Papers

Inflow of Atlantic-origin waters to the Barents Sea along glacial troughs

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Abstract

This paper discusses the role of glacial shelf topography in the formation of general oceanological and biological mechanisms in the Barents Sea. Analysis of geomorphological data and oceanographic observations obtained on board MMBI research vessels in 2001–08 has shown that: fluxes of Atlantic-origin waters pass along glacial troughs; the inflow of Atlantic waters to the Barents Sea from the west increased from 2001 till 2007, although this advection began to weaken in 2008; vertical and horizontal thermohaline gradients intensified during the investigated period; a warm period similar to that of the 1930s was observed in the Barents Sea at the beginning of the 21st century.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

Large troughs and shelf banks define many traits of the circulation and stratification of waters, distribution of sea ice fields and biogeographical features. Basic current streams and the borders of zoogeographical provinces run according to linear geomorphological elements of the seabed. The existence of a rich wildlife in the marginal Barents Sea is due to both the active light mode of the polar summer and the favourable topographical features of the shelf, which allow powerful streams of warm waters from the North Atlantic Current to reach such high latitudes (Matishov & Matishov 2004). Studies of the influence of the inflow of warm, saline Atlantic waters into the Nordic Seas and the Arctic Ocean have a long history (Knipowitsch 1905, Helland-Hansen & Nansen 1909).

Thermohaline conditions in the Barents Sea are determined by the interaction of three major water masses: Atlantic, Arctic, and coastal (Loeng 1991).

The major part of the sea water balance consists of the inflow of Atlantic waters along glacial troughs from the west, i.e. from the Norwegian Sea (Schauer et al. 2002, Smolyar & Adrov 2003).

According to different estimates, the rate of Atlantic water inflow into the Barents Sea from the west is 1.6 (O'Dwyer et al. 2001) to 2 Sv ($10^6 \times$ M^3 c^{-1}) (Blindheim 1989, Ingvaldsen et al. 2002).

Flowing in from the west, Atlantic waters are transformed in the Barents Sea under the influence of different processes, after which they flow out to the Kara Sea and the Arctic Ocean basin through the strait between Novaya Zemlya and Franz Josef Land (Figure 1), sometimes called the Barents Sea Exit. More than half of this flow consists of dense, saline waters formed during the winter period. The intensity of this flow (2.0 ± 0.6 Sv) varies from year to year (Gammelsrød et al. 2009).

Another part of the Atlantic water inflow enters the Barents Sea from the north, from the Arctic Ocean, through the Franz Victoria and St. Anna troughs (Figure 1) (Rudels et al. 1994, Pfirman et al. 1994). The mechanisms of Atlantic water advection from the north are poorly understood owing to the difficulties of carrying out field observations in the northern Barents Sea, where severe ice conditions occur even in summer months (Vinje 2001, Koenigk et al. 2009). The rate of Atlantic water inflow through the Franz Victoria Trough in the 100–250 m layer is estimated to be 0.15 ± 0.11 Sv (Panteleev et al. 2004).

The most convenient way of measuring the inflow and determine its spatial and temporal variability is to analyse the temperature and salinity data obtained along standard (secular) transects, where observations have been made since the beginning of the 20th century (Figure 1).

This is because of the difficulties of carrying out in situ measurements of sea current velocity and direction, and also because the largest number of temperature and salinity data have been gathered in such transects (World Ocean... 1994, Matishov et al. 1998a, 2000, 2004, Golubev et al. 2000). Therefore, analysis of the thermohaline characteristics of water masses along standard transects, e.g. calculation of the area of a flow limited by a definite isotherm or isohaline, comparison of the location of isotherms and isohalines in this transect in different years, or calculation of anomalies, is of particular importance.

The ecological role of the interaction of warm Atlantic waters, flowing on to the Barents Sea shelf from the north along the deep Franz Victoria, St. Anna and other troughs, with cold Arctic waters has not been studied to any great extent. An essentially specific under-ice type of arctic front develops here, and there is a further, azonal variety of the marine Arctic ecosystem, i.e. the ecosystem of the under-ice arctic front. The thermohaline picture of the arctic front in the shelf zone between the Kola Peninsula and Novaya Zemlya is also not yet clear.

2. Material and methods

Oceanographic data were collected during MMBI cruises onboard r/v 'Dalnie Zelentsy' and 'Pomor' in 2001–08. The thermohaline characteristics of the water masses were measured using CTD-profilers (SEACAT SBE 19 and SEACAT SBE 19plus): vertical profiles were taken from surface to bottom (SEACAT... 2001, SBE... 2005). Temperature, conductivity and pressure sensors were calibrated at laboratories of the All-Russia D. I. Mendeleyev Scientific and Research Institute for Metrology. The measurement accuracy of the temperature, conductivity and pressure sensors was better than $\pm 0.005°$C, ± 0.0005 S m^{-1} (SBE 19plus), ± 0.001 S m^{-1} (SBE 19) and $\pm 0.1\%$ (of the full pressure sensor scale) respectively. The data obtained from CTD-profiling were averaged by depth over 1 m bins in order to draw profiles of the water temperature and salinity distribution along the transects, and over 5 m bins to calculate anomalies at particular stations.

Investigations were focused on several transects crossing streams of Atlantic-origin waters. Observations were made on both standard (Kola Meridian Transect and Transect 25) and arbitrary transects. The Franz Victoria Trough Transect was sampled through its deepest part. In the area between Kola Peninsula and Novaya Zemlya a hydrological transect crossing the main geomorphologic elements of the bottom, the so-called 'Transect across Troughs' or Troughs Transect, was investigated. The

Troughs Transect has become practically standard in MMBI oceanographic observations since 1991, and has been investigated annually since 2005.

For a correct understanding of climate variability one must have a maximum of available data. The results of MMBI researches are based on environmental and biota electronic databases comprising data for the

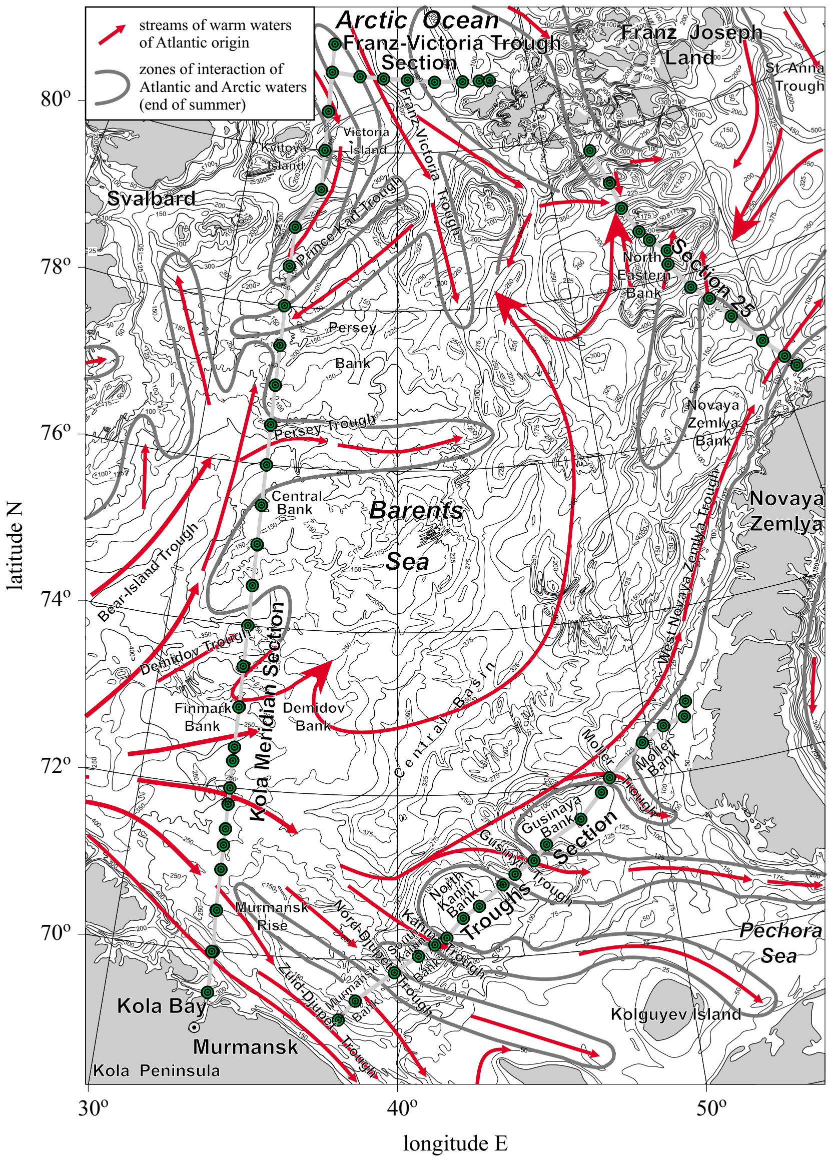

Figure 1. Location of the Barents Sea oceanographic transects considered in this paper and the scheme of Atlantic water inflow along glacial troughs

last 200 years (since 1810), which the Institute has been creating for almost twenty years together with NOAA (USA) (Matishov et al. 1998b, 2000, 2004, Matishov et al. 2008).

A water temperature anomaly is the difference between the temperature registered during observations and its average long-term value (norm) calculated by depth with an interval of 5 m for every station for the date of the observations. The water temperature norms on the Kola Meridian Transect are calculated on the basis of a database (Matishov et al. 2004) containing more than 219 000 stations over the period from 1880 to 2001 with use of the objective analysis method (Golubev et al. 1989, 1992).

The stations on our transects are situated according to the bottom topography (Matishov et al. 1995, Matishov 1997a), in the deepest and shallowest parts along an axial line of a transect. The present analysis examines more than 100 CTD-stations.

For this paper we have used detailed bathymetric charts of the Barents Sea made as early as 1975 (Matishov 1976, 1977, 1979, 1997a; Bathymetric Map... 1995). Figure 1 shows the complicated system of marginal and cross troughs of the Barents Sea.

3. Results

The Barents Sea has an extremely variable and rugged bottom topography. The average shelf depth is about 250 m, and maximum depths reach 400–500 m. The external margin of the shelf in the northern and western Barents Sea is situated at depths of 200–350 m along banks to 400–550 m along troughs (Figure 1). Marginal troughs stretch along the coastal shelf of the northern Scandinavian Peninsula, Spitsbergen, Novaya Zemlya, and Franz Josef Land. They make up a system of narrow (3–6 miles), superficial (100–200 m), consecutively arranged valleys and wide (20–40 miles) cavities with depths of 250–450 m. Shallow areas of the shelf (< 100 m) basically extend in the south-eastern Barents Sea and in a narrow coastal belt along the archipelagos of Novaya Zemlya and Svalbard. In other areas, only small areas on the bottom, such as the tops of some banks and ridges, are located at depths less than 80–100 m.

The thermohaline structure of the water masses in the transects investigated (Figures 2, 5–7) has been very carefully considered taking into account the geomorphology of the glacial seabed.

The Kola Meridian Transect ($33^\circ 30'$E) is, as a rule, regularly investigated only up to latitude 74°N (Tereschenko 1996). However, research into the thermohaline structure in this transect not only up to latitude 74°N but also far beyond – 700–800 km northwards – has yielded results of much

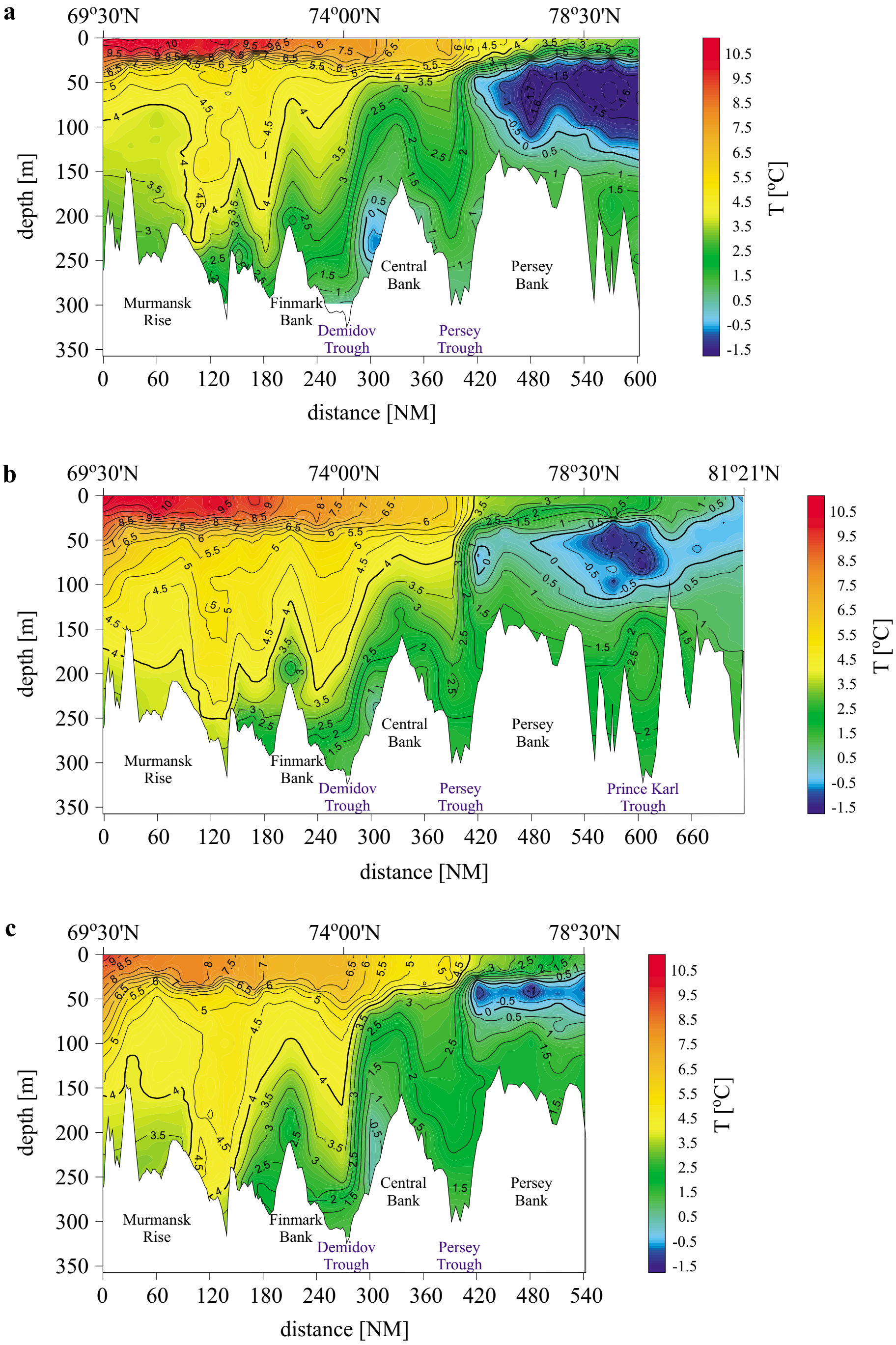

Figure 2. Temperature and salinity distribution along the Kola Meridian Transect in 2001 (a, d), 2007 (b, e) and 2008 (c, f)

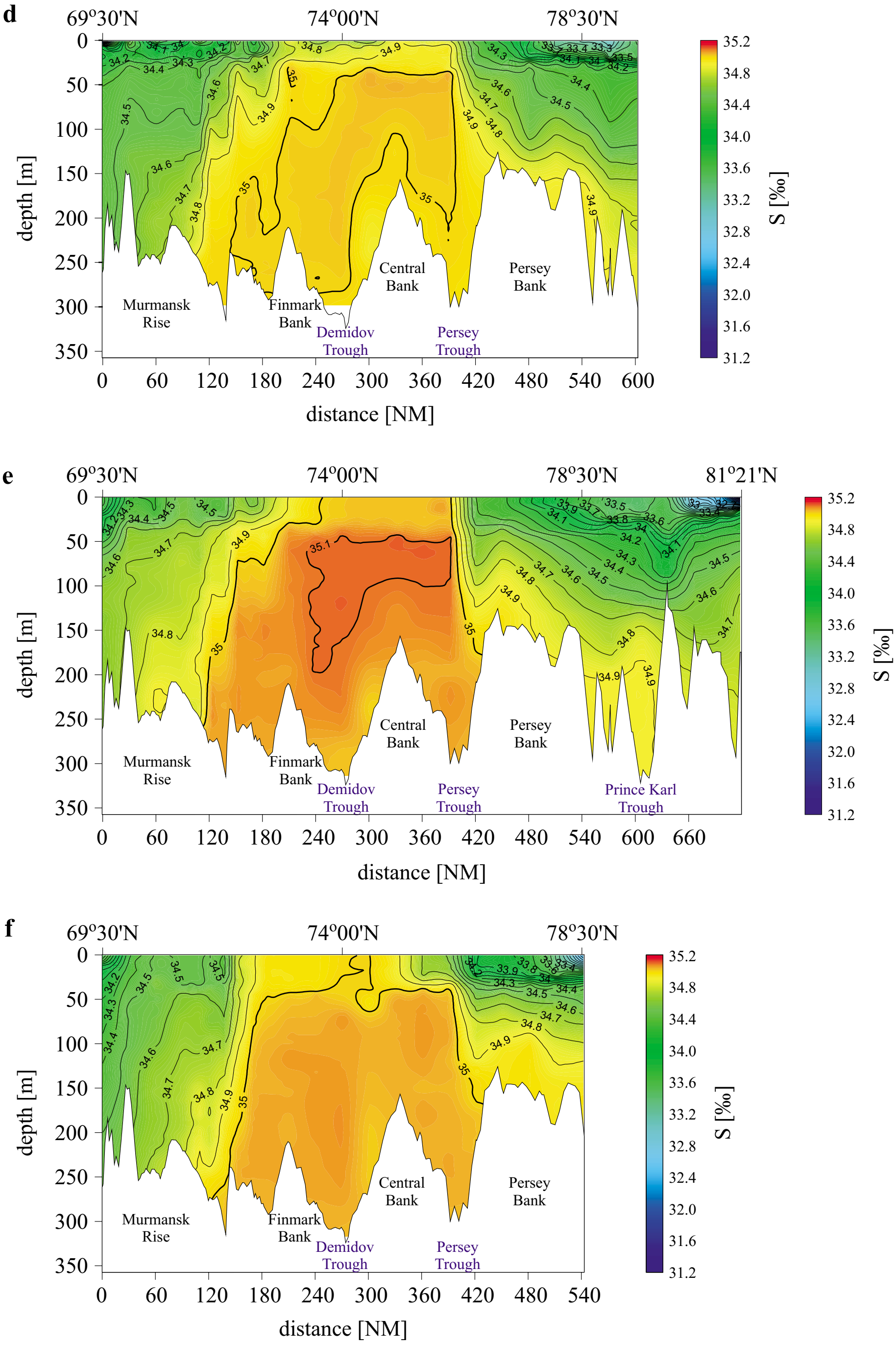

Figure 2. *(continued)*

greater interest. This is because below latitude 74°N the transect does not cross all the streams of Atlantic waters flowing into the Barents Sea from the west. For the summers of 2001, 2007 and 2008 the inflow of Atlantic waters at the part of the Kola Meridian Transect lying to the north of latitude 74°N (Figures 1, 2) has been visualised by temperature (Figures 2a, b, c), although these inflows are represented much better by the salinity values along the Transect (Figures 2d, e and f).

The Atlantic water inflow is limited by the 35‰ isohaline and is characterised by a wide range of temperatures (1 to 8°C). The core of this flow lies at a distance of approximately 300 nautical miles from the beginning of the transect at the Kola Bay mouth; this correlates well with earlier investigations (Panteleev et al. 2004).

The cross-sectional area of the Atlantic water flow in 2001 was calculated to be 61 km^2; in 2007 it increased to 98.2 km^2, but in 2008 decreased to 96.7 km^2. The salinity in the Atlantic water core was in excess of 35.1‰ in August 2007. The flow's cross-sectional area delimited by the 35.1‰ isohaline was 21 km^2. In 2001, a salinity of 35‰ was not recorded in the surface layer; in 2007, it could be traced for a distance of approximately 140 miles, but in 2008 for only about 15 miles (Figures 2d, e and f).

The temperature distribution indicates clearly that the heat content of the waters in the Transect reached a maximum in the summer of 2007.

A positive water temperature anomaly remained during 2001–08 in the Kola Meridian Transect (Barents Sea) (Matishov et al. 2007) (Figure 3a). This indicates intensification of Atlantic water inflow along the system of glacial troughs of the Barents Sea. It is worth mentioning that a similar warm phase was observed in the 1930s (Figure 3b) ('warming' of the Arctic) (Loeng 1991, Skagseth et al. 2008, Polyakov et al. 2009). Simultaneously with the Barents Sea warming, severe ice conditions (Matishov et al. 2007, 2008a,b, Borovskaya & Lomakin 2008) expressed in the form of ice hummocks and grounded hummocks, more characteristic of the Arctic seas, were observed in the Sea of Azov and the Caspian Sea as a result of the cold winters of 2006–09 (Figure 4). We consider these phenomena to be connected with the intra-century climate rhythm (Matishov 2008). Thus, four cases of water freezing (the winters of 1901–02, 1935–36, 1966–67, 1997–98 and 1998–99) in the usually non-freezing Kola Bay (Figure 3b), i.e. the southern extremity of the Kola Meridian Transect (Figure 1), have occurred in the Barents Sea in the last 100 years. At the same time, the last freezing of Kola Bay occurred in the modern warm period. Figure 3b shows that the cycle of Kola Bay freezing is 30–33 years, which corresponds approximately to three 11-year cycles of solar activity. Hence, Kola Bay will probably freeze over again in 2026 (Matishov 2008).

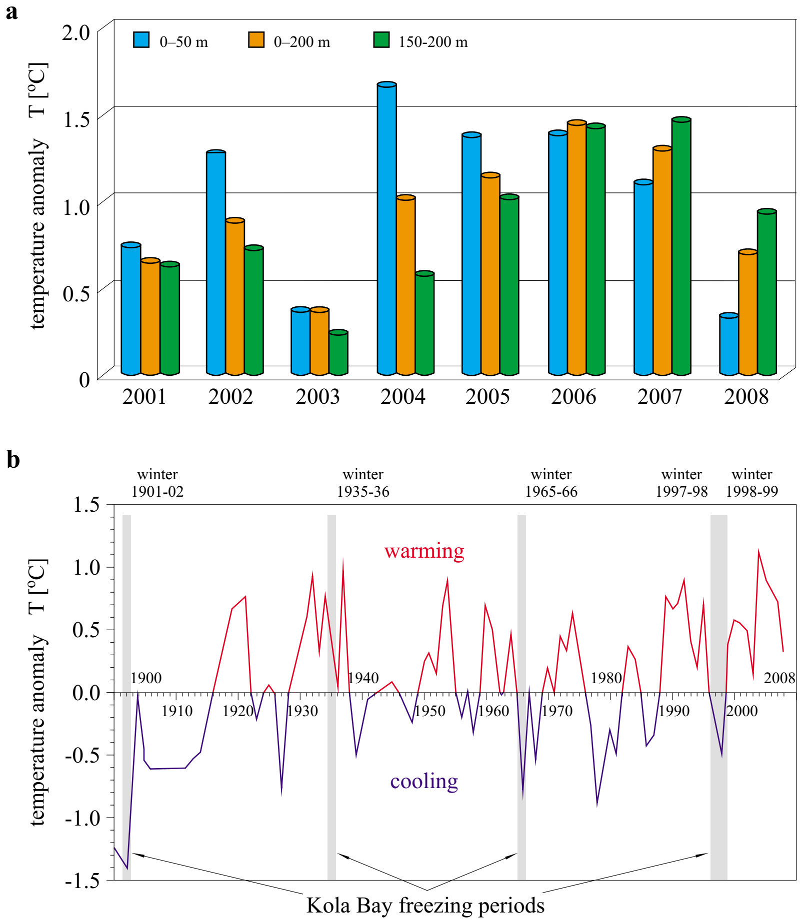

Figure 3. Temperature anomalies along the Kola Meridian Transect in the Barents Sea [°C]: by layers in the summers of 2001–08 (a) and in the 0–50 m layer from 1900 to 2008 (b)

Figures 2d, e, and f show the quasi-constant position of the arctic front (Løyning 2001, Kostianoy et al. 2004) at a distance of about 390 nautical miles from the southernmost station in the Transect. In 2007 and 2008, the horizontal salinity gradient in the arctic front became strongly peaked. Vertical and horizontal gradients have also increased in the northern part of the Transect (Figure 2). The peaking of gradients at the border between different water masses is likely to have been caused by both an increased Atlantic water inflow and intensive freshening due to ice melt in the marginal zone.

The **Franz Victoria Trough Transect** was sampled in the summer of 2007. Atlantic waters are always observed at hydrological transects across

Figure 4. Severe ice conditions in the Sea of Azov during the extremely cold winter of 2005–06

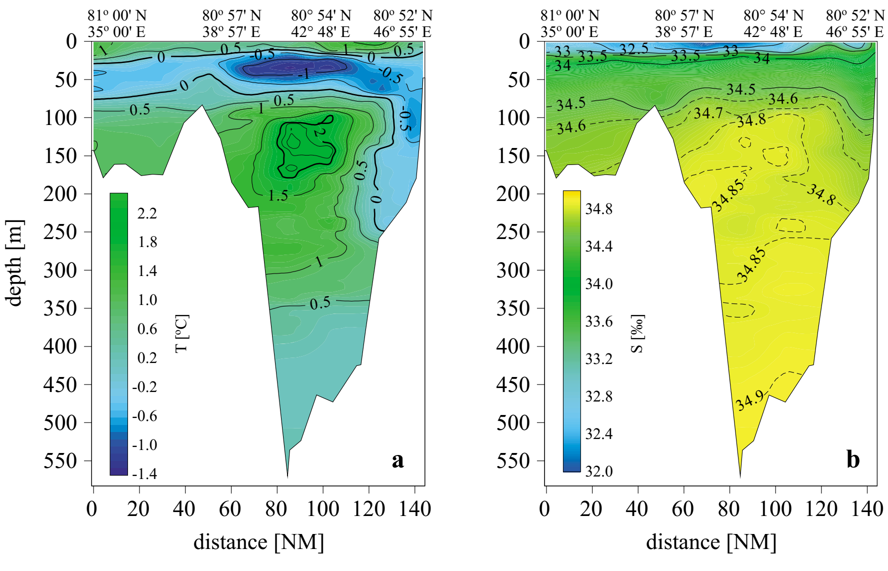

Figure 5. Temperature (a) and salinity (b) distribution along the Franz Victoria Trough Transect in 2007

trenches (Matishov et al. 1998a, Panteleev et al. 2004). In August 2007 Atlantic water inflow at the Franz Victoria Trough Transect was limited by the 0.5°C isotherm in the 70–350 m layer. The water temperature in the core of the Atlantic waters reached 2.2°C, and the salinity 34.85‰. Under the influence of the Coriolis force the core of the Atlantic water flow is pressed against the western side of the glacial trough. Owing to the nearness of the thawing edge of ice, a warmed and freshened 0–25 m layer was observed over the pycnocline. In the central part of the Transect, intermediate waters with a temperature < -1°C were registered in the 25–60 m layer. These waters must be the core of a cold flow directed from the Barents Sea to the Arctic Ocean and pressed against the eastern side of the Trough. In the deep part of the Trough near the bottom, the temperature decreased to 0.2°C with a salinity of > 34.9‰. Bottom waters with such characteristics can be described as transformed Barents Sea water masses (Figure 5).

Transect 25 crosses troughs between Franz Joseph Land and Novaya Zemlya (Figure 1).

In the 50–100 m layer of water in the area around 77°50′N 56°52′E, the core of the Atlantic water inflow had a temperature of > 0.5°C and a salinity of 34.6‰. This stream flows on to the Barents Sea shelf from the north-west through the St. Anna Trough, which was demonstrated by direct measurements of currents (Schauer et al. 2002, Gammelsrød et al. 2009).

In the north-western part of the Transect, huge spaces in the 5–140 m layer are occupied by intermediate cold waters with a temperature < -1.7°C in the core. The upper layer as a whole is warm and very much freshened in some places. Maximum freshening of the upper layer was observed in the area bound by the coordinates 78°32′N 55°19′E and 77°50′N 56°52′E. The temperature is also lower there, which may be evidence for flows of currents carrying cold freshened waters. In the south-east, transformed Barents Sea waters with maximum salinities reaching 34.96‰ were observed in the bottom layer (Figure 6).

The **Troughs Transect** (Figures 1, 7) allows the real features of the horizontal and vertical structure of water masses and the thermohaline picture for summer (August) to be characterised. A fundamentally new circumstance is that in the south-eastern Barents Sea the Nordkapp Current splits into six large flows under the influence of the shelf topography. One of the flows is the Murmansk Current, which has been thoroughly studied. Another branch, the Novaya Zemlya current, runs north-eastwards. Other independent flows of warm water run along troughs between large banks (Murmansk Bank, South Kanin Bank, North Kanin Bank, Gusinaya (Goose) Bank and Moller Bank) (Figure 1). As is well-known, only the largest Goose water stream situated between the North Kanin Bank and

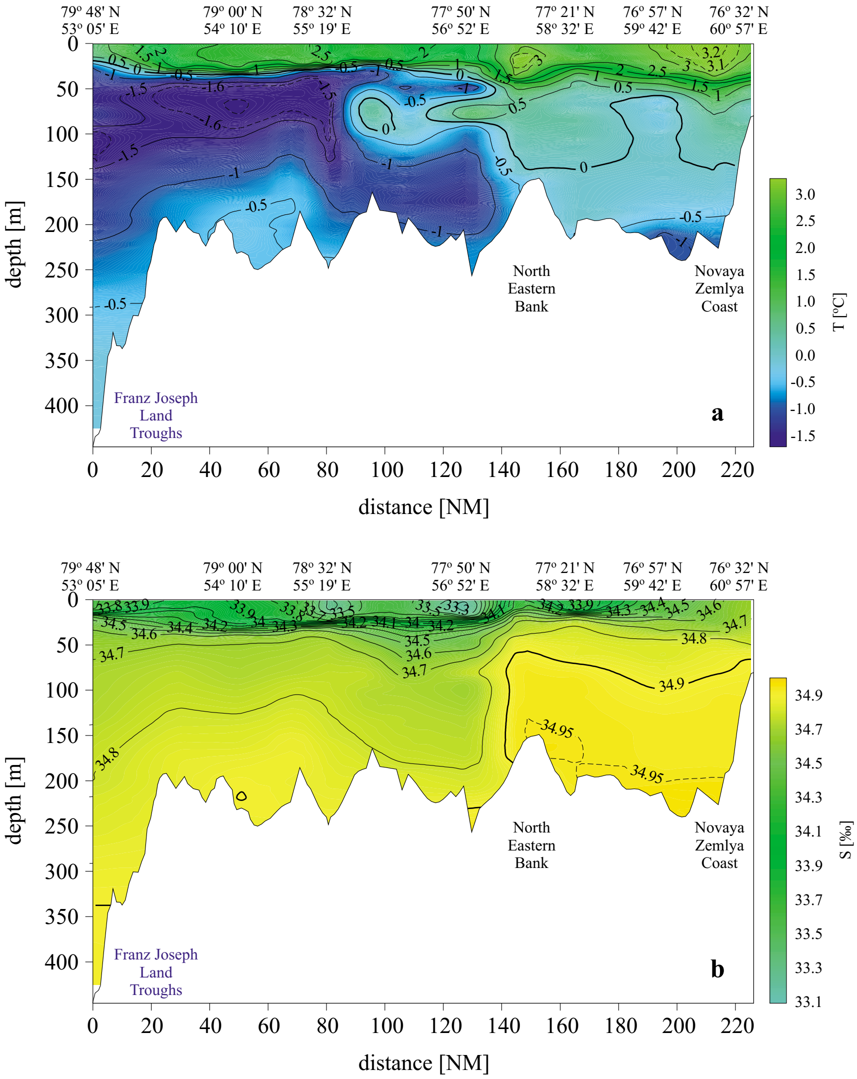

Figure 6. Temperature (a) and salinity (b) distribution along Transect 25 in 2006

the Goose Bank is usually marked on present-day water circulation maps (e.g. Tantsyura 1959). It has been suggested that the independent branches of the Nordkapp Current be given the names of the corresponding troughs: the Nord-Djupet, Kanin, Gusinoye (Goose) and Moller currents. These flows of Atlantic water are directed eastwards into the Pechora Sea. They are 20–30 to 50 km wide, and 100–140 to 200 m in vertical magnitude. The direction and sizes of the flows are traced by the position and form of the isotherms and isohalines (Figure 7).

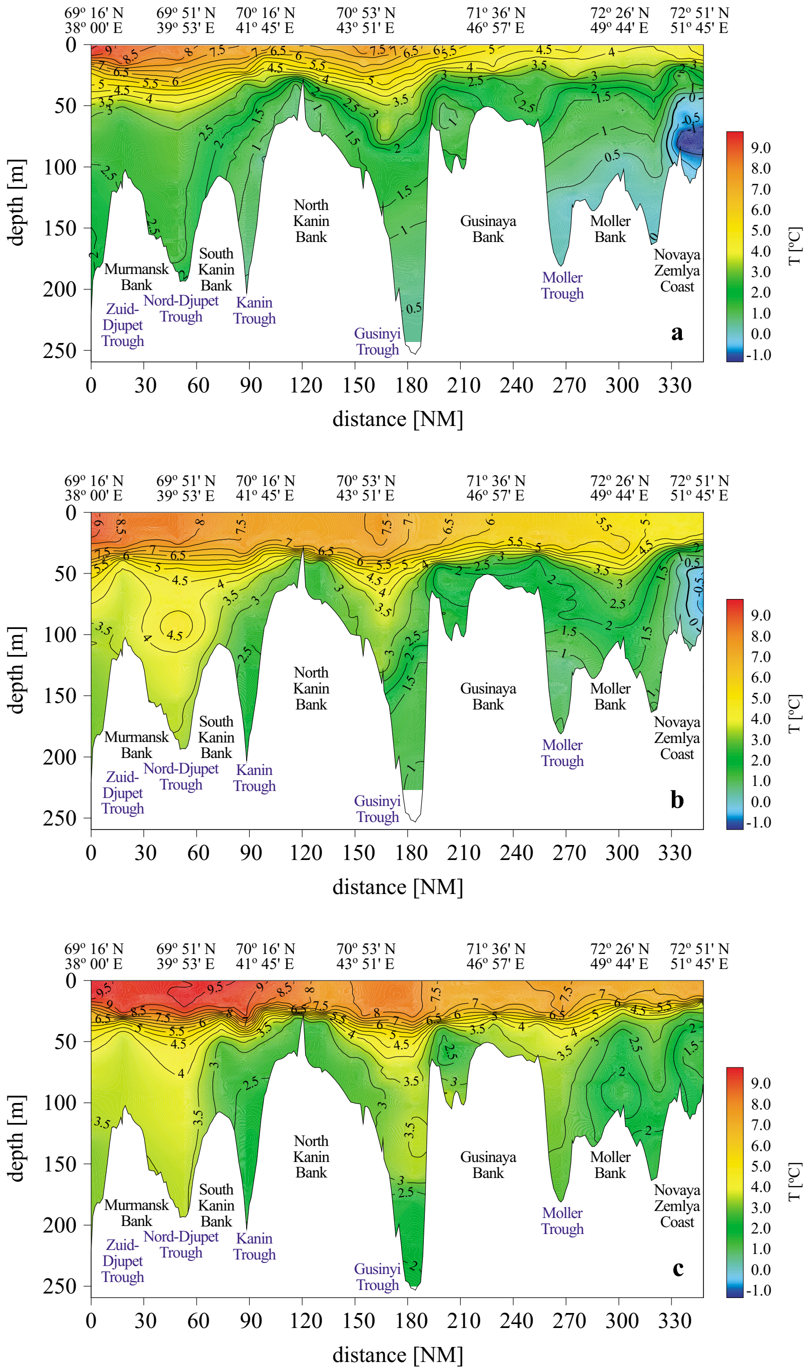

Figure 7. Temperature and salinity distribution along the Troughs Transect in 2005 (a, d), 2006 (b, e) and 2007 (c, f)

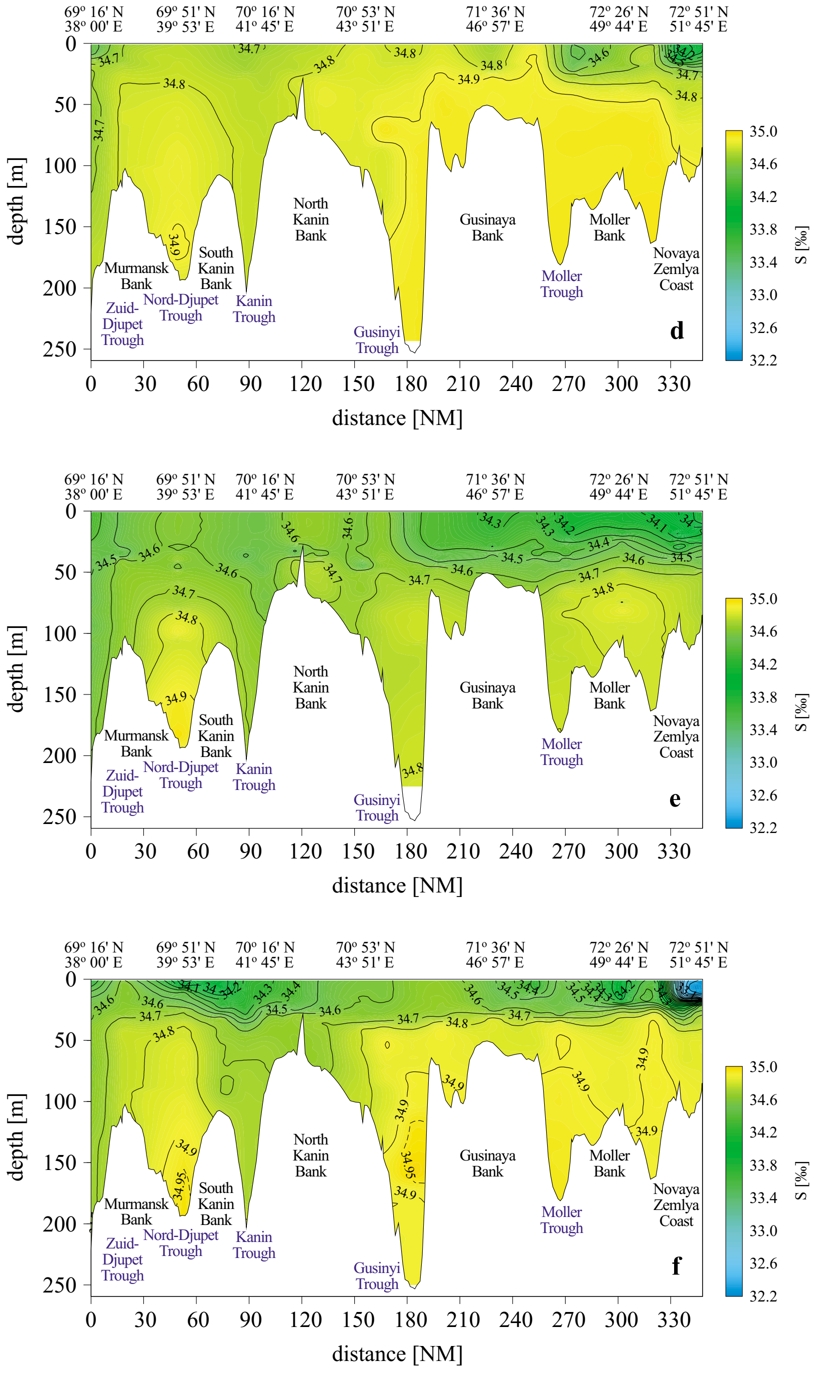

Figure 7. (*continued*)

In summer a seasonal thermocline develops in the whole investigated area of the Transect (Figure 7), from the sea surface to depths of 20–30 m. Warmed up (to 8–10°C) by solar radiation, somewhat freshened (34–34.6‰) water masses are observed above the thermocline. From the Murmansk Bank towards Novaya Zemlya, the temperature and salinity of waters decrease naturally (Figure 7). The banks below the thermocline (75–110 m) are occupied by local water masses with a temperature from 0° to 0.5–1.0°C and a salinity from 34.2 to 34.8‰. Sometimes in the bottom layers of the Moller Bank there are lenses of water of negative temperature (−0.1°C). On the Gusinaya Bank and the North Kanin Bank, relatively cold ($+0.3 - 0.6$°C) bottom waters usually flow down the slopes of the troughs. The origin of these waters is probably connected with winter cooling on shoals.

In 2005, a lens of cold winter water with a temperature < -1°C was observed in the bottom layer off the Novaya Zemlya coast. In 2006 and 2007, the temperature of the bottom waters in this area increased. Maximal warming ($>$ 9.5°C) of the upper layer in the Transect was recorded in the summer of 2007.

The maximal freshening (32.2‰) in the upper quasi-homogeneous layer near the Novaya Zemlya coast was registered in 2007. In the Transect as a whole, the salinity beneath the pycnocline was maximal in 2005 and 2007.

Figure 7 clearly indicates the increase in vertical and horizontal gradients of water salinity from 2005 to 2007. This must be connected with the increase both in the inflow of Atlantic-origin waters and the runoff of snow melt and land ice melt waters from Novaya Zemlya.

4. Discussion

Long-term observations of thermohaline characteristics allow changes in the Atlantic water inflow regime to be tracked along transects in different parts of the Barents Sea. The correct arrangement of stations along the transect that takes into account the features of bottom relief and the positions of inflowing Atlantic water streams is of particular importance.

Large underwater elevations, such as Murmansk, Central, Nordkapp and Medvezhinsko-Nadezhdinsky, serve as the main watersheds of all large currents and the circulation of the water masses. Deep troughs and vast banks largely control the vertical and horizontal circulation of waters. The complex bottom valley network opens the Barents Sea shelf to powerful water streams, which are directed here from the continental slope of the Norwegian-Greenland and Arctic basins. The complicated topography of the Barents Sea bed has a strong influence on the oceanographic features of this water body, where marginal and cross-shelf troughs play the leading role (Matishov et al. 1994, Matishov 1997b, 1999).

The Atlantic water inflow to the Barents Sea from the west increased during the period 2001–07 but then decreased in the summer of 2008. From 2001 to 2008 vertical and horizontal gradients of temperature and salinity intensified.

In the troughs, waters of Atlantic origin are characterised by a salinity of 34.8–35.1‰ and by a temperature of 1–4°C. Relatively cold (c. +0.5°C) waters lie near the bottom of troughs.

The seasonal thermocline forms in spring and summer at depths of 10–40 m. It disappears in autumn and winter as the upper layer of the sea cools under the influence of strong winds. An important condition for summer thermocline formation is the surface layer of fresh water located near the ice edge and in the area of snowmelt runoff near the coasts of Franz Joseph Land, Novaya Zemlya and Svalbard, which provides the initial density drop.

Most likely there exists a high-latitude (72–82°N) circulation of Atlantic water masses. They form the arctic front in interaction with cold Arctic waters. A lot of meanders and 17 eddies framing the general line of the arctic front are caused by the troughs crossing the shelf. Certainly, the intensity of water circulation, salt and heat transport via the system of bottom valleys depends on the inter-annual and secular fluctuations in the strength of the Gulf Stream.

The complicated system of marginal and cross troughs cutting the surface of the Barents Sea shelf provides easy access for North Atlantic current heat to high-latitude Arctic regions. The warm waters of the Nordkapp and West Spitsbergen Currents flow from the west and north (Skagseth et al. 2008) along troughs deep into the Barents Sea and, finally, are interlocked in the area between Franz Joseph Land and Novaya Zemlya.

On the basis of field observations and the MMBI oceanographic database (Matishov et al. 2004) we may conclude that at the beginning of the 21st century the water mass in the southern Barents Sea was relatively warm. Similar warm phases in the Barents Sea were observed in the 1930s and in 1989–92 (Figure 5) (Loeng 1991, Matishov 2008, Skagseth et al. 2008). These processes are most likely connected with intra-century fluctuations of the climate.

In 2008, values of the anomalies dropped (Figure 3), and the flow of Atlantic waters across the transect from the west decreased (Figure 2). Only further regular field observations with the use of databases can help to answer the questions of how long the modern warming of the Arctic will last, what major factors influence regional and planetary climatic rhythms, and what role human activity actually plays in climate changes.

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