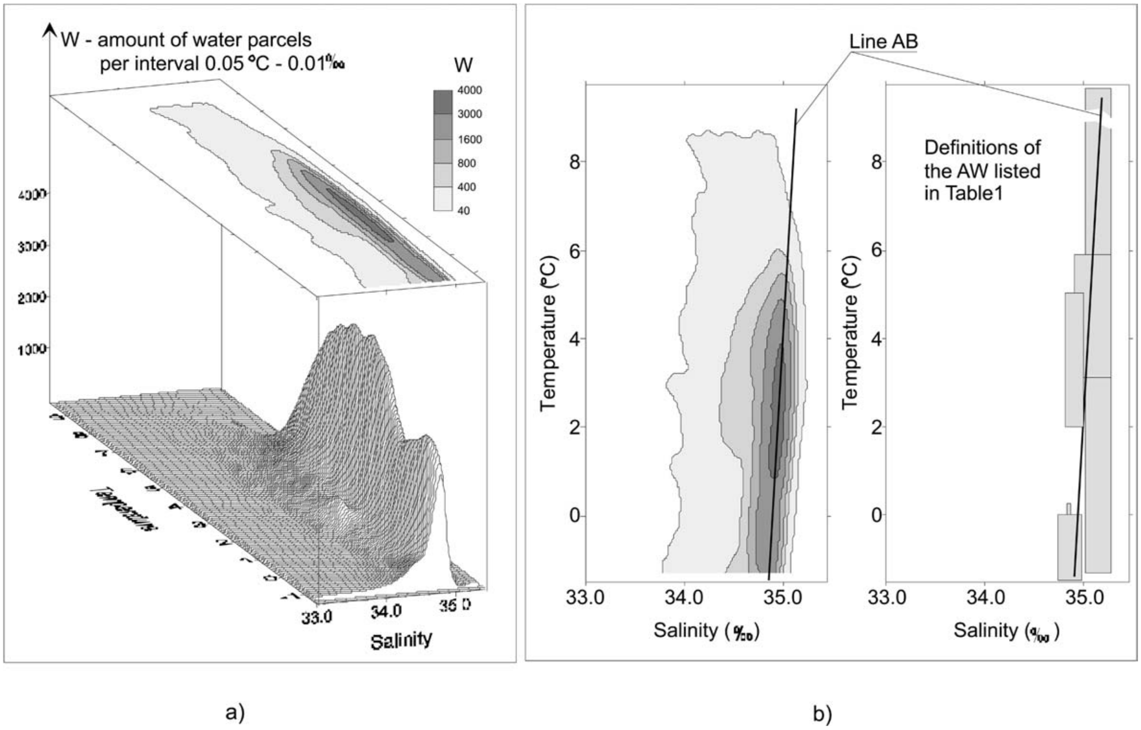

Figure 3. (a) A temperature–salinity diagram of the Barents Sea. (b) The linear relationship between temperature and salinity for the Barents Sea's AW.

Describing the first feature, the equation for line AB (Figure 4) is found to be

$$T\ (^\circ C) = 30 \times S - 1046. \qquad (1)$$

The slope of the line defining AW in the Barents Sea in Equation (1) is 30°C/‰, indicating that the AW definition is more sensitive to changes in salinity than to changes in temperature by a factor of 30. Because the ranges of temperature and salinity in the Barents Sea are known (Matishov *et al.*, 1998), it is possible to utilize a relative scale for these variables. Minimum values of temperature and salinity in this case will be associated with 0% salinity AW, and maximum values of salinity 100% AW. Minimum and maximum values of temperature and salinity for the Barents Sea are

$$T_{min} = -2^\circ C,\ T_{max} = 12^\circ C,\ S_{min} = 32,\ S_{max} = 35.2. \qquad (2)$$

The linear functions

$$S_i\ (\%) = [S_i - S_{min}]/[S_{max} - S_{min}] \times 100\%$$
$$T_i\ (\%) = [T_i\ (^\circ C) - T_{min}]/[T_{max} - T_{min}] \times 100\% \qquad (3)$$

set up the relationships between the physical and relative scales for temperature and salinity. Combining Equations (2) and (3) with Equation (1) results in the equation

$$T\ (\%) = 6.88 \times S\ (\%) - 602. \qquad (4)$$

The slope of the line in Equation (4) is 81.73°, so in the relative T–S space, the line AB is close to the vertical. Thus, the length of the line bd is close to the length of the line bc (Figure 4). Consequently, the length of the line bc can be used to approximate the deviation of the water-parcel from the line AB. The error (E) of this approximation is

$$\begin{aligned} E &= [(bd - bc)/bd] \times 100\% \\ bd^2 &= bc^2 - cd^2 = bc^2 - bc^2 \cos^2 R \\ E &= [\cos^2 R/(1 - \cos^2 R)]^{0.5} \times 100\% \\ &= (\cos R/\sin R) \times 100\%. \end{aligned} \qquad (5)$$

If bc is used as a measure of the deviation of the water-parcel from the line in Equation (1), then E = 14.53% in Equation (5). For this work, an error less than 15% is acceptable for the quantification of the AW. Thus, bc can be used as a measure of the deviation of water-parcel $b_i = (T_i,\ S_i)$ from the straight line AB.

Furthermore, the salinity values along the line AB are the maximal values for each temperature (Figure 5). These maxima are modal values of salinity $\check{S}_T$ for the fixed values of temperature. Because modal values have been associated with the AW, we assume that these modal values are

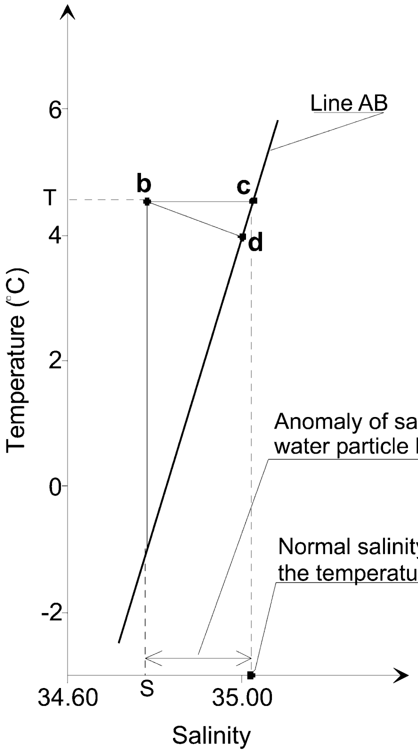

Figure 4. The distance between straight line AB and water-parcel b_i in T–S space.

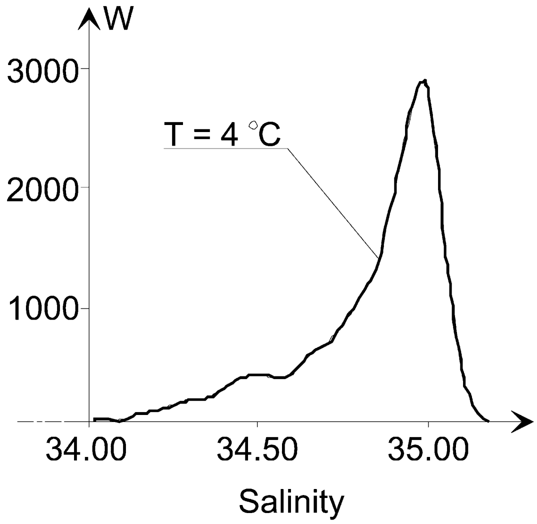

Figure 5. The salinity distribution for a fixed temperature value (4°C) for the Barents Sea.

normal values of salinity $\check{S}_T$ for fixed values of temperature (Harvey, 1982). So, the length of the line bc is the anomaly of salinity $S_a(b_i) = S_i - \check{S}_T$ for the temperature T.

Consider an example of water-parcels $b_1 = (7.0°C, 35.00)$, $b_2 = (-2°C, 34.70)$. According to Equation (1): $\check{S}(b_1) = 35.10$, $\check{S}(b_2) = 34.80$. Anomalies of salinity of water-parcels b_1 and b_2 are

$$S_a(b_2) = 34.70 - 34.80 = -0.10$$
$$S_a(b_1) = 35.0 - 35.1 = -0.10.$$

Thus, water-parcels b_1 and b_2 have equal deviation from the line in Equation (1), which means that b_1 and b_2 have equal degrees of AW even though they have a temperature difference of 9.0°C.

Variability of the AW

The interannual variability of AW in the Barents Sea is based on monthly observations along Section 29 (Figure 6a) for the period 1975–1989. Section 29 comprises 18 stations (Figure 6a) along 74°30′N, and between 19°30′E and 37°15′E.

In the Barents Sea, S_a values range from +0.2 to −5. If $S_a(b) \geq 0$, then water-parcel b belongs to AW. If $S_a(b) = -5$, then b belongs to non-AW. To map the boundaries of AW properly, we must consider "mixing water", the transformation of AW to non-AW, which takes place at all times and in all places where a parcel of AW is surrounded by parcels of non-AW water. Consequently, the range of S_a is divided into three intervals

$$\begin{aligned} -0.2 &\leq S_a \leq +0.2\text{—AW} \\ -0.7 &\leq S_a < -0.2\text{—mixing water} \\ -5 &\leq S_a < -0.7\text{—non-AW.} \end{aligned} \tag{6}$$

Figure 6b shows monthly-mean distributions—last row of the Figure 6b—of AW, non-AW and the mixing-water zone along Section 29. Empty cells on Figure 6b indicate a lack of data. Monthly-mean charts have been used to calculate the percentage-area coverage of AW along Section 29 (Figure 6c). Figure 7 shows the interannual variability of AW along Section 29.

Equation (6) is used to map the monthly-mean distribution of AW in the Barents Sea at depths 0, 30, 50 and 100 m (Figure 8). This figure shows two stable regimes of the AW distributions at 0–50 m associated with the two seasons of the Barents Sea: polar winter (January–May) and polar summer (July–October).

Discussion

To test the proposed method of AW depth and penetration into the Barents Sea, we compared the maps shown in Figure 8 with the commonly accepted circulation pattern of the Barents Sea. According to the existing point of view, there are two areas of AW intrusion into the Barents Sea. The main inflow occurs between Bear Island and the Kola Peninsula. It is limited by the coastal counter-current in the south and by water masses of Arctic origin in the north. Consequently, AW occupies the central region of the

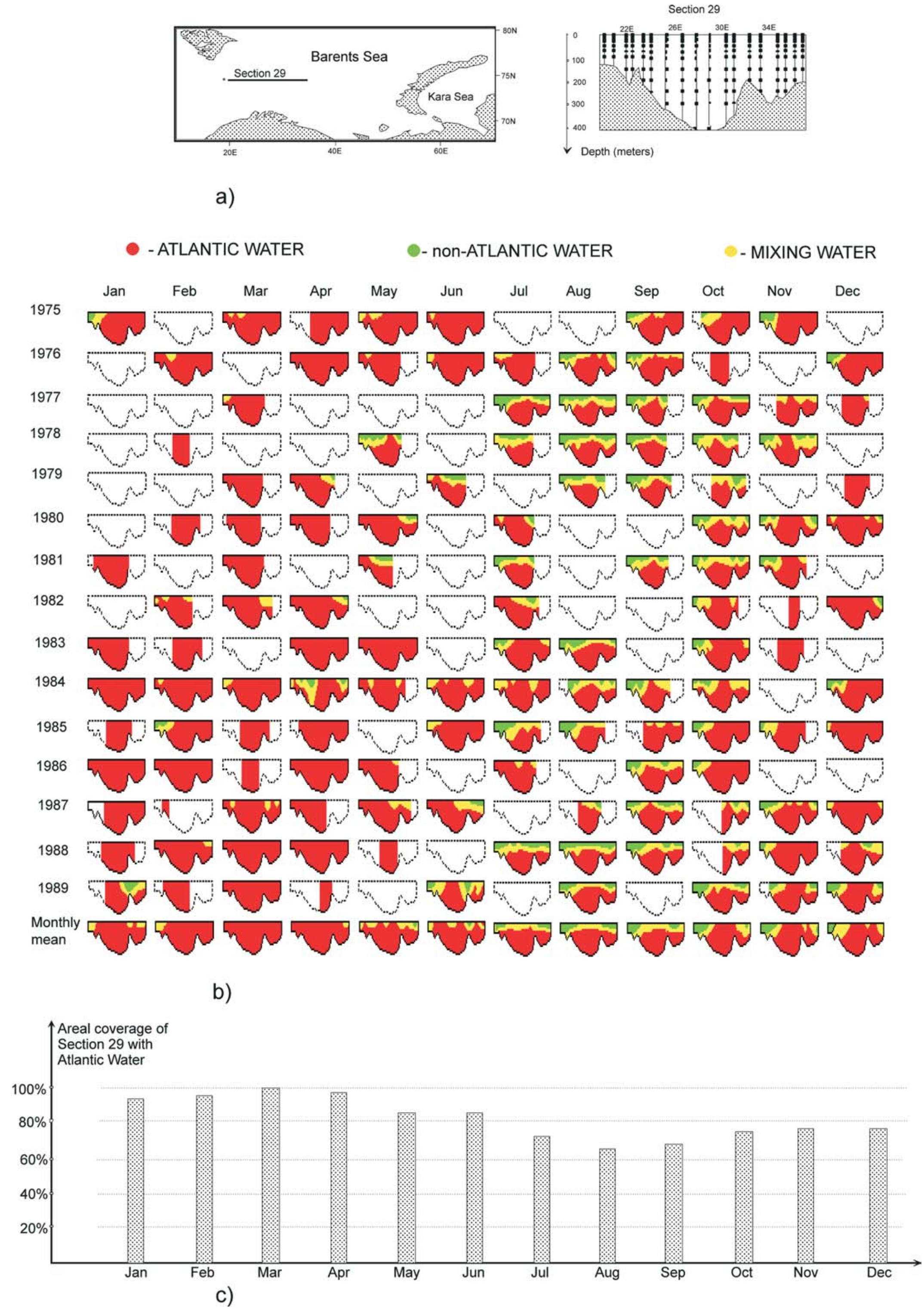

Figure 6. The position of Section 29 in the Barents Sea. (b) The monthly distribution of the AW along Section 29. (c) The annual cycle of the AW along Section 29.

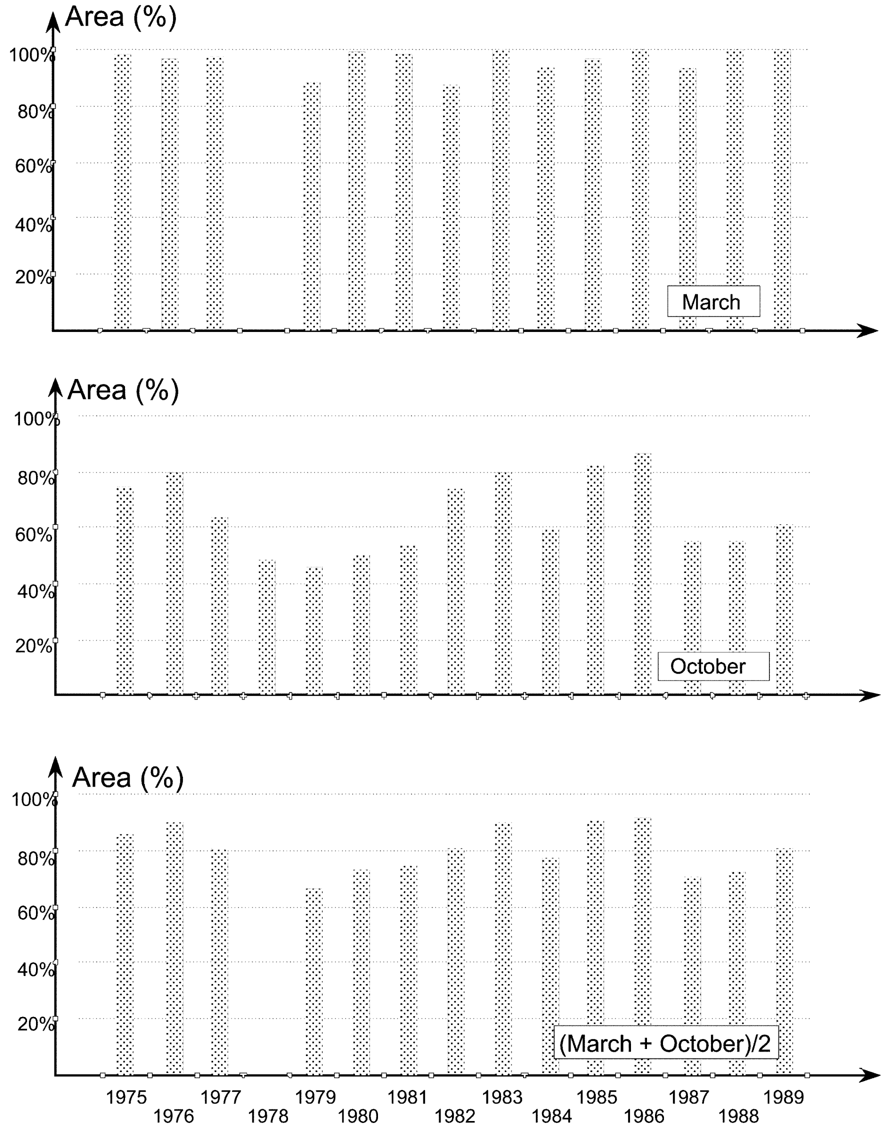

Figure 7. The interannual variability of the Barents Sea AW along Section 29.

Barents Sea. All the maps making up Figure 8 are in the good agreement with this concept. Small amounts of AW enter the Barents Sea from the north near East Svalbard. They appear at 0–50 m in March (Figure 8). The outflow of AW from the Barents Sea into the Arctic occurs north and south of the Novaya Zemlya archipelago. These features of AW are displayed in the July–October maps at 100 m (Figure 8).

Loeng (1991) describes two patterns of temperature and salinity distributions of AW in the Barents Sea. In winter, the temperature and salinity are the same at all depths. In summer (June–early October), temperature–salinity gradients occur between depths of 0–50 m. The maps making up Figure 8 also show winter and summer regimes of the distribution of AW. These two regimes are caused by the differences in AW–atmosphere interactions in winter and summer.

In winter, the air temperature is much lower than the surface-water temperature. As the AW transfers heat to the atmosphere, the density of surface-water parcels increases, and they sink. Because the Barents Sea is shallow—the average depth is 230 m—vertical convection creates a homogeneous water column from surface to bottom, and so the distribution of AW is constant at all depths during winter. Because heat fluxes from ocean to atmosphere prevent ice formation, the northern and eastern borders of AW distribution coincide, significantly, with the ice-edge position on winter climatic maps.

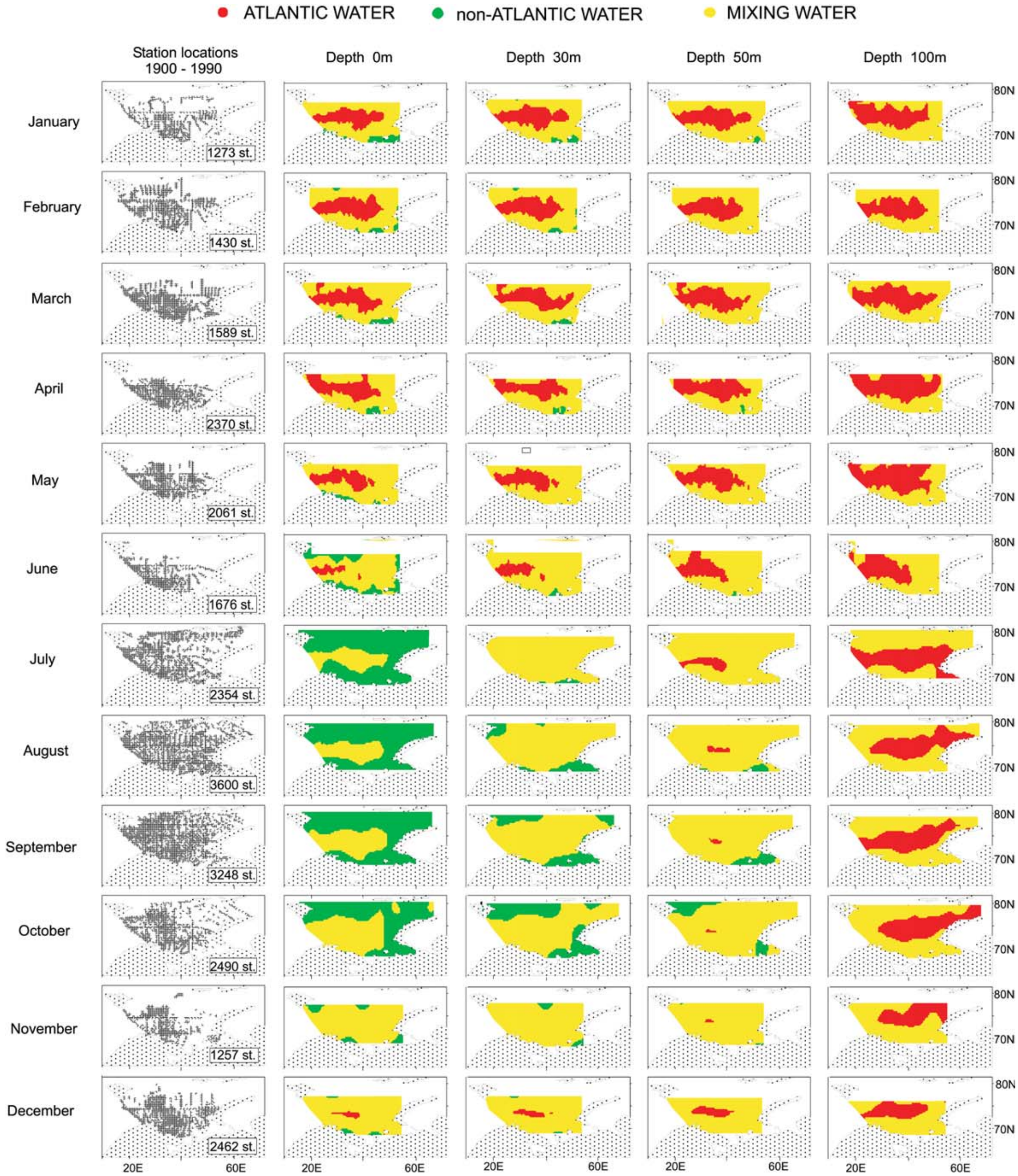

Figure 8. The annual cycle of the horizontal distribution of the Barents Sea AW.

In summer, vertical temperature and salinity gradients in the central Barents Sea are caused by two mechanisms: ice melt and surface warming (Loeng, 1991). These mechanisms lead to water density at the surface (depth 0–50 m) being much less than at depth (100–300 m). According to statement 2, water parcels within the depth-zone 0–50 m belong to non-AW (Figure 8, July–September). This layer of non-AW prevents both vertical mixing and the interaction of AW (50–200 m layers) with the atmosphere.

It should be stressed that the statement 2 is not a new definition of AW within the region. Equation (6) and statement 2 quantify the well-known fact that "during the transit through the Barents Sea AW becomes colder and fresher" (Mauritzen, 1996). The advantage of statement 2 over statement 1 for AW is that it accounts for the

Table 2. The characteristics of the Atlantic water (AW) inflow to the Barents Sea via meridional and longitudinal sections.

	Time frame	Meridional section (Loeng et al., 1997)	Longitudional section (present work)
			
Consistent results	Interannual variability	Minimum inflow: 1979	Minimum inflow: 1979
	Interannual variability	Maximum inflow: 1975, 1976, 1983	Maximum inflow: 1975, 1976, 1983, 1985, 1986.
	Annual variability	Minimum inflow: June-Sept. Maximum inflow: Winter	Minimum inflow: August-Sept. Maximum inflow: Winter
Inconsistent results	Monthly variability	Maximum inflow: December	Maximum inflow: March
	Seasonal variability	AW variability in winter > AW variability in summer	AW variability in winter < AW variability in summer

transformation of the core T–S characteristic of the AW, as it transits the Barents Sea along the straight line AB.

The definition of the AW given by Helland-Hansen and Nansen (1909) is the simplest and most accurate of the AW definitions listed in Table 1. The line AB is a good approximation of that definition (Figure 3b).

Figure 6c shows that the maximum intrusion of AW into the Barents Sea along Section 29 occurs in March, when 100% of Section 29 is covered by the AW. The minimum intrusion occurs in August and at that time 64.3% of the area of Section 29 is covered by AW. So, for the Barents Sea

$$(\text{AW March inflow})/(\text{AW August inflow}) = 100\%/64.3\% = 1.55$$

This result is in good agreement with estimates made byLoeng *et al.* (1993). They point out that AW inflow into the Barents Sea between Norway and Bear Island—the first station of Section 29 is located not far from it—varies between 2.1 Sv in winter and 1.4 Sv in summer. Thus,the ratio for the AW is

$$(\text{winter AW inflow})/(\text{summer AW inflow}) = 1.5$$

Figure 7 shows that the maximum intrusion of AW into the Barents Sea along Section 29 occurred in 1975, 1976, 1983, 1985, 1986, and the minimum in 1979. This is in agreement with AW intrusion into the Barents Sea across Section Fugløya–Bear Island (Loeng *et al.*, 1997) presented in Table 2. Thus, the characteristics of the annual and interannual variabilities of AW computed by Loeng *et al.* (1997) and Ådlandsvik and Loeng (1991) are consistent with the results of the quantification of AW in the present work. The difference between Loeng *et al.*'s (1997) results and this study is most possibly brought about by the geographical relationship of the comparative sections since the Section Fugløya–Bear Island is perpendicular to Section 29.

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