ISSN 0001-4370, Oceanology, 2010, Vol. 50, No. 5, pp. 643–656. © Pleiades Publishing, Inc., 2010.
Original Russian Text © A.G. Zatsepin, E.G. Morozov, V.T. Paka, A.N. Demidov, A.A. Kondrashov, A.O. Korzh, V.V. Kremenetskiy, S.G. Poyarkov, D.M. Soloviev, 2010, published in Okeanologiya, 2010, Vol. 50, No. 5, pp. 683–697.

MARINE PHYSICS

Circulation in the Southwestern Part of the Kara Sea in September 2007

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Received September 16, 2009; in final form, January 2, 2010

Abstract—During cruise 54 of the R/V *Akademik Mstislav Keldysh* to the southwestern Kara Sea (September 6 to October 7, 2007), a large amount of hydrophysical data with unique spatial resolution was obtained on the basis of measurements using different instruments. The analysis of the data gave us the possibility to study the dynamics and hydrological structure of the southwestern Kara Sea basin. The main elements of the general circulation are the following: the Yamal Current, the Eastern Novaya Zemlya Current, and the St. Anna Trough Current. All these currents are topographically controlled; they flow over the bottom slopes along the isobaths. The Yamal Current begins at the Kara Gates Strait and turns to the east as part of the cyclonic circulation. Then, it turns to the north and propagates along the Yamal coast over the 100-m isobath. The Eastern Novaya Zemlya Current (its core is located over the eastern slope of the Novaya Zemlya Trough) flows to the northeast. Near the northern edge of Novaya Zemlya, it encounters the St. Anna Trough Current, separates from the coast, and flows practically to the east merging with the continuation of the Yamal Current. A strong frontal zone is formed in the region where the two currents merge above the threshold that separates the St. Anna Trough from the Novaya Zemlya Trough and divides the warm and saline Arctic waters from the cooler and fresher waters of the southwestern part of the Kara Sea. This threshold, whose depth does not exceed 100–150 m, is a barrier that prevents the spreading of the Barents Sea and Arctic waters to the southwestern part of the Kara Sea basin through the St. Anna Trough.

DOI: 10.1134/S0001437010050024

INTRODUCTION

The information about the general circulation in the Kara Sea is contradictory because several different schemes of the mean currents exist. According to one of them, the circulation at the surface and in the deep layers is cyclonic [2, 18]. The main elements of this circulation include the following: (a) the Eastern Novaya Zemlya Current, which is a continuation of the western Novaya Zemlya Current in the Barents Sea flowing around Novaya Zemlya from the north and then turning to the southwest along the eastern slope of Novaya Zemlya; (b) the Yamal Current partly formed by the water flow propagating from the Barents Sea through the Kara Gates and the Yugorskii Shar straits flowing to the northeast along the western slope of the Yamal Peninsula; and (c) the western Taimyr Current, which is a continuation of the Yamal Current propagating along the coasts of Siberia up to the Vilkitskii Strait and then flowing into the Laptev Sea. Both the Yamal Current and the Western Taimyr Current branch and transport the waters of the Kara Sea freshened by the runoff of the rivers to the Central Arctic and the Laptev Sea. The deep saline waters of the Barents Sea and the transformed Atlantic waters are transported into the Kara Sea through the Kara Gates and the Yugorskii Shar straits, as well as through the deep St. Anna and Voronin troughs.

The circulation is different according to the other more recent schemes [12–17] based on the data of shipborne ADCP measurements, moored current measurements, and numerical and laboratory modeling. The flow of warmer and more saline water from the Barents Sea propagates as a rule to the northeast along the eastern coast of Novaya Zemlya up to its northern end. The freshwater runoff of the Ob and Yenisei rivers forms an anticyclonic gyre near the mouths of the rivers and north of them with intensification of the northeastern transport at its western periphery; part of the waters of this gyre merges with the northeasterly current along the coast of Novaya Zemlya.

Thus, we can state that even the direction of the transport by the main currents in the Kara Sea during the warm season is not unambiguously determined. The most contradictory question is related to the direction of the Eastern Novaya Zemlya Current.

Where is it directed: to the southwest or to the northeast? It is clear that the answer to this question is principally important in forming the concept about the water exchange in the southwestern part of the Kara Sea and for a number of practical problems related, for example, to the determination of the possible transport of radioactive pollution [18].

In this work, we present and analyze the new data on the currents and hydrological structure in the southwestern part of the Kara Sea obtained during cruise 54 of the R/V *Akademik Mstislav Keldysh* in September of 2007.

THE STUDIED REGIONS AND THE METHODS AND MEANS OF THE OBSERVATIONS

In the autumn of 2007, oceanographic research was carried out in several regions of the Kara Sea: (a) the region adjacent to the Yamal Peninsula from the west, where the influence of possible freshwater runoff is minimal, the depths change from 18–20 m to 100–120 m, and the region is influenced by the Yamal Current directed to the north-northeast; (b) the region of the Novaya Zemlya Trough with depths up to 380 m, where the Eastern Novaya Zemlya Current propagates over its western slope; (c) the region of the continental slope in the southern part of the St. Anna Trough, where the current flowing from the southwestern part of the Kara Sea interacts with the flow from the north (frontal (barrier) zones exist in this region); (d) the wide region between the estuary of the Ob River in the south and the slope of the St. Anna Trough in the north, where saline water freshened by the river runoff spreads; and (e) the estuary of the Ob River, which is a transition zone from the fresh waters to brackish waters with intense frontogenesis. Hydrophysical investigations were carried out in these regions.

The research was carried out using a wide set of equipment providing the following: (a) the continuous recording of the hydrophysical parameters in the surface layer from the moving ship (a CTD thermosalinograph, an SBE-911 in a pumped sea-water system); (b) the vertical profiling of the hydrophysical and bio-optical characteristics with the simultaneous water sampling at stations (a CTD thermosalinograph, an SBE-19 plus with a set of Niskin bottles and additional sensors of the transparency and fluorescence; (c) the frequent scanning of the water column by the vertical from the moving ship (using a CTD thermosalinograph (Idronaut) in the regime of the data transmission on a real time basis); and (d) the measurements of the vertical velocity profile from the moving ship using a towed acoustic Doppler current meter (an ADCP Workhorse, 600 kHz in a streamlined case in the "bottom tracing" regime).

Satellite information in the visual and IR spectrum ranges was used for the operative planning of the research.

The location of the oceanographic stations with the CTD profiling and water sampling, as well as a scheme with the numbers of the sections occupied using the towed profiling in the scanning regime, is presented in [9] (Figs. 1a and 1b, respectively). A total of four hydrographic sections (51 profiling stations) and 25 sections with a towed CTD profiler in the scanning regime (some of which were accompanied by the use of a towed ADCP) were occupied. Below, we shall describe only the sections that are the most important for forming the concepts about the current system in the southwestern part of the Kara Sea.

RESULTS OF THE OBSERVATIONS AND THE DATA PROCESSING

The region west of the Yamal Peninsula: hydrographic section no. 1. The distributions of the temperature and salinity over the section are shown in Figs. 1a and 1b, respectively. It is worth noting that the distribution of the density along this section (as well as over other sections) is not shown because it is practically identical to the salinity distribution.

The hydrological structure is characterized by a relatively warm (4–6°C) and slightly freshened (26–29 psu) upper quasi-homogeneous layer (UQL) whose thickness in the offshore part of the section is 10–20 m. A sharp thermohalocline with a thickness of 5–10 m is located below this layer. A cold subsurface layer (CSL) is located under the thermocline (with a range of temperatures from −1.4 to −1.6°C), which is formed in the winter due to the convective mixing. Warmer waters with higher salinity, which are likely of the Barents Sea origin, are located even deeper at 60–100 m. The salinity gradually increases with the depth reaching a value of 34.4 psu at a depth of 100 m. The frontal zone of the Yamal Current is located in the region of the bottom slope (with a depth change from 18–20 m to 100–120 m), where the contour lines of all the characteristics deepen in the direction to the coast and reach the sloping bottom. The UQL deepens to 30–40 m, displacing the CSL from the slope offshore, while the thermo-pycno-halocline widens and weakens. These facts, as well as the distribution of the turbidity (Fig. 1d), provide evidence that the vertical mixing is strong in the frontal zone, which is caused by the energy dissipation of the mean and tidal currents.

The geostrophic velocities were calculated from the temperature and salinity data assuming that the reference level is located at the bottom. These calculations are quite conditional because the velocity at the bottom can be nonzero. Therefore, the presented distribution of the geostrophic velocities can be considered only as the first approximation to the real pattern of

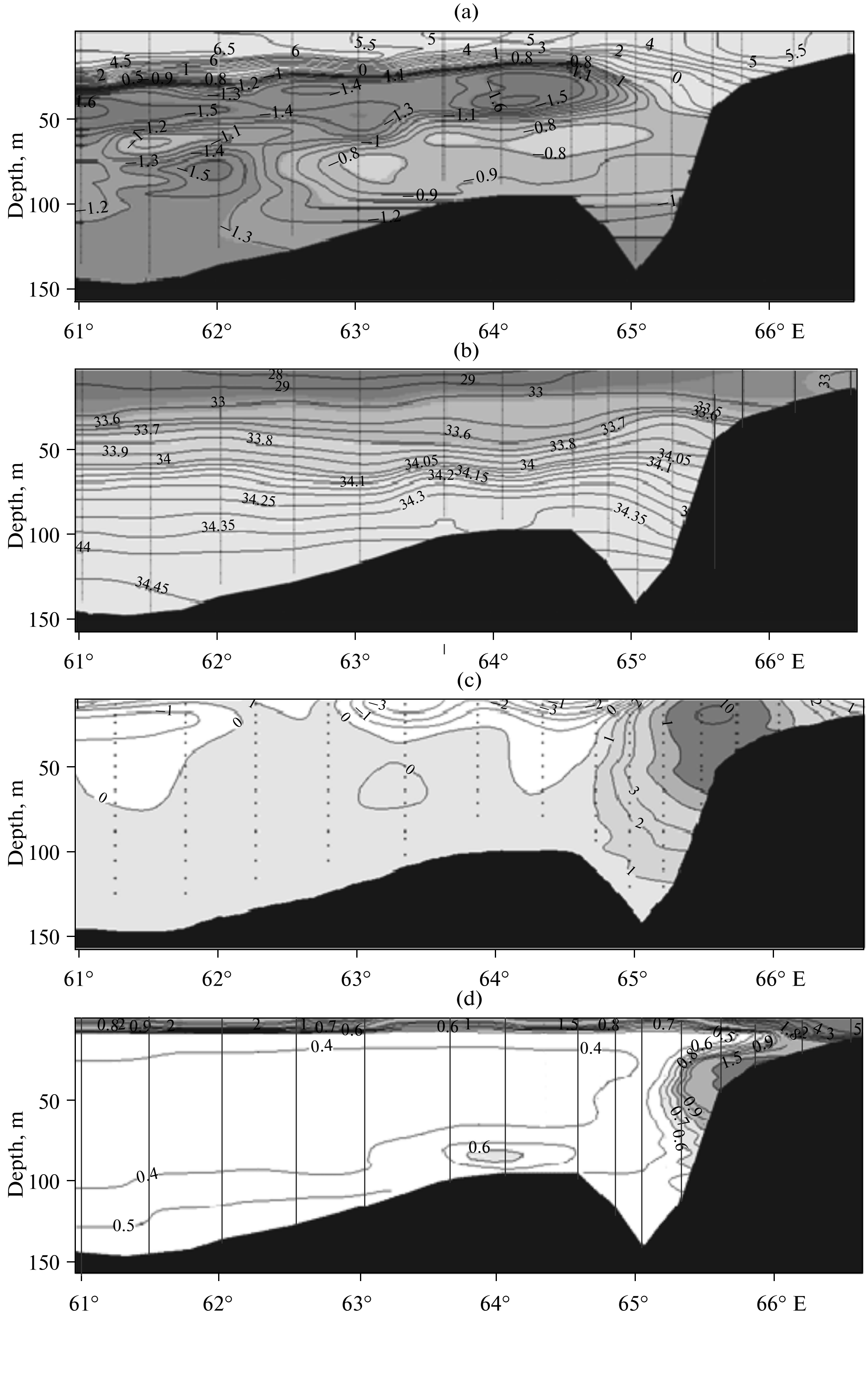

Fig. 1. Distributions of the temperature °C, (a); the salinity, psu (b); the geostrophic current velocity, cm/s (c); and the turbudity, relative units (d), along the Yamal section. The solid vertical lines denote the locations of the profilings; the dashed vertical lines denote the sections for which the current velocity was calculated.

the currents. However, a comparison of the geostrophic calculations with the individual measurements using the towed ADCP shows that they are in good agreement not only in the direction of the transport but also in their amplitude.

The distribution of the geostrophic velocities of the currents over the section is shown in Fig. 1c, where the Yamal Current directed to the north-northwest is clearly pronounced over the slope. The width of the current zone is on the order of 30 km. The maximum velocity in the core of the current at the level of approximately 10 m exceeds 10 cm/s. The total estimate of the geostrophic transport in the Yamal Current is approximately 0.2 Sv. This is slightly less than the mean transport of the Barents Sea water inflowing into the Kara Sea through the Kara Gates Strait (0.3–0.6 Sv) [12, 16, 18]. It is worth noting that the T, S characteristics of the waters here are close to the similar characteristics in the region of the Kara Gates Strait.

A current of southern direction is found in the surface layer 10–15 m thick in the offshore region. This current covers the region of the freshest waters along the section, and it is possibly related to the general anticyclonic circulation in the surface freshened layer described in detail in [3].

A few more sections using the towed CTD profiler in the scanning regime were occupied to the west and northwest of the Yamal Peninsula to locate the Yamal Current more exactly (sections nos. 3, 24, 23, 15, and 19 [9]). All of them demonstrated the further continuation of the Yamal Current to the north along the continental slope.

Hydrographic section no. 2 across the Novaya Zemlya Trough to Novaya Zemlya. The distributions of the temperature and salinity are shown in Figs. 2a and 2b, respectively. Both the isotherms and isohalines/isopycnals are characterized by a specific slope with their elevation in the direction to the coast of Novaya Zemlya. A UQL with a thickness of approximately 10 m that is cooler (2–4°C) than along Yamal section no. 1 is clearly distinguished in the temperature section. A sharp thermocline is located below it, and a CSL is located even lower in the depth range of 20–50 m. The minimum temperature in this layer is below –1.7°C. A layer of warmer water (–0.8°C) admittedly of the Barents Sea origin is clearly seen in the southeastern part of the section in the depth range of 70–140 m. As the depth increases, the temperature monotonously drops down to the bottom, reaching a value of –1.5°C and even less. Admittedly, the deep and bottom waters of the Novaya Zemlya Trough are formed in the winter under the influence of the downwelling of cold saline water from the shelf of Novaya Zemlya during the period of intense ice formation.

The surface layer along this section is strongly freshened. Its minimum salinity is approximately 15 psu. It is likely that this freshening is a joint result of the propagation of the Yenisei and Ob waters to the west under the influence of the dominating winds from the north and the melting of the Novaya Zemlya ice massif in June–August [3]. The component of the geostrophic velocity normal to the section across the Novaya Zemlya Trough is shown in Fig. 2c. A strong northeasterly current with surface velocities exceeding 20 cm/s is found near the coast. The transport is estimated at 0.1 Sv; it was noted by the drift of the ship during the work on the section at very weak winds. As the distance from the coast increases, the current deepens under the surface. Over the western slope of the Novaya Zemlya Trough, deeper than the 100-m isobath, the geostrophic calculations result in a countercurrent directed to the southwest. A weaker current of southerly direction (10 cm/s) in the surface layer (10–15 m) is found in the entire southeastern part of the section.

Section no. 21 according a towed profiler from the eastern end of Novaya Zemlya to the northern end of the Novaya Zemlya Trough. The distributions of the temperature and salinity are shown in Fig. 3. The elevation of the very cold water core from the depths of 40–60 m to 15–40 m and its disappearance south of the eastern end of Novaya Zemlya is a characteristic feature of the temperature distribution here. A sharp temperature front exists here between the cold subsurface water and the relatively warm water of the Atlantic origin propagating to the south along the western slope of the St. Anna Trough [18]. This front is located over the threshold dividing the St. Anna Trough and the Novaya Zemlya Trough (Fig. 3a). Its location coincides with the salinity (Fig. 3b), density, and dynamic fronts caused by the interaction of two opposing currents over the threshold: a current to the southeast along the western slope of the St. Anna Trough and the northeasterly Eastern Novaya Zemlya Current. These currents converge at the eastern end of Novaya Zemlya and then diverge. The current of the St. Anna Trough turns to the northwest and returns back to the Arctic along the eastern slope of the trough, while the Eastern Novaya Zemlya Current propagates further to the east and on this pathway possibly merges with the Yamal Current. Such a pattern of the currents is illustrated well by the satellite image of the sea surface temperature in the satellite image taken on December 21, 2007 (Fig. 4). The Eastern Novaya Zemlya Current (1) is marked by cold (dark hue) waters of the coastal upwelling. The flow does not reach the northern end of Novaya Zemlya and separates from the coast to continue its flow along the southern periphery of the St. Anna Trough (2); then, the flow splits into two branches: one is directed to the northwest along the western end of the trough (3), while the second turns to the east (4). The abundance of filaments in the current zone is worth noting, which provide evidence that

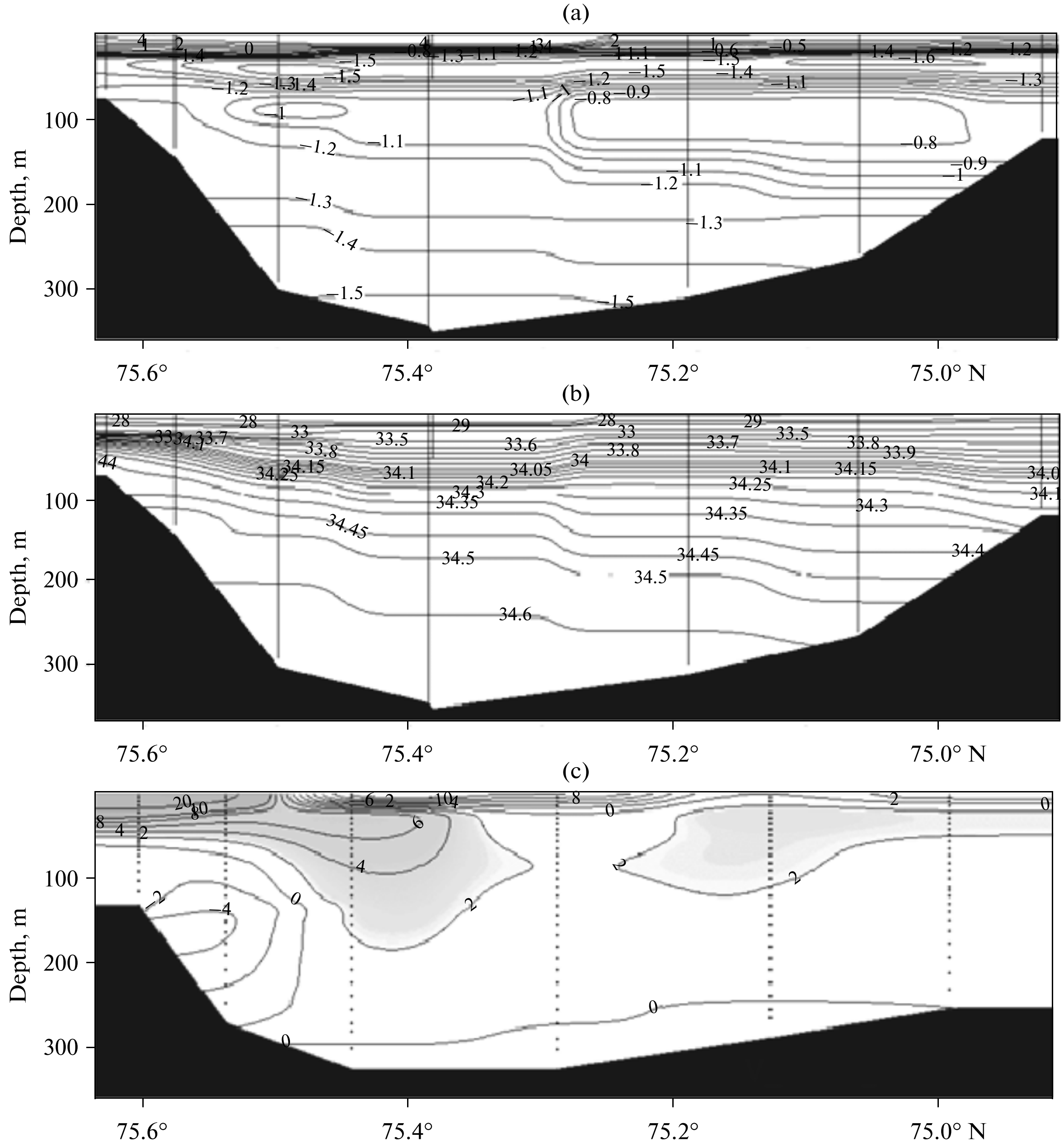

Fig. 2. Distributions of the temperature °C, (a); the salinity, psu (b); the geostrophic current velocity normal to the section, cm/s (c); and the eastern component of the geoctrophic current, cm/s (d), along the section to Novaya Zemlya. The solid vertical lines denote the locations of the profilings; the dashed vertical lines denote the sections for which the current velocity was calculated.

the current is characterized by turbulence, as well as that it strongly interacts with the surrounding waters.

Section nos. 11–12 according to a towed profiler along the St. Anna Trough. The sections were generally performed to a depth of 250 m. The sections of the temperature and salinity are shown in Figs. 5a and 5b, respectively. Two different structural types are clearly pronounced along the temperature section (Fig. 5a): the Arctic waters with the location of the cold intermediate layer (Arctic CIL) at depths of 160–240 m and the Kara Sea waters with the location of the cold subsurface layer at depths of 20–100 m. These layers are formed as a result of the winter cooling and the convective mixing. However, in the Arctic, the convection penetrates deeper and occupies a significantly thicker layer than in the Kara Sea. However, the temperature of the Arctic CIL (–0.6°C) is significantly higher than in the Kara Sea (–1.1°C) due to the greater thickness of the winter mixed layer. We also note that it is likely that the vertical turbulent heat exchange in the Arctic Basin is more effective than in the southwestern part of

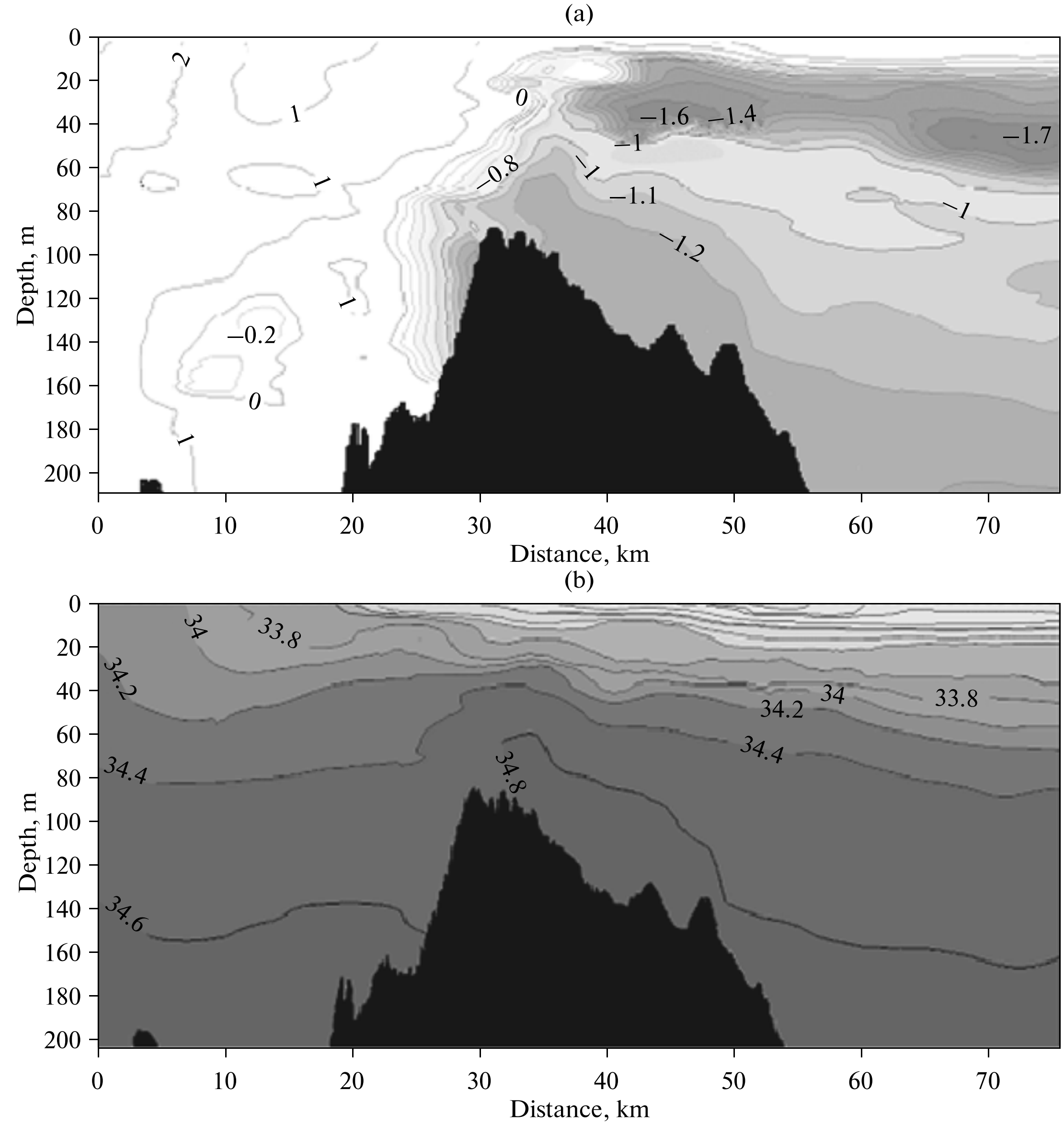

Fig. 3. Distributions of the temperature, °C (a), and the salinity, psu (b), along the section along the eastern coast of Novaya Zemlya.

the Kara Sea. This is determined by two factors: the strong density stratification caused by the freshening of the waters in the upper layer by the runoff of the rivers (Fig. 5b) and the weaker wind forcing at the surface layer in the Kara Sea compared with the Arctic Basin. It is noteworthy that the temperature in the CSL in the Kara Sea near the coasts of Novaya Zemlya is lower and close to the freezing temperature (−1.78°C). It is possible that this phenomenon is caused by the fact that the basin southeast of Novaya Zemlya is protected by the island from the northern winds and swells from the Arctic, while there is not enough fetch for the southern winds to form strong swells. The open regions of the Kara Sea east of Novaya Zemlya are not protected from the northern winds and swells from the Arctic, which enhances the mixing. Therefore, the temperature in the CSL's core is higher. However, these considerations require quantitative verification.

The gap between the two cold subsurface layers over the southern slope of the St. Anna Trough described above is another peculiarity of the temperature distribution. The warm water of the Atlantic origin transported here by the cyclonic current flowing over the St Anna Trough occupies the whole water column. The existence of this current will be clearly shown below in the section across this trough.

The salinity distribution reflects the freshening of the upper layer of the sea caused by the runoff of the rivers, which is well pronounced in the southern part of the section. It is limited from the north by the cur-

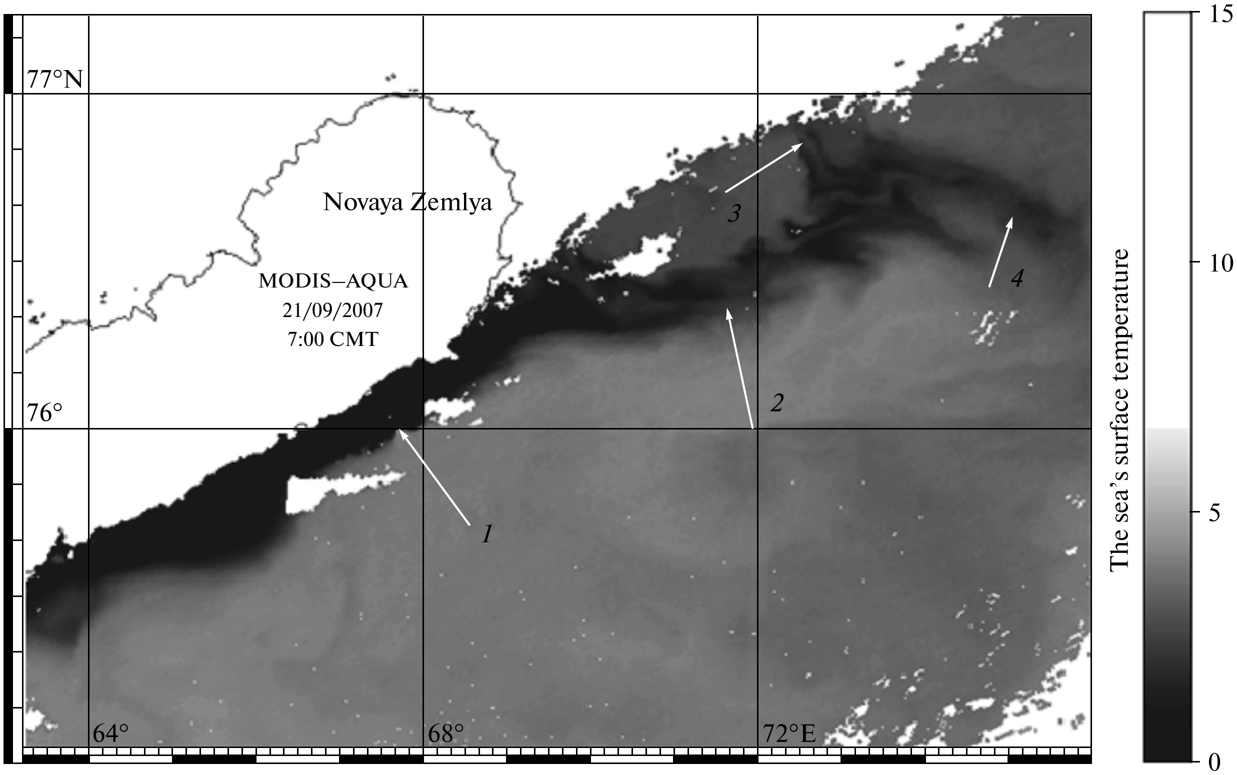

Fig. 4. The sea's surface temperature in the Kara Sea the northern end of Novaya Zemlya (data from the MODIS–AQUA satellite scanner on September 21, 2007, at 07:00 GMT). The arrows denote the following: (*1*) the Eastern Novaya Zemlya Current; (*2*) the current along the southern periphery of the St. Anna Trough; (*3*) the northeasterly branch of the current; (*4*) the easterly branch of the current.

rent front transporting warm waters of lower salinity over the slope of the St. Anna Trough.

The distributions of the properties shown in Figs. 3 and 4 provide evidence that the warm and saline Atlantic waters propagating along the western slope of the St. Anna Trough do not spread to the southwestern part of the Kara Sea. This makes us doubt the correctness of the repeated opinion [18] that the St. Anna Trough is a "channel" for the water exchange between the northern and southern parts of the Kara Sea. Judging from our observations, the frontal zone located over the threshold dividing the St. Anna trough and the Novaya Zemlya Trough is a difficultly penetrable barrier for such water exchange. At the same time, the biological investigations (Flint, personal communication) demonstrated the presence of the pelagic flora and fauna species in the Novaya Zemlya Trough characteristic of the open waters of the Arctic, which provides evidence of the existence of deep water exchange between the Arctic Basin and the southwestern part of the Kara Sea. The discussion concerning this problem will be continued in the next section of this article.

Section no. 14 performed using a towed profiler from Novaya Zemlya across the St. Anna Trough. This section of the fields of the temperature and salinity is shown in Figs. 6a and 6b, respectively. It is seen that the warmest and least saline water transported by the cyclonic current over the slopes of the trough, which we mentioned above, is located over the slope of Novaya Zemlya. The core of the coldest water related to the CSL of the Arctic origin is located at depths of 150–200 m. The entire deep part of the St. Anna Trough is filled with water with salinity greater than 35 psu. Since water with such salinity is not observed in the other regions of the Kara Sea, it is likely that this water has an Arctic origin.

The temperature stratification deeper than the core of the CSL makes the vertical density distribution unstable. The density stratification of the deep waters is weakly stable due to the contribution of the salinity. In such conditions, one should expect the development of double diffusion convection in the diffusion regime [8] in the deep part of the St. Anna Trough, which can become the main mechanism of the vertical mixing of the deep waters in the trough.

The weak vertical density stratification in the St. Anna Trough causes the quasi-barotropic character of the current and the fact that it is confined to the slope. This is indirectly confirmed by the absence of silt sediments on the slope of the trough, which are

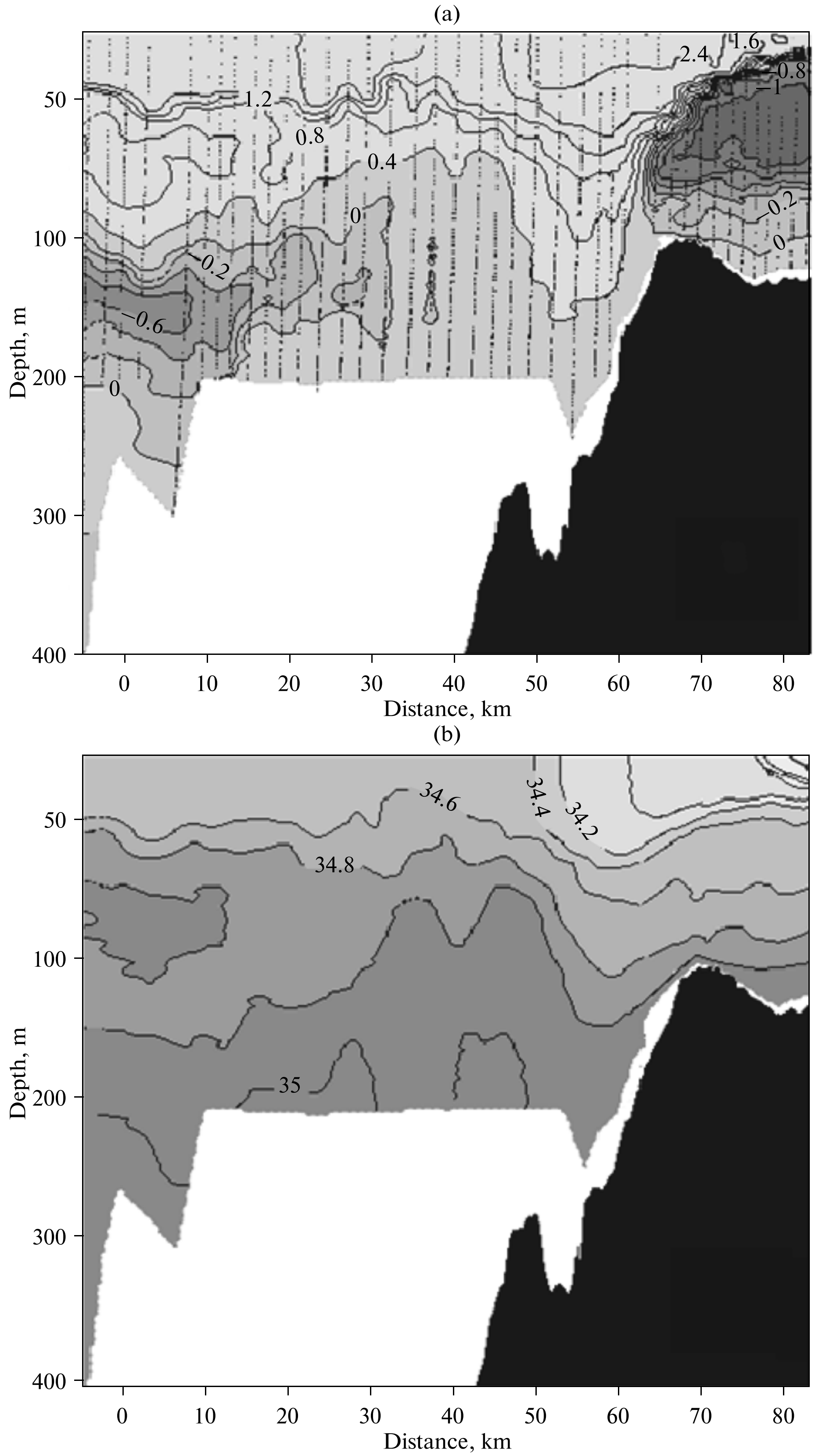

Fig. 5. Distributions of the temperature, °C (a), and the salinity, psu (b), based on the towed CTD-profiler data along the section along the St. Anna Trough.

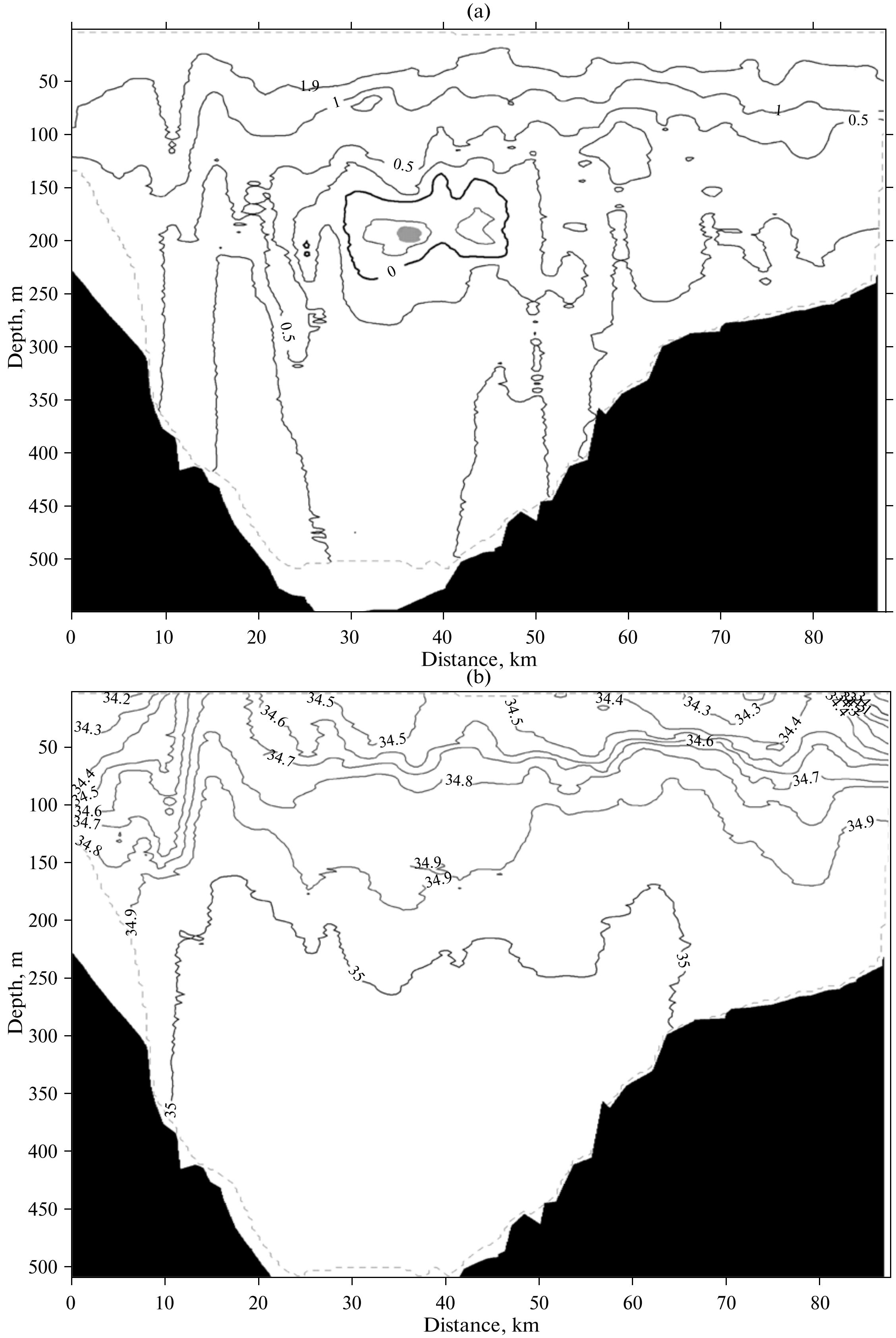

Fig. 6. Distributions of the temperature, °C (a), and the salinity, psu (b), based on the towed CTD-profiler data along the section across the St. Anna Trough.

likely transported away by a strong bottom current. In addition, sestonofags dominate in the species of the bottom fauna found on the slopes of the St. Anna Trough. These are animals that feed on the suspension from the water flow (Galkin, personal communication). According to our observations, the core of the cyclonic current around the trough is located over isobaths of 200–300 m. The southeasterly current was narrower (10–15 km) and strong over the steep western slope of the trough adjacent to Novaya Zemlya. Judging from the drift of the ship, the velocity in its core reached 50 cm/s (the geostrophic calculations for a quasi-barotropic current do not give representative results). The northwesterly current over the flatter eastern slope was wider (20–25 km), and its velocity hardly exceeded 30 cm/s. The cores of the currents over the western and eastern slopes of the trough (Fig. 8b) are well marked by regions of low salinity (<34.4 psu) in the upper 80-m water layer (between 0–15 km and 55–80 km of the abscissa scale of the section, respectively). This provides additional evidence that the circulation in the St. Anna Trough is circular and the currents are confined to the slope region.

Section nos. 15–17 performed using a towed profiler from the offshore regions near the Ob to the Ob estuary. Figure 7 shows the sections of the temperature, salinity, and density fields; the profiles of the density related to their locations along the sections are also shown. Owing to the fact that the distance between the neighboring profiles using the scanning profiler was 2–5 km, the data allow us to reproduce the detailed pattern of the transition from the pure river water in the Ob estuary (between 220 and 180 km along the section) to the double layer stratification of the water column in the offshore region (between 150 and 0 km along the section). This transition is a clearly pronounced frontal zone and is topographically controlled at the threshold separating the offshore region from the river's mouth. The surface salinity changes from 3–4 psu to 20 psu across the frontal zone over a distance of 30 km from the crest of the threshold (the depth of the location is 10–12 m) to its foot (at a depth of 28–30 m). The bottom salinity changes to a value of up to 30 psu. The formation of the frontal zone is caused by the interaction between the river water outflowing to the sea and the waters of the surface freshened layer with a salinity of about 20 psu and a thickness of 10–15 m formed in the offshore region during the flooding in June–July [3]. The sea waters with a salinity of about 30 psu underlie the surface freshened layer. These waters almost do not penetrate to the river's mouth due to the blocking effect of the estuary's threshold. The partial mixing of the marine and river waters occurs immediately in the threshold zone especially from the sea side; however, it is difficult to estimate the intensity of this process. Long internal waves ($\lambda \sim$ 30–40 km) most likely caused by the internal tide contribute to the water mixing. The existence of such waves at a latitude of 73° south of the critical latitude is theoretically possible [6]. Two such waves are indicated with arrows in Fig. 7a. They manifest themselves at the density interface between the waters of the surface freshened layer and the underlying saline waters. Such waves can break and cause strong mixing when they approach the threshold and appear in the region of the sloping bottom. The interaction of the internal tidal waves with the shear intensified near the threshold and with the onshore–offshore wind currents and turbulence in the upper layer of the sea can cause peaks of the mixing between the contacting water masses with different salinities, thus changing the location and internal structure of the frontal zone. Such a supposition is confirmed by the fact that the repeated hydrographic section in the opposite direction in a short period of time (1–2 days) (from the Ob's mouth to the offshore region) demonstrated a significant change in the frontal zone's structure: a freshwater meander was found in its structure (see Fig. 3 in [3]).

It is likely that the structure and location of the frontal zone are subjected not only to their short-period variation but also to their long-period variation (first of all, seasonal and interannual). For example, the observations carried out in September 1973 showed that the frontal zone was sufficiently dissolved and penetrated deep into the mouth of the Ob River occupying a position from 71° to 73°30′N [1] even containing a freshwater meander. It is worth noting that the frontal zone in the region of the interaction between the river and sea waters is manifested not only in the sections of the hydrophysical characteristics but also in the fields of the chemical parameters [5], as well as in the fields of the phyto- and zooplankton [7, 10]. This frontal zone is one of the main elements of the marginal filter determining the sedimentation of organic and inorganic matter transported by the rivers to the sea [4].

Section 25 performed using a towed profiler from the western coast of Yamal to the Kara Gates Strait. A characteristic feature of this section (Fig. 8) is the disappearance of the CSL (which exists practically everywhere in the Kara Sea) at a distance of approximately 100 km to the Kara Gates Strait. This fact undoubtedly provides evidence that the warm Barents Sea waters propagate to the Kara Sea through this strait, which gives origin to the Yamal Current.

The currents based on the towed ADCP data. The measurements of the vertical profiles of the currents using the ADCP from a moving ship were carried out along the major part of the sections but only in the shallow water part of the sea. The depth of the sea limited the measurements because the bottom tracking regime, which gives representative values of the horizontal components of the current velocity with an accuracy up to a few cm/s, could be realized with the

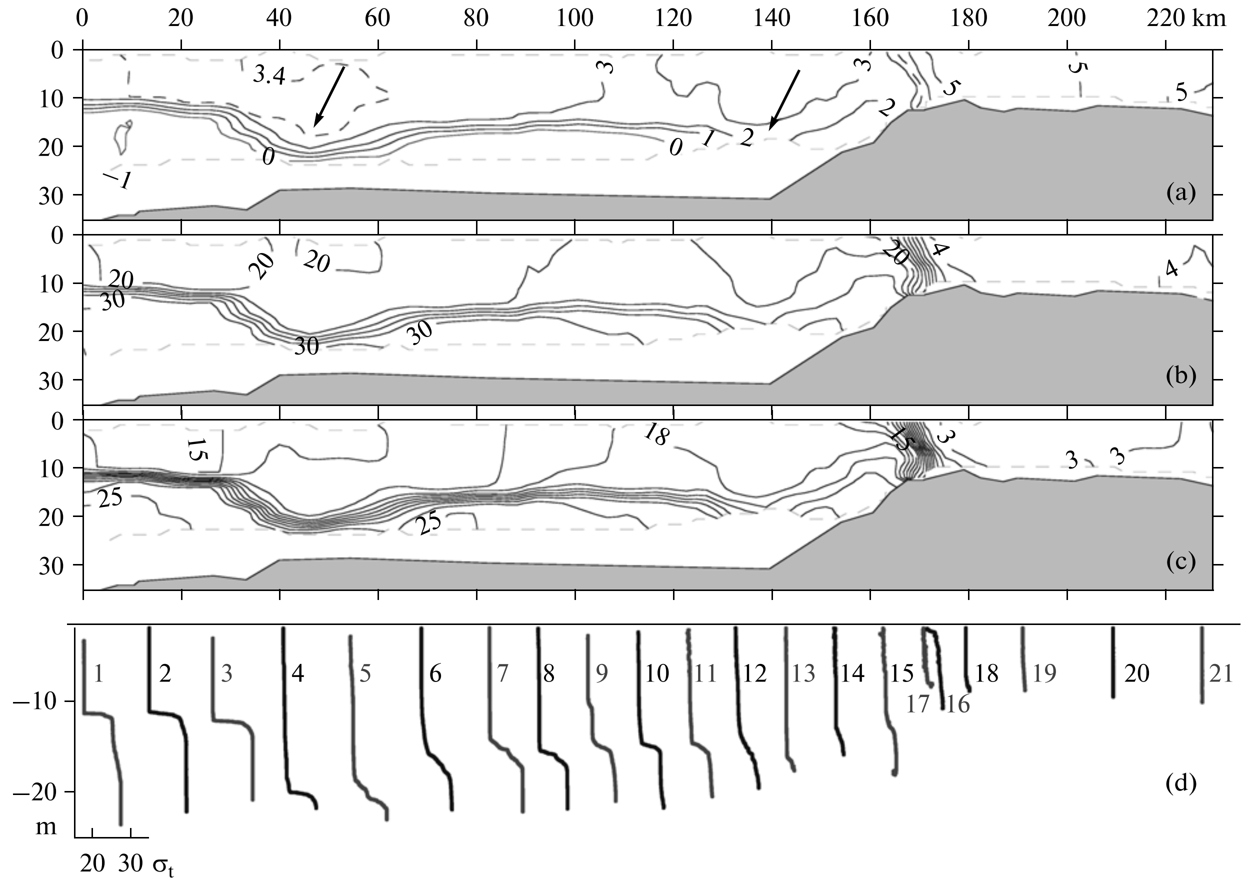

Fig. 7. Distributions of the emperature, °C (a); the salinity, psu (b); the density, conv. units (c); and the vertical profiles of the density (d) at the places of the measurements along the meridional section from 74° to 72°N based on the towed CTD-profiler data. The arrows in Fig. 7a denote internal waves admittedly generated by the tide.

ADCP model used only to a sea depth that did not exceed 80–100 m. During such a measurement regime, it was possible to obtain realistic profiles of the horizontal velocity components in the water column from 10 to 50 m. The lower boundary was determined by the power restriction of the acoustic signal, while the upper was related to two factors: the towing depth of the case with the instrument (2–6 m) and the existence of the ship's swirl covering the entire surface layer of the sea (0–10 m). Since the towing was in the swirl, the data of the measurements could not be considered representative.

Taking into account such technical limitations, we analyzed the data of the velocity measurements in the layer of 15–45 m. Figure 9 presents the current velocity vectors averaged over the thickness of this layer for several sections in the southwestern part of the Kara Sea. Despite the fact that filtering out the inertial and tidal components of the velocity was not performed, the pattern of the currents obtained from the LADCP data agrees with the other results of the current measurements. For example, the Yamal and Eastern Novaya Zemlya currents are clearly distinguished in Fig. 9, coinciding in their direction with the geostrophic currents. The absolute value of the velocity based on the ADCP data is sufficiently close to the geostrophic calculations. The strongest easterly currents from the Barents to the Kara Sea based on the ADCP data were observed in the Kara Gates Strait (up to 70 cm/s). It is worth noting that the existence of an intense current (exceeding 50 cm/s) with the same direction was revealed from the analysis of the data of the current meter measurements (POTOK-2M) in the end of September–beginning of October of 1997 by three moorings deployed across the Kara Gates Strait [11].

A strong easterly current with a velocity up to 50 cm/s was recorded near the northern end of Novaya Zemlya. The characteristic velocity of the Yamal Current mainly of the northern direction was 20–40 cm/s, which also corresponds well with the geostrophic estimates.

We can conclude, in general, that direct measurements of the current velocity carried out using a towed ADCP confirmed the soundness of the results of the geostrophic calculations of the currents in the southwestern part of the Kara Sea.

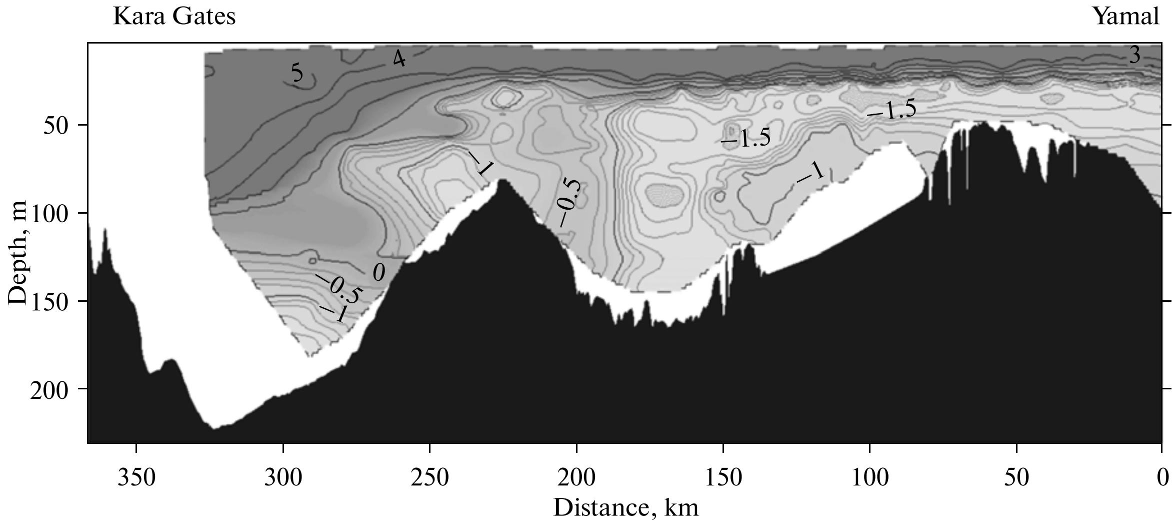

Fig. 8. Distribution of the temperature, °C, along the section from Yamal to the Kara Gates Strait based on the towed CTD-profiler data.

GENERAL CIRCULATION IN THE SOUTHWESTERN PART OF THE KARA SEA IN SEPTEMBER OF 2007

The general scheme of the circulation in the southwestern part of the Kara Sea in the upper 100-m layer based on the joint analysis of the hydrophysical measurements in September 2007 is shown in Fig. 9. The scheme presents the Yamal Current originating at the Kara Gates Strait, the eastern Novaya Zemlya Current along the coasts of Novaya Zemlya, and the current in the St. Anna Trough. This scheme is not completely consistent with any of the schemes discussed in the Introduction. This scheme differs from the scheme in [2, 18] by the northeasterly Eastern Novaya Zemlya Current, which coincides with the results of the observations and modeling in [12–17]. However, on the other hand, the Yamal Current is not seen in these publications, but it is clearly manifested and confined to the slope of the Yamal shelf in our observations.

The description of the circulation near the northern end of Novaya Zemlya (Figs. 3–6, 9) is an important result of this research. It is shown that the current in the St. Anna Trough is barotropic and topographically controlled. This current is reciprocating: the waters that propagate to the southeast along the western slope of the trough flow back to the northwest along its eastern slope. These waters do not propagate to the southwestern part of the sea, which is divided by a frontal zone located over the elevation of the bottom topography (threshold) between the St. Anna and Novaya Zemlya troughs. This frontal zone is a region where the St. Anna Trough Current and the Eastern Novaya Zemlya Current, which separates from the northern end of Novaya Zemlya, encounter and interact. Both currents are quite intense: up to 50 cm/s and greater. It is likely that their interaction has a “turbulent” character, which results in the formation of submesoscale and mesoscale lens structures, eddies, and filaments, which are seen in the sections crossing the frontal zone (Fig. 3) and in the satellite images (Fig. 4). It is possible that the trasnsfrontal exchange maintained by such hydrophysical structures provides for the penetration of the arctic plankton species from the St. Anna Trough to the Novaya Zemlya Trough and vice versa. It is likely that the Eastern Novaya Zemlya Current and the Yamal Current merge east of the St. Anna Trough.

The frontal zone between the St. Anna Trough Current and the Eastern Novaya Zemlya Current limits the northward propagation of the surface freshened waters formed under the influence of the Ob and Yenisei rivers’ runoff. A detailed description of the formation and evolution of the surface freshened layer in the Kara Sea is given by Zatsepin and coauthors [3]. Here, we only mention that, according to the hydrodynamic laws, the vast lens of fresher waters observed offshore of the mouths of the Ob and Yenisei rivers and west of this region [3] should form an anticyclonic circulation in this basin, especially in its periphery in the zone of the frontal boundaries. During the second half of the summer, the anticyclonic currents, precisely, should maintain the propagation of the waters freshened by the runoff of the Ob and Yenisei rivers from the offshore region of these rivers to the coasts of Novaya Zemlya in the west and can facilitate the separation of the Eastern Novaya Zemlya Current from the coast increasing its subsurface velocity due to the frontal salinity gradients (density and pressure). The coincidence of the boundaries of the freshened waters’ spreading region and the frontal zone of the easterly

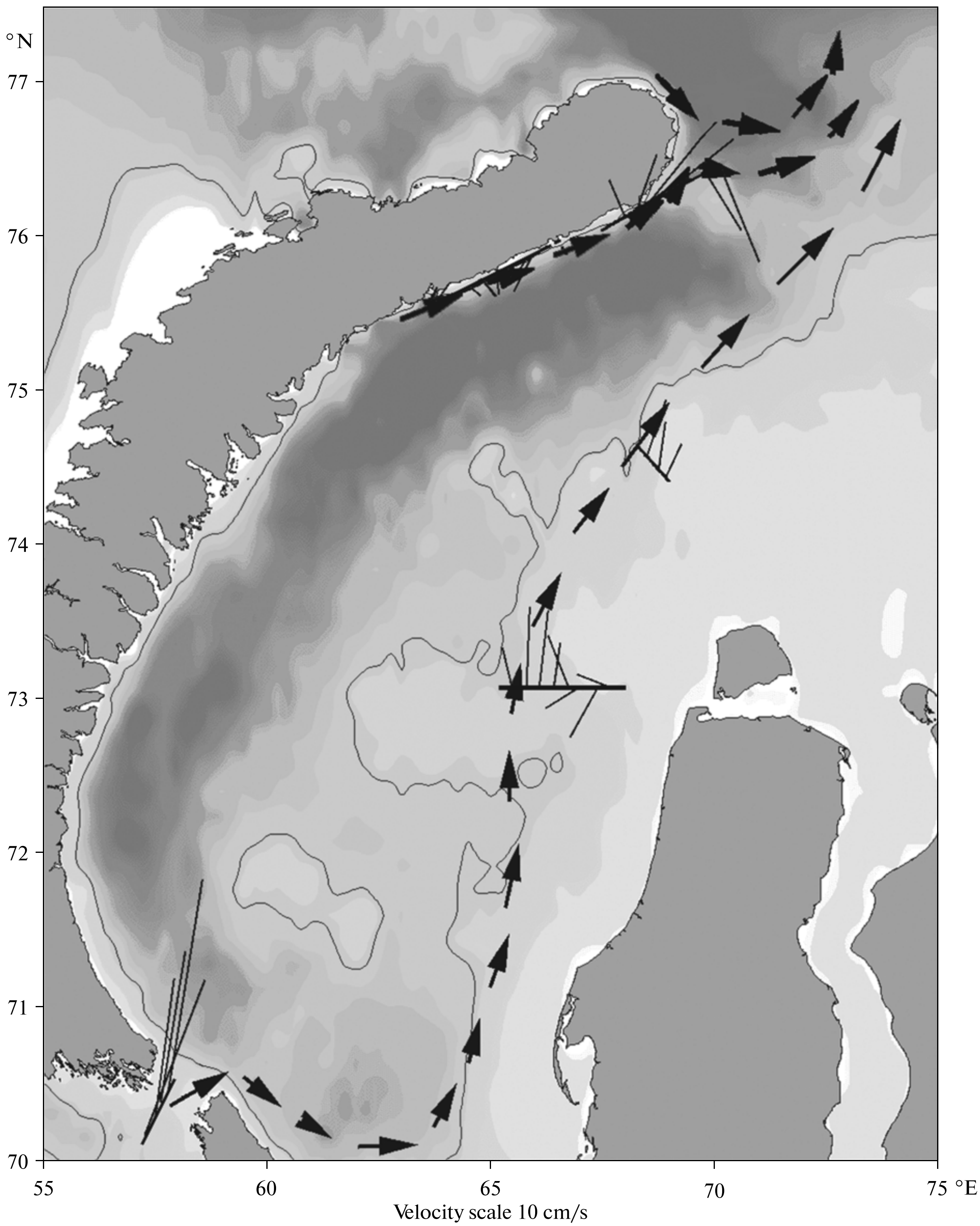

Fig. 9. The average current vectors (segments of a straight line) in the layer between 15 and 45 m based on the data of the measurements with a towed ADCP along the sections in different regions of the southwestern part of the Kara Sea and a scheme of the circulation in the upper 10-m layer in the southwestern part of the Kara Sea based on the observations in September 2007. The arrows show the main currents. The solid line denotes the 100-m isobath.

Eastern Novaya Zemlya Current is not occasional and gives a synergetic contribution to the circulation.

CONCLUSIONS

In conclusion, we shall briefly discuss the possible causes of the current system's formation in the southwestern part of the Kara Sea, which was discussed above. It is known that wind forcing is one of the most important factors generating the circulation in comparatively shallow shelf seas. In this case, the Ekman transport and its divergence are the determining factors. The southern wind dominating over the southern and central parts of the Kara Sea from the middle of August 2007 provided the Ekman transport from west to east (see Fig. 6b in [3]). Thus, during our expedition, the sea level should have been decreased near the eastern coast of Novaya Zemlya and increased near the western coast of Yamal, while the slope of the isopycnal (isohaline) surfaces should be opposite, which was actually observed (Figs. 1b and 2b). The geostrophic currents over the submarine slopes of Yamal and Novaya Zemlya induced by these slopes of the sea level and the isopycnals were directed to the north and to the northeast, respectively (Figs. 1c and 2c). Thus, the assumption about the dominating role of wind forcing in the formation of the main currents in the Kara Sea does not contradict the data of the observations. However, as was shown in the publications on modeling the circulation in the Kara Sea [12–17], the actual currents also strongly depend on such external factors as the freshwater runoff and the water exchange through the straits with the neighboring seas and the Arctic Ocean. The variability of the circulation and hydrology of the Kara Sea and their seasonal and interannual variations are poorly studied. Additional field and model investigations are needed to describe their dependence on the external forcing.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 09-05-13574ofi_c.

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