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ОРИГИНАЛЬНАЯ СТАТЬЯ ORIGINAL ARTICLE

TRANSFORMATION OF ATLANTIC WATER IN THE NORTH-EASTERN BARENTS SEA IN WINTER

VLADIMIR V. IVANOV[1,2], IVAN E. FROLOV[2], KIRILL V. FILCHUK[2]*

[1] — *Lomonosov Moscow State University, Moscow, Russia*
[2] — *State Scientific Center of the Russian Federation Arctic and Antarctic Research Institute, St. Petersburg, Russia*

*vladimir.ivanov@aari.ru

Summary

Hydrographic observations, carried out in March-May, 2019 during "Transarktika-2019" expedition onboard R/V "Akademik Tryoshnikov" allowed studying mechanisms of Atlantic Water (AW) transformation in the Barents Sea. Although this research topic is rather traditional for oceanographic studies, there are still a number of questions, which require clarification. Among these is a deeper understanding of the AW transformation in specific regions in cold season, when the coverage by observations is scarce. In this study we performed temperature and salinity (*TS*) analysis of conductivity — temperature — depth (CTD) data, collected in the north-eastern "corner" of the Barents Sea — this is the area with difficult access in winter due to high concentration of pack ice. The results allowed identification of areas along the pathways of AW branches, where various types of open sea convection and cascading acted as dominant processes of AW properties change. We distinguish several driving mechanisms controlling modification of the waters of Atlantic origin. An advantage of winter measurements is that the active stage of AW transformation mechanisms is explicitly observed at the consecutive CTD sections.

Keywords: Arctic Ocean, Atlantic Water, Barents Sea, cascading, field observations, open sea convection, sea ice, *TS*-analysis.

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ТРАНСФОРМАЦИЯ АТЛАНТИЧЕСКОЙ ВОДЫ В СЕВЕРО-ВОСТОЧНОЙ ЧАСТИ БАРЕНЦЕВА МОРЯ В ЗИМНИЙ СЕЗОН

В.В. ИВАНОВ[1,2], И.Е. ФРОЛОВ[2], К.В. ФИЛЬЧУК[2]*

[1]— *Московский государственный университет им. М.В. Ломоносова, Москва, Россия*

[2] — *ГНЦ РФ Арктический и антарктический научно-исследовательский институт, Санкт-Петербург, Россия*

*vladimir.ivanov@aari.ru

Резюме

Гидрологические наблюдения, выполненные в марте–мае 2019 г. во время экспедиции «Трансарктика-2019» на борту НЭС «Академик Трёшников», позволили изучить механизмы трансформации Атлантической воды (АВ) в Баренцевом море. Хотя эта тема является довольно традиционной при изучении океанографии Баренцева моря, сохраняется ряд вопросов, которые требуют прояснения. Среди этих вопросов можно выделить более глубокое понимание процессов трансформации АВ в определенных районах моря в холодное время года, когда количество натурных наблюдений ограничено. В данном исследовании был проведен *TS*-анализ гидрологических профилей, выполненных в северо-восточном регионе Баренцева моря — области, в которой зимние полевые исследования затруднены из-за сложных ледовых условий. Полученные результаты позволили определить зоны, расположенные вдоль ветвей распространения АВ, где различные типы вертикальной конвекции и каскадинга являются доминирующими механизмами, обеспечивающими трансформацию АВ по мере их движения. По результатам анализа было выделено несколько характерных механизмов трансформации. Преимущество использованных в данной работе зимних измерений заключается в том, что активная стадия механизмов трансформации явно прослеживается в данных наблюдений на последовательных гидрологических разрезах.

Ключевые слова: Атлантическая вода, Баренцево море, вертикальная конвекция в океане, каскадинг, морской лед, полевые наблюдения, Северный Ледовитый океан, *TS*-анализ.

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INTRODUCTION

The Barents Sea occupies a special niche among the Arctic Ocean (AO) shelf seas, due to its marginal location between the AO deep interior and the Nordic Seas. Prevailing direction of zonal atmospheric transport in mid-latitudes of the Northern hemisphere - from west to east, places the Barents Sea on the pathway of cyclones and ocean currents that carry heat and moisture/salt to the AO. This feature makes the Barents Sea very sensitive part of the AO, quickly responding to atmospheric and oceanic “signals” coming from mid-latitudes. On the other hand, hydrological and ice conditions in the Barents Sea play significant role in the formation of feedbacks between the North Atlantic Ocean and the Arctic Ocean, and affecting the climate of the Eurasian continent [1].

Large-scale advection of warm and salt water from the North Atlantic Ocean is the main external source of heat and salt for the AO [2]. An increase in the amount of ocean heat entering the Barents Sea from mid-latitudes in 2000s caused significant decrease in the winter ice area in the Barents Sea [3]. Recent studies indicate that the most dramatic changes in the 2010s occurred in the northern Barents Sea [4]. The observed warming is primarily associated with atmospheric thermodynamic forcing, which gradually affect most of the water column. Noticeable increase in temperature and salinity in this area has been observed since the mid-2000s. Another hypothetical mechanism of the observed changes is associated with general decrease of sea ice volume in the Arctic Ocean [5]. Decrease in ice import to the Barents Sea and subsequent salinization leads to weakening of density stratification, intensification of vertical mixing and an increase of heat and salt supply from the deep to the surface water layer. The ultimate outcome of such changes is a further reduction of sea ice, i.e. implementation of positive feedback, defined as “atlantification” [3, 6]. Due to the fact that the Barents Sea is a relatively shallow basin (the average depth of the sea is 230 m), atlantification is progressing here much faster than in the neighboring deep Nansen Basin. Thus, the scenario, that hydrological regime in the northern part of the Barents Sea may completely transform in the coming years to sub-Arctic type, a characteristic feature of which is almost year-round absence of ice cover [5], should be considered as a rather realistic one.

Despite the large number of instrumental observations carried out in the Barents Sea in the past, the coverage by observations is very uneven. Most of the field data were collected in the permanently ice-free western and central parts of the sea [7], while the northern and north-eastern parts appeared to be understudied, especially in the winter season. On the other hand, as will be shown in the next section, processes in the northern and northeastern parts of the sea are of high theoretical and practical importance, because of vigorous water masses transformation within this area. End products of this transformation spread over different water layers in the deep Arctic Ocean, affecting thermohaline and hydrochemical structure of the water column.

The paper consists of five sections, including this one. The present knowledge on the role of Atlantic water in the formation of the hydrological regime of the north-eastern part of the Barents Sea is briefly summarized in the next section. The study is based on the unique field data, obtained in late winter and spring 2019 in the Barents Sea during the “Transarktika-2019” expedition (1st leg). The data and methods, used for analysis are briefly described in section 3. Results of the analysis are presented in section 4. Results are discussed and summarized in the final section.

THE ROLE OF ATLANTIC WATER IN THE FORMATION OF THE HYDROLOGICAL REGIME OF THE NORTH-EASTERN BARENTS SEA

To give an overview on how the waters coming from the North Atlantic may affect the hydrological regime of the north-eastern part of the Barents Sea, we briefly describe their pathways to the study area. After crossing the Faroe-Icelandic Ridge, the continuation of the North Atlantic Current — the Norwegian Current follows to the north-north-east along the coast of Norway. In the northwestern part of the Norwegian Sea, the stream is divided into the West Spitsbergen Current, which flows into the AO through the Fram Strait, and the North Cape (Nordkapp) Current, which enters in three branches the Barents Sea between Medvezhy Island (Bjørnøya) and the Scandinavian Peninsula.

In the marginal ice zone north and northeast of Spitsbergen (Svalbard), an upper part of the Atlantic water (AW) layer is cooled and freshened through interaction with the atmosphere and ice cover [8]. The deep part of the AW layer, which is commonly referred as the Fram Strait branch of the Atlantic water (FAW), preserves above-zero temperature and high salinity (~34.9 — 35.2). FAW and the transformed upper layer are carried by the boundary current eastwards, along the continental slope of Eurasia. These waters reach the Barents Sea, entering from the north, through Victoria and Franz-Victoria channels between Svalbard and Franz Josef Land (FJL) archipelagos [9], and from the northeast, through St. Anna Trough in the northern part of the Kara Sea and the strait between FJL and Novaya Zemlya [10].

Atlantic water entering the Barents Sea from the west with the North Cape current - the so-called Barents Sea Atlantic Water (BAW), is strongly cooled down to the seafloor in the winter season. This is traditionally explained by the fact that winter convection often reaches the bottom in a relatively shallow Barents Sea [11].

The main outflow of BAW from the Barents Sea occurs in the Kara Sea through the strait between the Novaya Zemlya and the FJL archipelago. In the Kara Sea BAW moves north along the eastern slope of the St. Anna Trough, finally reaching the deep AO interior [10, 12].

Intensive mixing, leading to formation of new water masses take place in the FAW and BAW contact zones in the northeastern region of the Barents Sea. In particular, this refers to the Shelf Atlantic water (SAW) recently recognized as a distinct water body [13]. Formation of SAW occurs in a marginal ice zone in the northern part of the Barents Sea in summer season in similar manner as north-east of Spitsbergen. The upper part of the Atlantic Water layer cools and freshens, forming a thin quasi-homogeneous layer. Winter convection deepens this layer. However, low density at the surface (due to reduced salinity) prevents convection from penetrating below the underlying pycnocline. As a result, cooled and freshened water mass is formed within the 0 — 100 m top layer. Due to the prevailing wind regime and constrains from the bottom topography SAW moves through the strait between FJL and Novaya Zemlya. In the Kara Sea SAW follows along the eastern slope of the St. Anna Trough and finally enters the Nansen Basin [13]. After reaching its density level (at 150 — 250 m) SAW is transported by the boundary current generally eastwards [13]. Mixing of BAW with cold dense waters, produced in winter on shallow banks and on the western shelf of Novaya Zemlya, creates bottom waters of the Barents Sea [14]. It is assumed that, depending on external conditions (atmospheric forcing, ice concentration, thermohaline parameters of BAW), the density of bottom waters of the Barents Sea can reach extreme values exceeding the density of deep waters in the AO [15].

DATA AND METHODS

The field data, used in this study, were collected during “Transarktika-2019” research cruise onboard R/V “Akademik Tryoshnikov” in March — May, 2020. The cruise narrative is described in [16]. *In situ* measurements of temperature and electrical conductivity of sea water at vertical sections were used in this study. The measurements were carried out while the ship was in drift using the CTD 911 device, manufactured by SeaBird Electronics Inc. (USA). Temperature and conductivity sensors at the time of the measurements had calibration certificates and after the expedition was completed, the sensors passed standard calibration in a certified company. The accuracy of the measurements of electrical conductivity and temperature was 0.0005 S/m and 0.005 °C, respectively. Location of oceanographic sections and stations, used in this study, is shown in Figure 1. To quantify the transformation of water masses, the traditional *TS* diagram analysis was used [17].

RESULTS

The Atlantic water entering from the Norwegian Sea loose about 80 % of its heat content on the entrance to the northern Kara Sea [10]. However, how and where this happens is still a matter of debates. Traditionally, the main processes are assumed to be deep convection through warm Atlantic water layer and cascading of dense water from shallow shelf and banks to the neighbouring deeper basins [18]. However, relative contribution of these processes is not clear. Sections I — III (see Fig. 1) allow tracking of changes in vertical thermohaline structure of BAW from the central Barents Sea to the north-eastern boundary of the Kara Sea. Changes in FAW, entering from the Kara Sea and Nansen Basin, are studied through comparison of sections III — VI (Fig. 1).

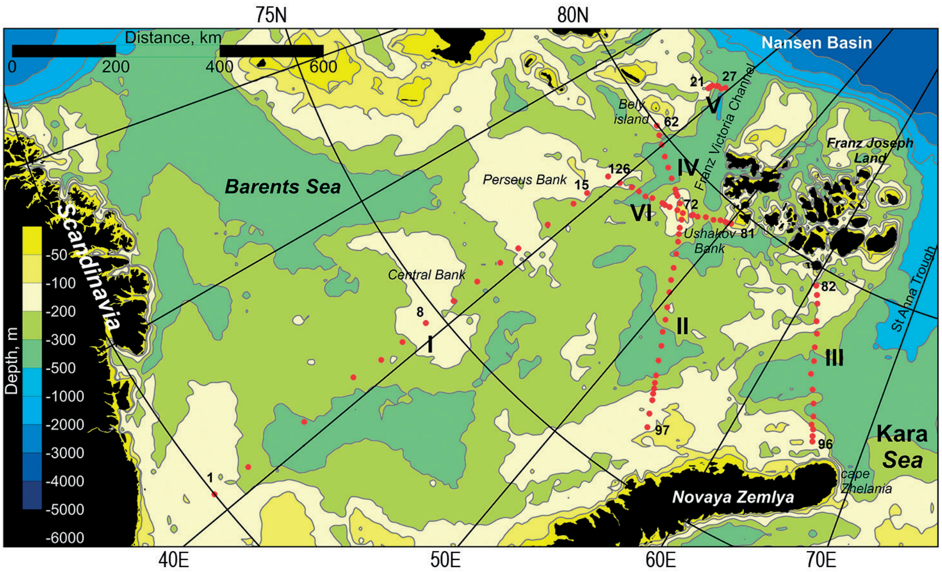

Fig. 1. Location of CTD sections occupied during the expedition “Transarktika-2019” (1st leg) in March — May, 2019 used in this study. CTD stations are shown by red dots. Roman numerals denote sequential number of specific sections. Arabian numerals denote boundary CTD stations at each section. Bathymetry of the Barents Sea is shown by colour and contours [19].

Рис. 1. Пространственное положение гидрологических разрезов в экспедиции «Трансарктика-2019» (1-й этап) в марте — мае 2019 года, использованных в данном исследовании. Гидрологические станции обозначены красными точками. Римскими цифрами показаны номера последовательных разрезов. Арабские цифры обозначают граничные CTD-станции на каждом разрезе. Рельеф дна Баренцева моря показан цветными контурами [19].

Barents Sea branch of Atlantic Water transformation

The warmest and freshened core of BAW (T = 3.87 °C, S = 34.74 PSU) at a depth of 100 m is located at the southern border of the Section-I over the flank of the Central Basin (Fig. 2). Almost uniform water column (T = 0.25 °C, S = 34.94 PSU), which may be attributed to the central branch of the North Cape current, is observed to the north of the warm core. Vertical homogeneity at stations 5 — 7 indicates an active stage of thermal convective mixing reaching the seabed. Thermal convection does not change mean salinity, but evenly redistributes salt within the water layer, affected by convective mixing. This explains high salinity through the entire water column. Minimum temperature (–1.12 °C) and the highest potential density (1028.11 kg/m^3) are present over the top of the Central Bank, indicating the localised zone of dense water formation due to topographic control mechanism [16, 20]. Another local core of BAW with maximum temperature 1.15 °C and salinity 34.93 PSU at 50 m depth above the bottom is observed in the trench between the Central Bank and the Perseus Bank. This core represents the northern branch of the North Cape current. Warm core is separated from the sea surface by relatively cold and fresh upper mixed layer. Sharp gradients of temperature and salinity at the base of the upper mixed layer represents the depth of convection (75 m). However, very weak density stratification at stations 9 and 10 down to greater depth points out that convective mixing in this region was still active during the survey.

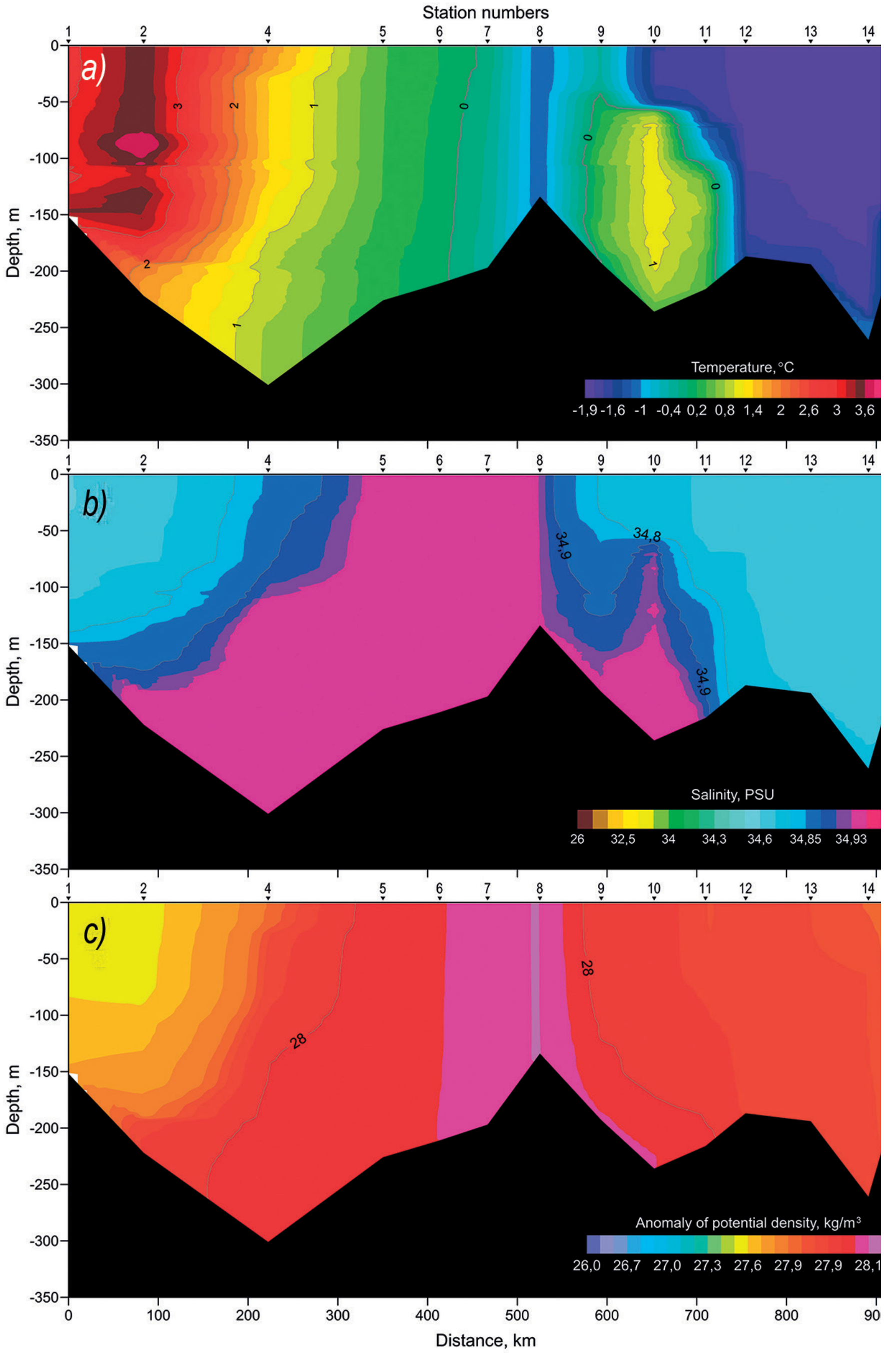

Fig. 2. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m^3 relative to 1000 kg/m^3 (*c*) at Section-I

Рис. 2. Вертикальное распределение температуры, °C (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м^3 относительно 1000 кг/м^3 (*c*) на разрезе-I.

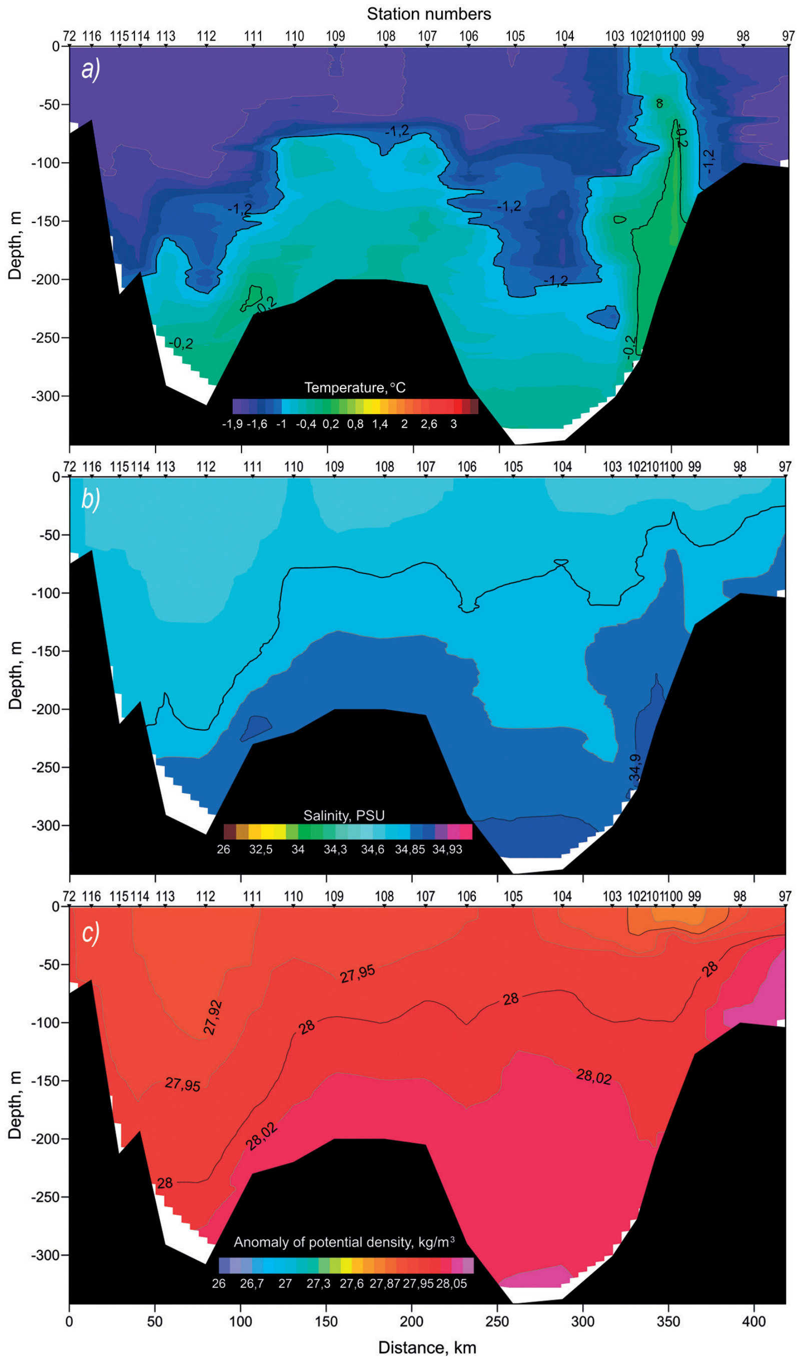

Fig. 3. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m^3 relative to 1000 kg/m^3 (*c*) at Section-II

Рис. 3. Вертикальное распределение температуры, °C (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м^3 относительно 1000 кг/м^3 (*c*) на разрезе-II

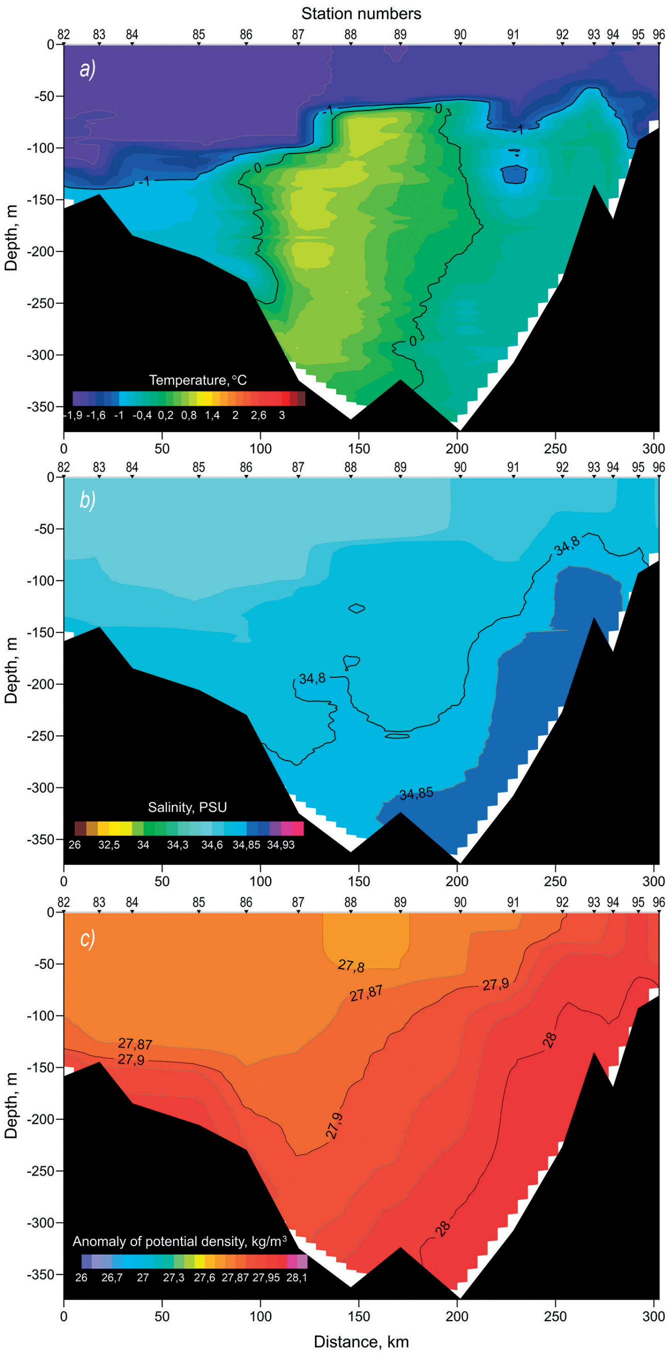

Fig. 4. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m³ relative to 1000 kg/m³ (*c*) at Section-III

Рис. 4. Вертикальное распределение температуры, °C (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м³ относительно 1000 кг/м³ (*c*) на разрезе-III

Vertical distribution of thermohaline properties at Section-II (Fig. 3) demonstrate two cores of warm water near the seabed. The narrow eastern core (stations 100—102) is located over the steep bottom slope and presumably represents the end product of mixing of BAW branches with shelf-origin dense waters. Sharp density gradient at 50 m over the slope excludes the possibility of deep reaching vertical convection. From the other hand, potential density in the cold-water pool, sitting on shelf (stations 97, 98), is about the same as potential density at the base of the slope. The warm core (0.25 °C) is located over the bottom slope near the seabed. Salinity in the warm core (34.90 PSU) is

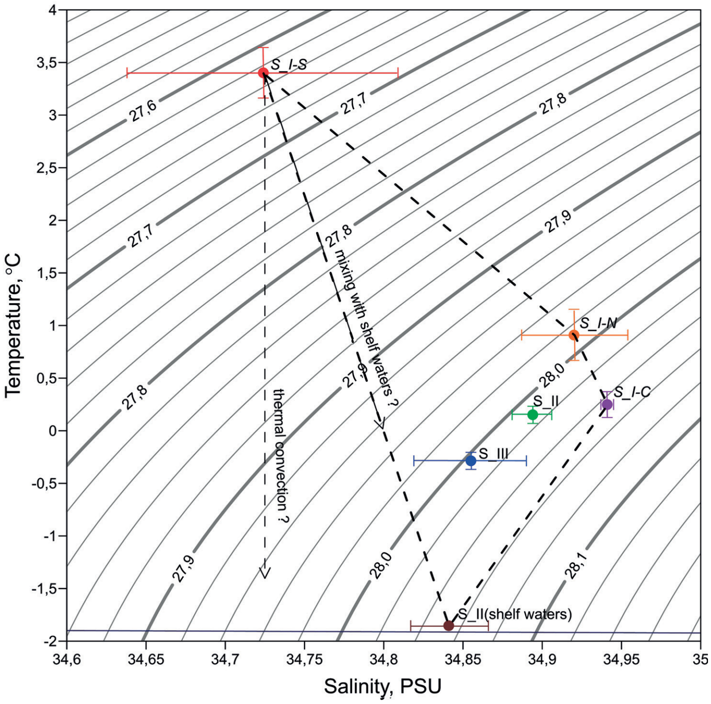

Fig. 5. *TS*-diagram, illustrating transformation of BAW between sections I — III. Color dots show mean temperature and salinity in the BAW core at sequential sections: red (section-I, southern BAW branch (S_I-S)); magenta (section-I, central BAW branch (S_I-C)); orange (section-I, northern BAW branch (S_I-N)); green (section-II (S_II)); blue (section-III (S_III)); brown (section-II, (S_II shelf waters)). The range of spatial variation in each point is shown by horizontal and vertical lines, which represent sample standard deviation (SSD). Navy-blue line shows freezing point temperature. Dashed lines show possible trajectories of BAW transformation between sections (see explanation in the text).

Рис. 5. *TS*-диаграмма, иллюстрирующая трансформацию БАВ между разрезами I — III. Цветные точки показывают среднюю температуру и соленость в ядре БАВ на последовательных разрезах: красный (разрез-I, южная ветвь БАВ (S_I-S)); пурпурный (разрез-I, центральная ветвь БАВ (S_I-C)); оранжевый (разрез-I, северная ветвь БАВ (S_I-N)); зеленый (разрез-II (S_II)); синий (разрез-III (S_III)); коричневый (разрез-II, (S_II шельфовые воды)). Диапазон пространственных изменений в каждой точке ограничен горизонтальными и вертикальными линиями, которые показывают среднеквадратическое отклонение (СКО). Темно-синяя линия обозначает температуру замерзания. Пунктирные линии показывают возможные траектории трансформации БАВ между разрезами (см. объяснение в тексте) substantially higher, than salinity in the southern branch, but slightly lower than salinity in the central and northern branches at Section-I. Mean salinity in the shelf waters at Section-II (34.84 PSU) is lower than salinity in the warm core.

At the Section-III the BAW also occupies the bottom slope of Novaya Zemlya (at stations 90 — 95). Thermohaline properties at this section are within the typical limits of BAW (–0.25... –0.5 °C, 34.86 — 34.88 PSU), known from earlier studies [18, 21, 22]. High potential density over the slope reaching the sea surface at station 95 points out that shelf convection and cascading may also contribute to the additional cooling of BAW in this region [20]. It should be noted, that the observed vertical distribution with sloping isopycnals also points out on strong baroclinic component of current in the upper water layer, directed. to the south-west, i.e. opposite to the general BAW propagation.

Described spatial changes of thermohaline characteristics of BAW between sections I, II, and III are illustrated in the TS diagram (Fig. 5). Specific color dots correspond to mean temperature and salinity in the BAW core at sequential sections, while brown dot shows mean properties of shelf waters at Section-II. The range of spatial variation in each point is shown by horizontal and vertical lines, which represent sample standard deviation (SSD). Thermohaline properties of BAW at sections II and III fall inside the polygon (limited by thick dashed line) with apexes in 4 points representing mean properties at Section-I and in the point, representing shelf waters at Section-II. This means that mixing of these source waters may theoretically produce end products, which represent BAW properties at sections II and III. However, very low potential density in the southern branch of BAW at Section-I (1027.62) requires at least strong cooling of this water on its pathway to the Section-II. This hypothetical temperature decrease, which is shown in Fig. 4 by thin dashed line, can be caused by progressing heat loss at the surface and thermal convection. Another possible option is mixing with shelf-origin dense water, which form over Novaya Zemlya shelf to the south of Section-II [14]. It is important to stress, that without some sort of preconditioning, admixture of waters from the southern branch in the BAW core at Section-II would not be possible due to large difference in potential density. From the other hand, without addition of some portion of waters from the southern branch, the observed BAW properties at sections II and III would not be reached.

Fram Strait branch of Atlantic Water transformation in the north-eastern region

The FAW flow, which enters the Barents Sea from the Kara Sea is distinguished at Section-III by positive temperature from the bottom to 75 meters between stations 87 and 90 (see Fig. 4*a*). Maximal temperature (0.92 °C) is observed at the depth 150 m, while salinity maximum (34.84 PSU) is located near the bottom (see Fig 4*b*). Vertically uniform potential density in the upper 100 m at stations 82 — 87 (see Fig. 4*c*) point out on convective mixing down to this depth, probably confirming formation of Shelf Atlantic Water (SAW) in this area [13].

According to summer measurements [23], the route of FAW from the Kara Sea crosses the northern part of Section-IV (between Ushakov island and southern shelf of Franz Joseph Land), and presumably, the northern part of Section-II (see Fig. 1). At the northern part of Section-IV relatively warm water (over –1 °C) occupies thin (50 — 75 m) bottom layer (see Fig. 6*a*). The most part of the water column (from the sea surface to 150 — 200 m) is filled with cold water with temperature slightly above the freezing point. Elevated salinity (34.75 — 34.78 PSU, see Fig. 6*b*) and maximal density

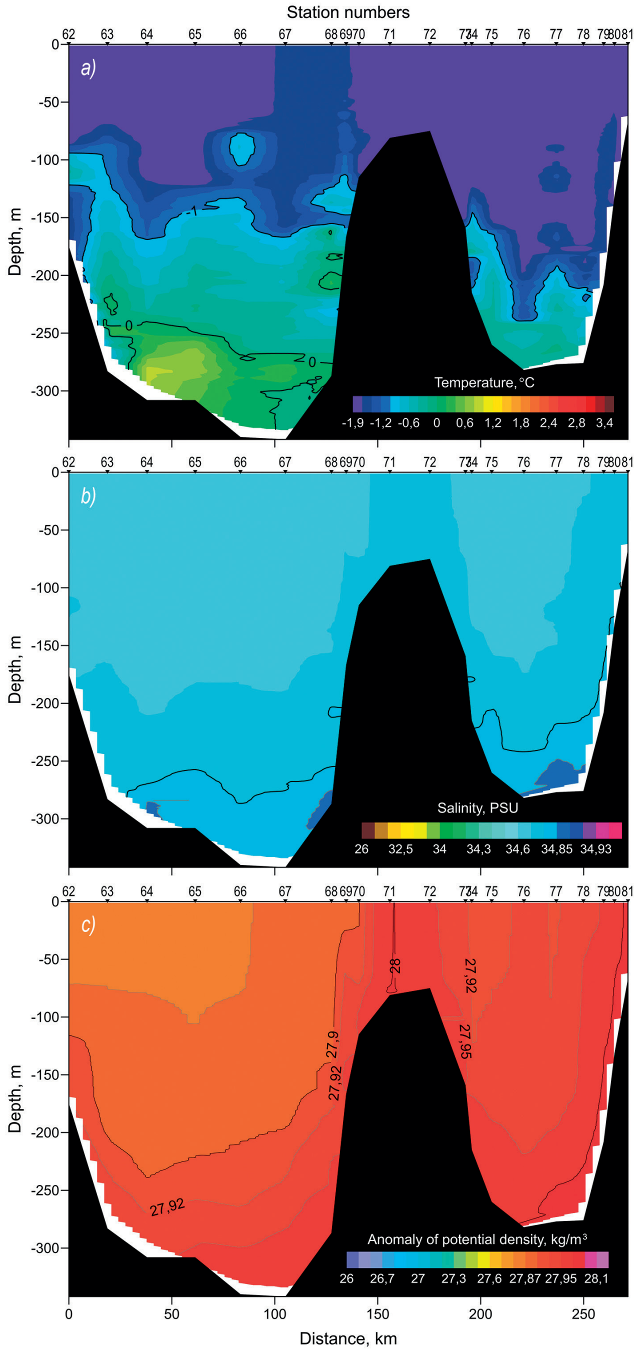

Fig. 6. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m^3 relative to 1000 kg/m^3 (*c*) at Section-IV

Рис. 6. Вертикальное распределение температуры, °C (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м^3 относительно 1000 кг/м^3 (*c*) на разрезе-IV

(1028.00 kg/m^3, see Fig 6*c*) is observed at the top of Ushakov bank (stations 71, 72) and over the shallow shelf (station 81). Described distribution of thermohaline properties at deep stations (75 — 78) points out that on the way between Section-III and Section-IV vertical convection penetrated through the warm core of FAW, and substantially reduced water temperature in the entire water column. Lower salinity at stations 75 — 78 (except thin bottom layer), compared with the salinity in the FAW core at Section-III, indicates that thermal forcing was the major driver of convection. Cascading of dense water from Ushakov Bank and from the shallow shelf of Franz Joseph Land, which is distinguished by sloping isopycnals, is a secondary mechanism, which contributes to modification of the deepest part of FAW at Section-IV.

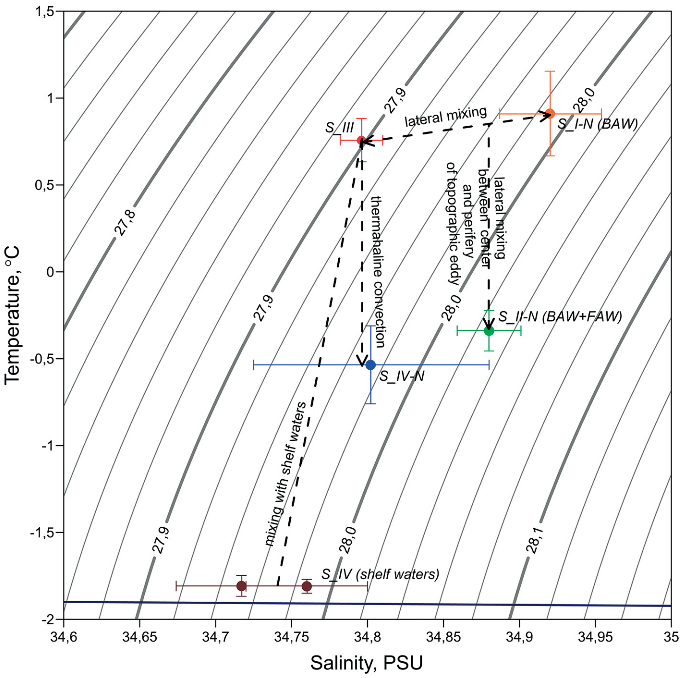

Fig. 7. *TS*-diagram, illustrating transformation of FAW, entering from the Kara Sea, between sections III, IV and II. Color dots show mean temperature and salinity in the FAW and BAW cores at sequential sections: red (section-III, FAW (S_III)); orange (section-I, northern BAW branch (S_I-N)); green (section-II, FAW+BAW (S_II-N)); blue (section-IV northern part, FAW (S_IV-N)); brown (section-IV, (S_IV shelf waters)). The range of spatial variation in each point is shown by horizontal and vertical lines, which represent sample standard deviation (SSD). Navy-blue line shows freezing point temperature. Dashed lines show possible trajectories of FAW transformation between sections (see explanation in the text)

Рис. 7. *TS*-диаграмма, иллюстрирующая трансформацию ФАВ, поступающей из Карского моря, между разрезами III, IV и II. Цветные точки показывают среднюю температуру и соленость в ядрах ФАВ и БАВ на последовательных разрезах: красный (разрез-III, ФАВ (S_III)); оранжевый (разрез-I, северная ветвь БАВ (S_I-N)); зеленый (разрез-II, ФАВ+БАВ (S_II-N)); синий (разрез-IV северный сегмент (S_IV-N)); коричневый (разрез IV, (S_IV шельфовые воды)). Диапазон пространственных изменений в каждой точке ограничен горизонтальными и вертикальными линиями, которые показывают среднеквадратическое отклонение (СКО). Темно-синяя линия обозначает температуру замерзания. Пунктирные линии показывают возможные траектории трансформации БАВ между разрезами (см. объяснение в тексте)

In the central part of Section-II there is wide area in between stations 106 and 111 with relatively warm (over –1°C) and salty (34.81 — 34.88 PSU) water from 75 m to the top of the bank at 200 m depth. Taking into account the present knowledge on the FAW and BAW possible pathways in this region of the Barents Sea [23], it can be anticipated that the observed distribution of thermohaline properties forms as a result of lateral mixing of the northern branch of BAW (see previous subsection) and FAW branch, which deviates to the south. The “dome” of warm and salty waters over the top of the bank probably indicates closed circulation (topographic eddy), formed by FAW and BAW branches. This local circulation causes ascent of water over the center of the bank and descent at its periphery. This hypothesis corroborates by deep reaching (200 m) “cones” of cold and relatively fresh water at stations 105 and 112, which reach substantially deeper than the marginal level of free gravitational convection.

Described transformation of FAW in the north-eastern Barents Sea is schematically shown at *TS*-diagram (Fig. 7). Thermohaline properties are shown in the same manner as on Fig. 4, where different colors represent specific water masses at sequential sections. Change of water properties between Section-III and the northern part of Section-IV is illustrated by two dash lines, representing thermal convection and mixing with shelf origin dense waters. Lateral mixing of FAW with the northern branch of BAW and further cooling of this product due to mixing with cold waters, descending at the periphery of topographic eddy, is shown by “T-shaped” dash lines.

Transformation of the Fram Strait branch of Atlantic Water entering through Franz-Victoria channel

“Initial” thermohaline properties of FAW entering the Barents Sea through Franz-Victoria channel were taken at Section-V, close to the deep “mouth” of the channel at the Eurasian continental slope (see Fig. 1). The branch of FAW, which separates from

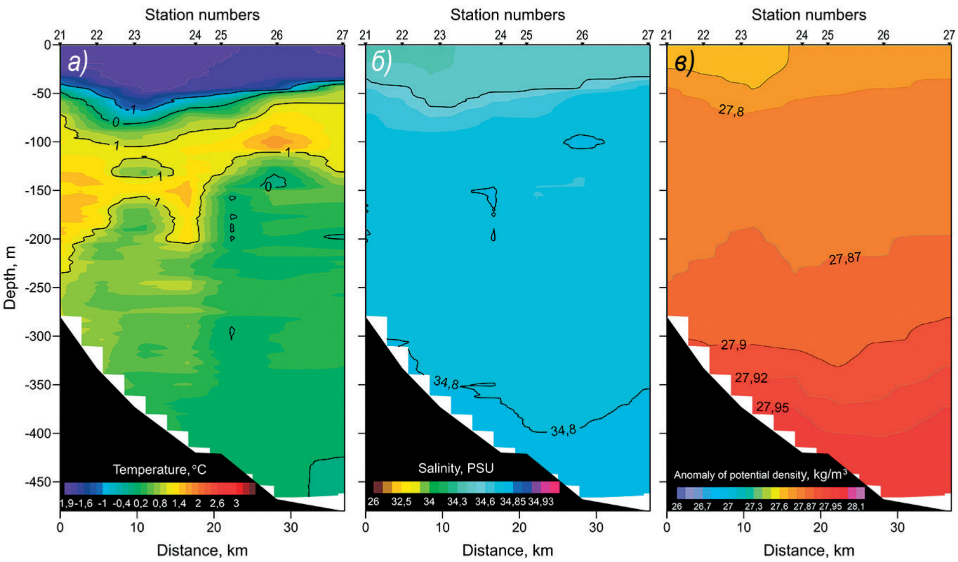

Fig. 8. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m^3 relative to 1000 kg/m^3 (*c*) at Section-V

Рис. 8. Вертикальное распределение температурыб °С (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м^3 относительно 1000 кг/м^3 (*c*) на разрезе-V the general eastward flow in the Eurasian Basin and enters Franz-Victoria channel is identified by temperature maximum (1.53 °C) at 150 m depth over the eastern flank of the channel (Fig. 8). Moving to the south along the eastern flank of the channel, part of this water makes cyclonic loop, returns to the Nansen Basin and finally merges with the main flow [24]. Another part of this water continues to the south and penetrates in the northern Barents Sea [25]. Traces of this water are identified by local temperature maximums (0.25 — 0.75 °C) and elevated salinity (34.80 — 34.85 PSU) near the seabed at sections IV (Fig. 6) and VI (Fig. 9).

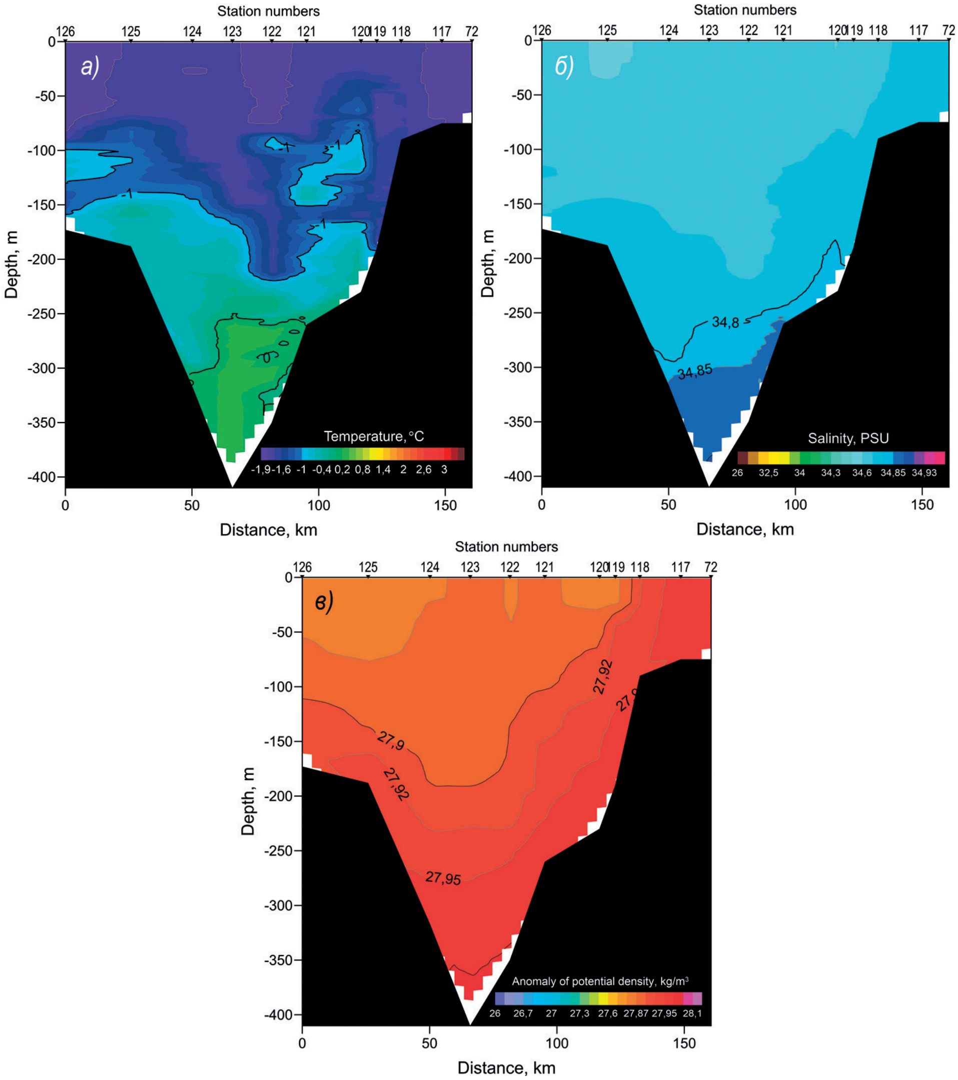

Fig. 9. Vertical distribution of temperature, °C (*a*), salinity, PSU (*b*) and anomaly of potential density, kg/m^3 relative to 1000 kg/m^3 (*c*) at Section-VI

Рис. 9. Вертикальное распределение температуры, °C (*a*), солености, ЕПС (*b*) и аномалии потенциальной плотности, кг/м^3 относительно 1000 кг/м^3 (*c*) на разрезе-VI

Transformation of the FAW, entering through Franz-Victoria channel, is shown at the *TS*-diagram in Fig.10. Contrary to changes, typical for other AW branches in the Barents Sea, temperature decrease in this case is accompanied by salinity increase. In the *TS*-plane such changes are directed almost along potential density gradient. Hypothetical explanation of this sort of changes may be mixing with cold and salty waters, which originate through haline convection under growing ice over shallow areas to the west of FJL [26]. Corresponding mixing line (thin dashed line) with such waters is shown in Fig. 10. However, to fit with this mixing line, shelf waters have to gain salinity over 35 PSU. Although salinification of shelf water up to 35.1 PSU in this region as a result of recurrent ice formation in polynyas is not impossible [27], during the survey the shelf water with such high salinity was not detected. Possible explanation of this fact is that by March, Franz-Victoria channel and surrounding shelves were completely covered by

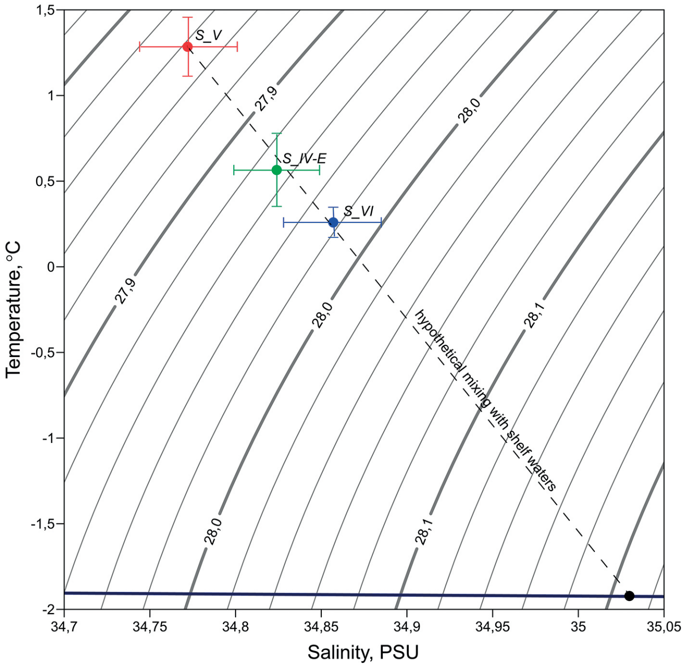

Fig.10. *TS*-diagram, illustrating transformation of FAW, entering from the Nansen Basin, between sections V, IV and VI. Color dots show mean temperature and salinity in the FAW core at sequential sections: red (section-V (S_V)); green (section -IV eastern part, (S_IV-E)); blue (section-VI (S_VI). The range of spatial variation in each point is shown by horizontal and vertical lines, which represent sample standard deviation (SSD). Navy-blue line shows freezing point temperature. Dashed line shows possible trajectory of FAW transformation between sections (see explanation in the text)

Рис. 10. *TS*-диаграмма, иллюстрирующая трансформацию ФАВ, поступающей через желоб Франц-Виктория, между разрезами V, IV и VI. Цветные точки показывают среднюю температуру и соленость в ядре ФАВ на последовательных разрезах: красный (разрез-V (S_V)); зеленый (разрез-IV восточный сегмент, (S_IV-E)); синий (разрез-VI (S_VI)). Диапазон пространственных изменений в каждой точке ограничен горизонтальными и вертикальными линиями, которые показывают среднеквадратическое отклонение (СКО). Темно-синяя линия обозначает температуру замерзания. Пунктирные линии показывают возможную траекторию трансформации ФАВ между разрезами (см. объяснение в тексте) ice [28]. Under ice-covered conditions dense water production on shelves is suppressed. Thence, one possible option is that the observed transformation of the FAW entering through Franz-Victoria channel could happen in early winter, when the ice was actively forming on and intensive ejection of salt in the water column could produce dense water with required properties over the vast shelf around Bely island. The other possibility is that the warm FAW observed near the bottom at sections IV and VI actually represents the remnants of FAW, which came from the north long before the survey. This hypothesis is in line with features of bottom topography (see Fig.1), showing that warm bottom water may be "trapped" in the deep southern and south-western corners of Franz-Victoria channel. In this case the observed changes actually represent temporal (annual/interannual?) variability of FAW properties.

DISCUSSION AND CONCLUSIONS

Hydrographic observations, carried out in March-May, 2019 during "Transarktika-2019" expedition allowed revisiting the issue of the Atlantic water transformation in the Barents Sea. Although this topic is rather traditional theme of oceanographic studies, based on field data and modelling there are still a number of questions, which are not perfectly clear. Among these questions is deeper understanding of the AW transformation in specific regions in winter, when the coverage by observations is scarce. In this study we performed analysis of CTD-data, collected in late winter-early spring in the north-eastern "corner" of the Barents Sea — the area with difficult access in the cold season due to high concentration of drifting ice.

Obtained results allowed specification of areas along the pathways of AW branches, where various types of open sea convection and cascading are likely to be the main agents in charge of AW properties change. The pathways of AW branches, which are in line with high resolution model simulation [29], along with proposed location of zones, where definite acting process is dominant, are schematically shown in Figure 11. The suggested scheme is based on the presented analysis and supplemental knowledge from existing publications, which considered AW transformation in the north-eastern part of the Barents Sea.

We distinguish several driving mechanisms, which control modification of the waters of Atlantic origin. These mechanisms are identified and discussed further on.

(1) Thermal convection, driven by fall-winter temperature decrease at the surface. This driver effectively works in the central and southern regions of the Barents Sea, which are located to the south of the winter ice edge. Intensive heat loss to the atmosphere decreases water temperature, but does not affect salinity. As a result, water cools down, its density increases and convection mixing penetrates deeper. Along the central branch of BAW, this thermal convective mixing reaches the seabed, producing a homogeneous water column with low temperature and high salinity.

(2) Thermohaline convection, driven by salinity increase in the surface waters as a result of salt ejection in the water column. This process is typical for the ice-covered regions, where temperature decrease to the freezing point is insufficient to overcome stable density stratification in the underlying water. Additional density increase occurs under growing ice. In the studied area this process is likely to play the key role in the modification of the FAW, entering from the Kara Sea. It is important to stress that density excess, required for convection, is mostly caused by cooling, while salinity increase provides only small addition to density increase. However, this small contribution by

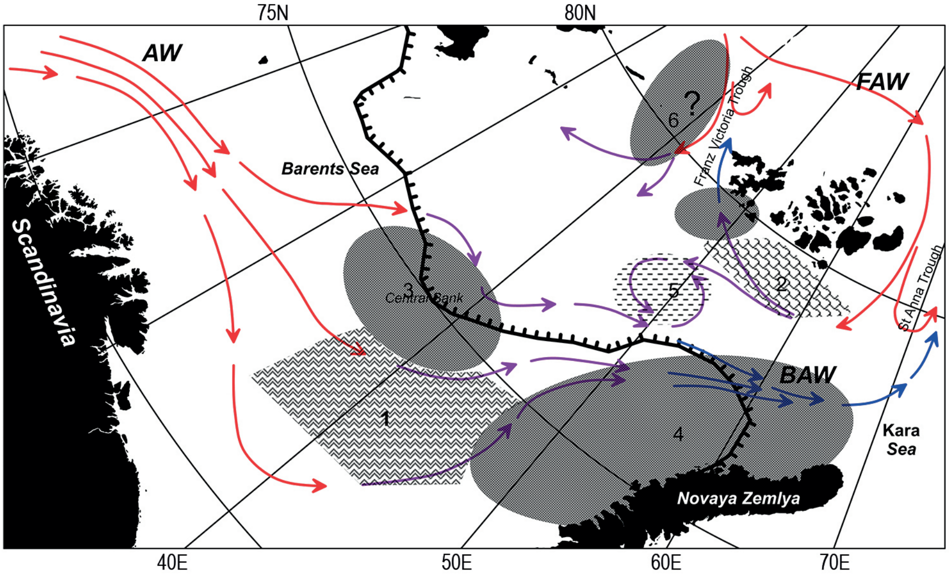

Fig. 11. Scheme of the AW branches in the Barents Sea and proposed location of zones, where definite transformation mechanism is dominant: (*1*) thermal convection; (*2*) thermohaline convection; (*3*) cascading of dense waters, originated through differential cooling; (*4*) cascading of dense waters, originated through ice formation and export; (*5*) enhanced lateral mixing over specific features of bottom topography; (*6*) cascading of excessively salty water, originated through ice formation in polynyas. Mean location of the ice edge with concentration 50 % in April, 2019 is shown by thick black line [28]

Рис. 11. Схема ветвей АВ в Баренцевом море и предполагаемое расположение зон, в которых доминирует определенный механизм трансформации: (*1*) термическая конвекция; (*2*) термохалинная конвекция; (*3*) каскадинг плотных вод, сформировавшихся в результате дифференциального охлаждения; (*4*) каскадинг плотных вод, сформировавшихся в результате ледообразования и последующего выноса льда на открытую воду; (*5*) усиленное боковое перемешивание над характерными особенностям рельефа дна; (*6*) каскадинг высокосоленой воды, сформировавшейся в результате ледообразования в полыньях. Среднее положение кромки льда со сплоченностью 5 баллов в апреле 2019 г. показано жирной черной линией [28]

salinization is crucial to initiate mixing through the FAW and changing its properties between sections III and IV (see Fig. 7).

(3) Cascading of dense water from shallow regions, preconditioned by cooling of the water column from surface to bottom. Typical example of this mechanism is observed over and around the Central Bank. Due to topographic control [20], the water over relatively shallow Central Bank in the fall-winter season cools faster than the water in the adjacent deep basins. This differential cooling results in formation of density gradient between shallow and deep waters, which forces gravitational leakage of dense (cold) waters down slopes of the Central Bank. This cold water mixes up with Atlantic water (carried in the central and northern branches of BAW). This process does not noticeably affect salinity.

(4) Cascading of dense water from shallow regions, preconditioned by salinization of the water column from surface to bottom as a result of ice formation. This mechanism is very well recognized as the major one for Arctic shelves [30]. In the studied area this

mechanism efficiently works for modification of BAW on its path along the western shelf of Novaya Zemlya. This area is located within quasi-permanent marginal ice zone (MIZ), which provides favorable conditions for occasional export of newly formed ice on the open warm water [14]. Recurrent ice formation and its export leads to fast salinization/densification of shallow waters [14]. While on summer surveys there only tracks of this process [30], during the winter survey, the developed "tongues" of cold and dense waters spreading from Novaya Zemlya shelf to the base of the nearby deep basins are explicitly observed (see Figs 3 and 4). According to the obtained results, this process is the ultimate one in changing of BAW thermohaline properties to those, observed at the entrance to the Kara Sea (north of Cape Zhelania).

(5) Lateral mixing of BAW and FAW with surrounding waters over specific features of bottom topography. The "dome" of warm and salty waters over the top of the bank on the way of northern branch of BAW and southern branch of FAW, probably indicates closed circulation (topographic eddy), formed by FAW and BAW branches (see Fig. 3). Local closed circulation causes ascent of water over the center of the bank and descent at its periphery. Lateral mixing of waters between warn and salty core of the Atlantic origin waters with cold and freshened peripherical waters may provide gradual cooling and freshening in the AW core over the bank.

(6) Cascading of dense water from shallow regions, preconditioned by excessively strong salinization of the water column from surface to bottom as a result of ice formation. This process may be in charge of modification of FAW entering to the Barents Sea from the North through Franz-Victoria channel. Although, during the expedition shelf waters with required salinity (over 35 PSU) were not found at shallow shelves around Franz-Victoria channel, the possibility of formation of extremely salty shelf waters in this region was substantiate in earlier studies [27]. Hypothetical explanation is that the observed transformation of the FAW entering through Franz-Victoria channel could happen in early winter, when the ice was actively forming on and intensive ejection of salt in the water column could produce dense water with required properties over the vast shelf around Bely island. Another hypothesis is that FAW entering through Franz-Victoria channel is "trapped" in the deep southern and south-western corners of Franz-Victoria channel in the bottom layer. In this case the observed during the cruise changes of this branch of FAW actually represent temporal (annual/interannual?) variability of properties.

Based on the shipborne winter measurements in the Barents Sea we identified specific areas in the north-eastern part of the sea, where particular mechanisms might contribute to the Atlantic Water transformation. An advantage of winter measurements is that action of several of the discussed transformation mechanisms was explicitly revealed in the CTD-data at sequential sections. However, some of the proposed conclusions are only hypothetical (cannot be directly confirmed by the obtained data), and, therefore, should be considered with caution.

Competing interests. The authors have no competing interests

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Трансформация атлантической воды в северо-восточной части Баренцева моря в зимний сезон (расширенный реферат)

Гидрологические наблюдения, выполненные в марте–мае 2019 г. во время экспедиции «Трансарктика-2019» на борту НЭС «Академик Трёшников», позволили изучить механизмы трансформации Атлантической воды (АВ) в Баренцевом море. Хотя эта тема является довольно традиционной при изучении океанографии Баренцева моря, сохраняется ряд вопросов, которые требуют прояснения. Среди этих вопросов можно выделить более глубокое понимание процессов трансформации АВ в определенных районах моря в холодное время года, когда количество натурных наблюдений ограничено. В данном исследовании был проведен *TS*-анализ гидрологических профилей, выполненных в северо-восточном регионе Баренцева моря — области, в которой зимние полевые исследования затруднены из-за сложных ледовых условий. Полученные результаты позволили определить зоны, расположенные вдоль ветвей распространения АВ, где различные типы вертикальной конвекции и каскадинга являются доминирующими механизмами, обеспечивающими

трансформацию АВ по мере их движения. По результатам анализа были выделены следующие механизмы трансформации:

1. Термическая конвекция, вызванная сезонным понижением температуры на поверхности. Этот механизм эффективен в центральных и южных районах Баренцева моря, которые круглогодично находятся к югу от кромки дрейфующего льда. Интенсивные теплопотери в атмосферу уменьшают температуру воды, но не влияют на ее соленость. Охлаждение поверхностного слоя вод ведет к возрастанию плотности и конвективному перемешиванию, которое может распространяться до дна. В результате образуется однородная по вертикали водная масса с пониженной температурой и высокой соленостью.

2. Термохалинная конвекция, обусловленная увеличением солености поверхностных вод в результате выпадения соли в воду при ледообразовании. Этот процесс характерен для областей, покрытых льдом, где уменьшения температуры до точки замерзания недостаточно для преодоления устойчивой плотностной стратификации. Дополнительное увеличение плотности происходит под нарастающим льдом, следствием чего является вертикальное конвективное перемешивание, приводящее к охлаждению слоя воды, охваченного перемешиванием, и незначительному распреснению. Последнее связано с тем, что соленость АВ, как правило, больше солености верхнего перемешанного слоя, даже после увеличения его солености в процессе ледообразовании.

3. Каскадинг плотной воды из мелководных областей, обусловленный ускоренным охлаждением толщи воды в мелководной зоне. При одинаковой теплоотдаче с поверхности моря вертикальное перемешивание в мелководной зоне быстрее достигает дна. Вследствие этого толща воды в мелководной зоне охлаждается быстрее, чем в соседнем более глубоководном районе. Такое неоднородное охлаждение приводит к образованию градиента плотности между расположенными рядом мелководной и глубоководной зонами, что вызывает гравитационное стекание плотных (холодных) вод вдоль уклонов рельефа дна.

4. Каскадинг плотной воды из мелководных районов, обусловленный осолонением толщи воды в мелководной зоне в процессе образования льда. Непрерывное образование льда и его вынос в прикромочную ледовую зону приводит к быстрому осолонению и уплотнению воды в мелководной зоне. В результате этого формируется горизонтальный градиент плотности, обеспечивающий гравитационное стекание уплотненных вод вдоль уклонов рельефа дна.

5. Боковое перемешивание АВ с окружающими более холодными водами, обусловленное формированием замкнутых циркуляций над неоднородностями донной топографии.

6. Каскадинг плотной воды из мелководных районов, обусловленный очень сильным осолонением толщи воды от поверхности до дна в результате продолжительного образования льда в периодически открывающихся полыньях в одном и том же районе.

В случаях, описанных в п. 3, 4 и 6, стекающая плотная вода смешивается с АВ на глубине, где плотность стекающей воды выравнивается с плотностью АВ, что приводит к локальному изменению термохалинных характеристик в зависимости от глубины и параметров стекающих вод.