River run-off influence on the water mass formation in the Kara Sea

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Abstract

The Kara Sea is a region with highly variable physical and biogeochemical processes. The considerable influence of freshwater inflow means that the Kara Sea is well stratified throughout the year. Water column structure of the sea is very complex and changeable. The river plume area in the central part of the sea constitutes a vast frontal zone where waters of different origin interact and mix. Historical and new data obtained during the Russian-German expeditions are used to develop the enumeration of the main types of water masses in the Kara Sea. Water masses are distinguished by different temperature and chemical and biological properties. Oxygen, silicon and other chemical tracers proved to be very useful for the study of the mosaic and multilayered structure of the water column. A great number of water masses in the Kara Sea can be separated into several types according to their position in the structural zones and places and time of their formation. River run-off influence on the water mass formation occurs in different ways, the main of those are: thermal influx, salinity decreasing (freshening), an additional import of dissolved and suspended organic and inorganic matters into the sea system, and pycnocline formation because strong stratification impedes energy and matter exchange between different layers of water.

1 Introduction

The Kara Sea is located far to the north from the Polar circle on the shallow Siberian shelf. Climate conditions are severe and the sea is covered by ice during most part of the year. The shelf is indented from the north by two deep troughs: the Saint Anna trough (maximum depth is 600 m) and the Voronin Trough (depth up to 450 m). The Central Kara Plateau is located between the troughs. The narrow and deep Novozemelskaya depression (depth up to 420 m) stretches along the eastern coasts of the Novaya Zemlya archipelago. Numerous islands are concentrated mostly in the central and northeastern parts of the sea (Atlas of the Arctic, 1985). The Kara Sea connects with the adjacent Barents and Laptev seas and has an open boundary with the Arctic Basin.

The two largest Siberian rivers (Ob and Yenisei) and a great number of medium and small rivers bring into the sea about 1350 km^3 of water and more than 150 million tons of suspended and dissolved organic and inorganic matter annually (Ivanov, 1976; Gordeev et al., 1996).

As a result of highly variable hydrometeorological, ice, and biological conditions a multilayered and mosaic water column structure forms in the Kara Sea. The basic element of

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the structure is a water mass – a volume of water having “common formation history” (Tomczak, 1999) and “possessing during a long time almost constant and continuous distributions of physical, chemical, and biological characteristics, constituting a united complex” (Dobrovolsky, 1961). These physical definitions were given for oceanic water masses and implied a water mass as a big volume of water. In the shallow Arctic seas, we deal with water masses having relatively small volumes (sea, regional, and local water masses), this allows us to simplify the cumbersome common definition. We shall name as a water mass an aggregate of single volumes of water which are similar by temperature, chemical composition, and biological signs. Moreover, the similarities are the result of common geographical, hydrometeorological and biological conditions at which water properties are formed.

According to suggested earlier classifications (Nikiforov and Shpaikher, 1980; Rusanov et al., 1979), there are six water masses in the Kara Sea, namely: River Waters, Surface Arctic Waters of the Kara Sea, Barents Sea Waters, Winter Surface Waters, Deep Atlantic Waters and Bottom Waters. The word “waters” was used as a synonym of the term “water mass”, not a type of water masses.

The main aim of this article is to show that even the enumeration of the main types of water masses in the Kara Sea is considerably larger than suggested before. River run-off influence on water mass formation in the Kara Sea is considered in the discussion part of the article. It was made an attempt to apply the fundamental thesis of Stepanov’s theory about the structure and structural zones of the World Ocean (Stepanov, 1983) to the shallow Kara Sea. The water column of the Kara Sea was divided into three structural zones, namely: the surface structural zone, where processes on the boundary between sea and atmosphere (or ice) influence the water mass formation; the bottom structural zone, where bottom sediments and bottom topography influence the water mass properties; and the intermediate structural zone which is located between the above mentioned structural zones. It is necessary to note that there are some regions in the shallow Kara Sea where the water column may be homogeneous from the surface to the bottom either all year round or during a part of the year. The intermediate structural zone in such regions is absent.

The enumeration of the main types of water masses in the Kara Sea with short descriptions of their formation history and their distinguishing physical and chemical properties are given in the article. A name of type reflects genetic properties (place and time of formation) and the location in the structural zones of water masses belonging to the given type.

2 Data

The main types of water masses were assigned on the background of temperature, salinity, oxygen, silicate, phosphate, nitrate, pH, and alkalinity distributions in the Kara Sea. The data were obtained during Russian and international expeditions from 1906 till 2000 and were compiled in the US-Russian Hydrochemical Atlas of the Arctic Ocean (Colony et al., 2002). The locations of oceanographic stations and their temporary distribution are shown in Figure 1. The total number of stations in the data set is 15738. Oxygen was measured at 8071 stations; silicate – at 5791 stations; phosphate – at 2794 stations; nitrate – at 573 stations; pH – at 5895 stations; and alkalinity – at 1883 stations. Measurements were carried out at the standard levels (depths) in the Kara Sea (0, 5, 10, 15, 25, 50, 75, 100, 150, 200, 250, 300, 400, 500, and near bottom), sometimes there were additional levels. The data were subject to rigid quality control using automatic range check algorithms as well as extensive visual checks by data quality experts.

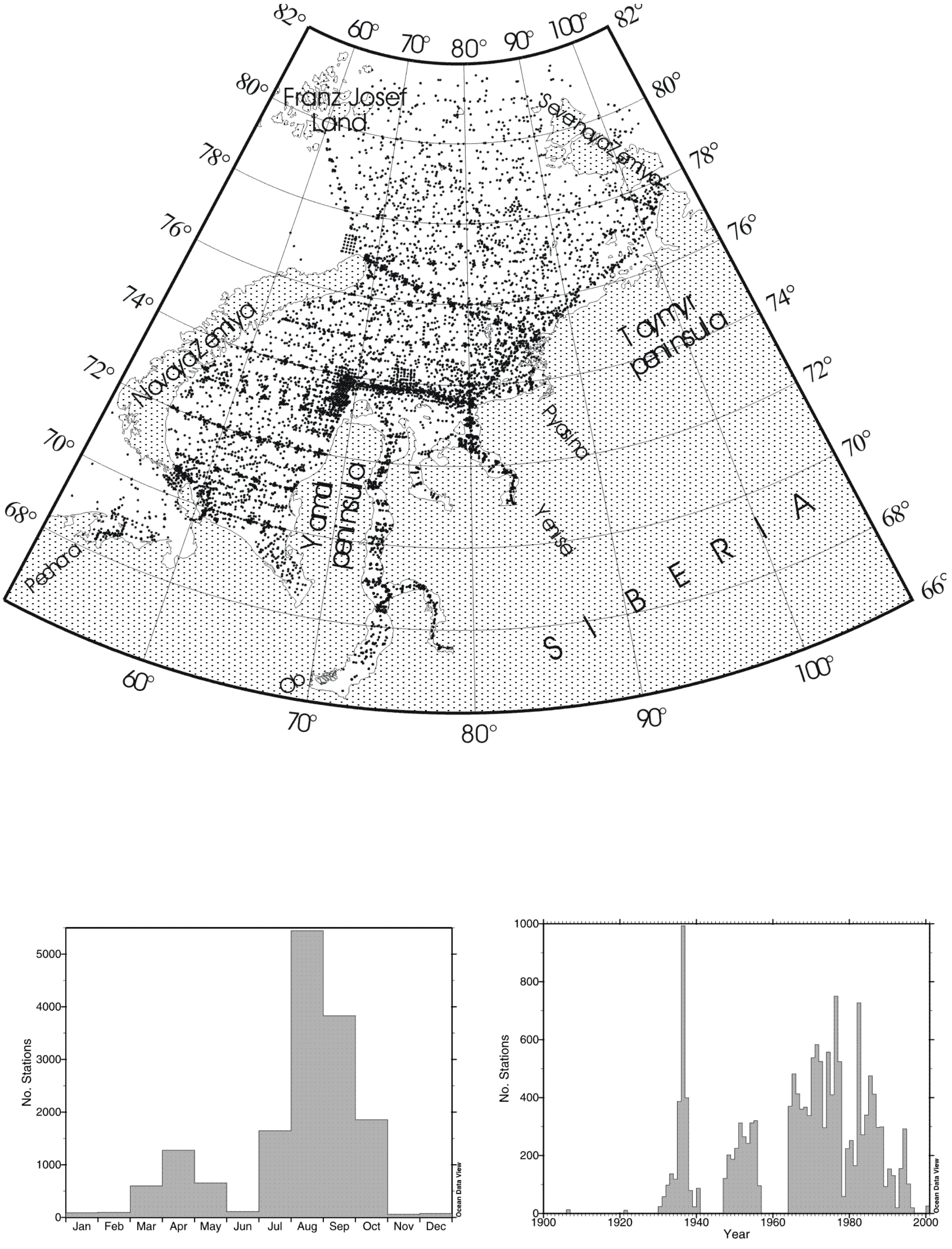


Fig. 1: Spatial and temporal distributions of oceanographic stations occupied in the Kara Sea from 1906 till 2000.

The data set was analyzed by the so-called expert method (Stepanov, 1974), which simultaneously analyzes the spatial distributions of all available parameters. Extremes and high gradient areas of the parameters were considered as properties of water masses and boundaries between water masses, respectively. Criteria are different for different types of water masses, and they are designated qualitatively, possible ranges of temperature, salinity, nutrients, and other parameters are pointed out for some types of water masses. Ocean Data View software (Schlitzer, 2002) was used for data visualization, data selection, and to construct maps, profiles, and transects.

3 The Main Types of Water Masses in the Kara Sea

3.1 The river water masses

The southern regions of the Ob and Yenisei gulfs are occupied by the River Water Masses. Temperature, chemical and biological properties of river water change during the annual cycle. Total mineralization and nutrient concentrations are highest at the end of winter; minimum values of these parameters are observed during the spring flood. In spite of the differences in the thermal, water, chemical, and biological regimes of the Ob, Yenisei, Pyasina, and other rivers flowing into the Kara Sea, their water masses can be approximated to one type. The main criteria for such approximation are a low mineralization (less than 1 g/l) and the typical ion composition which characterize the main Arctic rivers (Gordeev et al., 1996). However, it is necessary to distinguish the Summer River Water Masses (Figs. 2 and 3) and the Winter River Water Masses (Figs. 4 and 5) because the differences of their properties are obvious. Moreover, so-called, “stagnant” or “mortal” winter water masses are formed in the southern regions of the Ob Gulf and sometimes in the Yenisei Estuary. These kinds of river water masses are characterized by deep oxygen deficit (sometimes anoxia) and high nutrient concentrations (Rusanov et al., 1979).

3.2 The estuarine water masses

The Estuarine Water Masses are formed in the northern part of the Ob Gulf, in the Yenisei and Pyasina gulfs as a result of interaction between river and sea waters. The water column is strongly stratified in these regions. And there are three structural zones there. In summer, the surface structural zone consists of the Estuarine Summer Surface Water Masses. Their salinities usually do not exceed 10, the highest temperature is about 13 °C, silicate concentrations are very high (100-150 µmol/l). These water masses are saturated by oxygen up to 90-95%. The life spans of the Estuarine Summer Surface Water Masses are very short ranging from a few days to a few weeks.

The intermediate structural zone constitutes the pycnocline where different Estuarine Intermediate Water Masses alternate vertically. The water mass properties are formed at different time as a result of mixing with overlaying waters and by influence of riverine influx of suspended matter.

The bottom structural zone consists of the Estuarine Bottom Water Masses. These are very cold winter water masses generally having negative temperatures and salinity range from 25 up to 33.5. However, it is possible to observe some bottom water masses having positive temperature (up to 5 °C) and salinities from 10 to 20 in the Ob Gulf and the southern regions of the Yenisei Gulf at the end of summer.

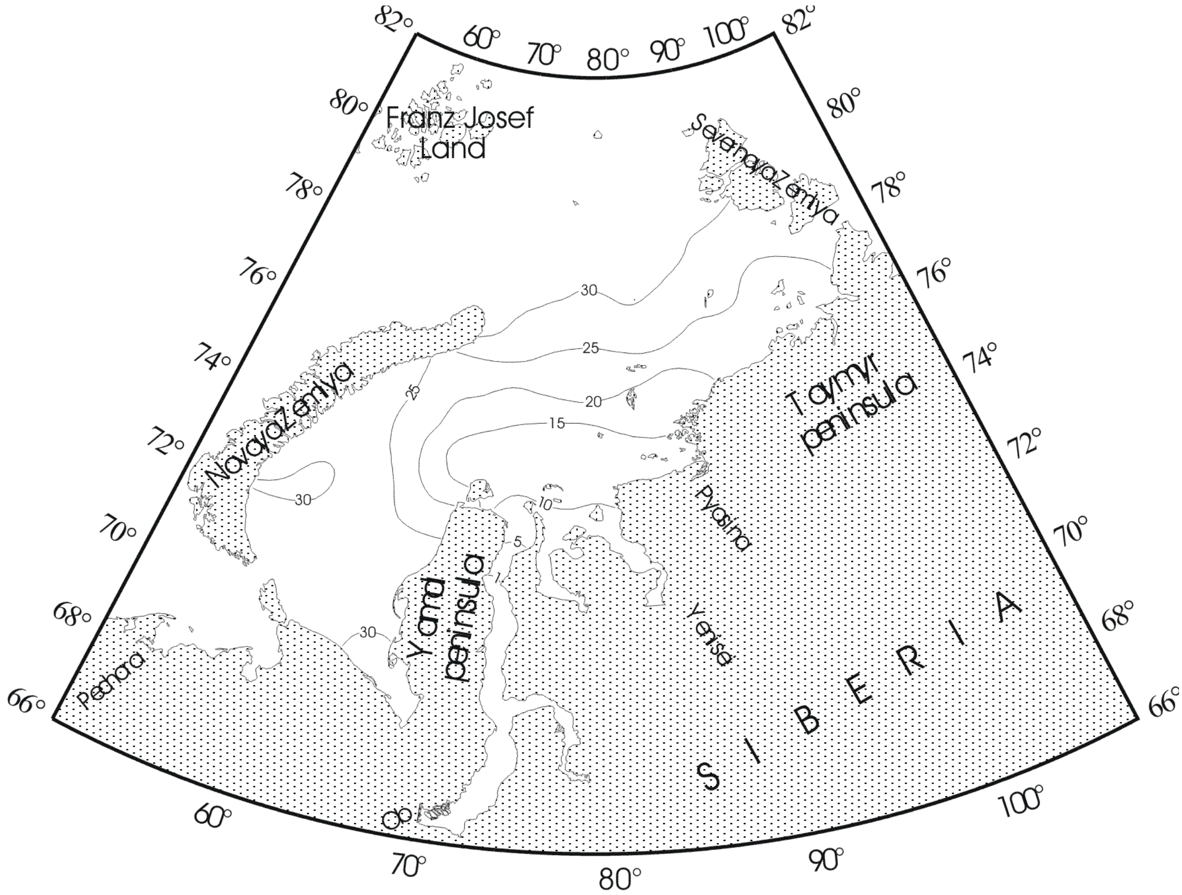


Fig. 2: An average salinity distribution at the surface of the Kara Sea in summer (August-September). Ocean Data View software was used for averaging and gridding.

The Estuarine Bottom Water Masses are usually characterized by high nutrient and low oxygen concentrations. Nevertheless, it is possible to recognize relatively well-ventilated water masses spreading from the north into the Ob and Yenisei gulfs along the western slopes of the underwater valleys at the northern parts of the gulfs (Pivovarov, 2000). Water masses of both types can be situated both in the intermediate and bottom structural zones. Their positions depend on the water density and the bottom topography in the estuaries.

3.3 The river plume water masses

The river plume area occupies all central part of the Kara Sea from the estuaries to the northern end of Novaya Zemlya archipelago in summer. It is assumed that the boundary of this huge area is approximated by the salinity 25 isoline at the sea surface (Fig. 2). It is considered however that silicate distribution (Fig. 3) shows the river plume area at the surface of the sea more evident and correctly because low surface salinity can be caused by melting of ice too. Isoline 10 µmol/l of silicate concentration is usually used as a boundary of the river plume (Rusanov et al., 1979). Both classifications using salinity and silicate give approximately the same results if a long time data set is used (Figs. 2-5).

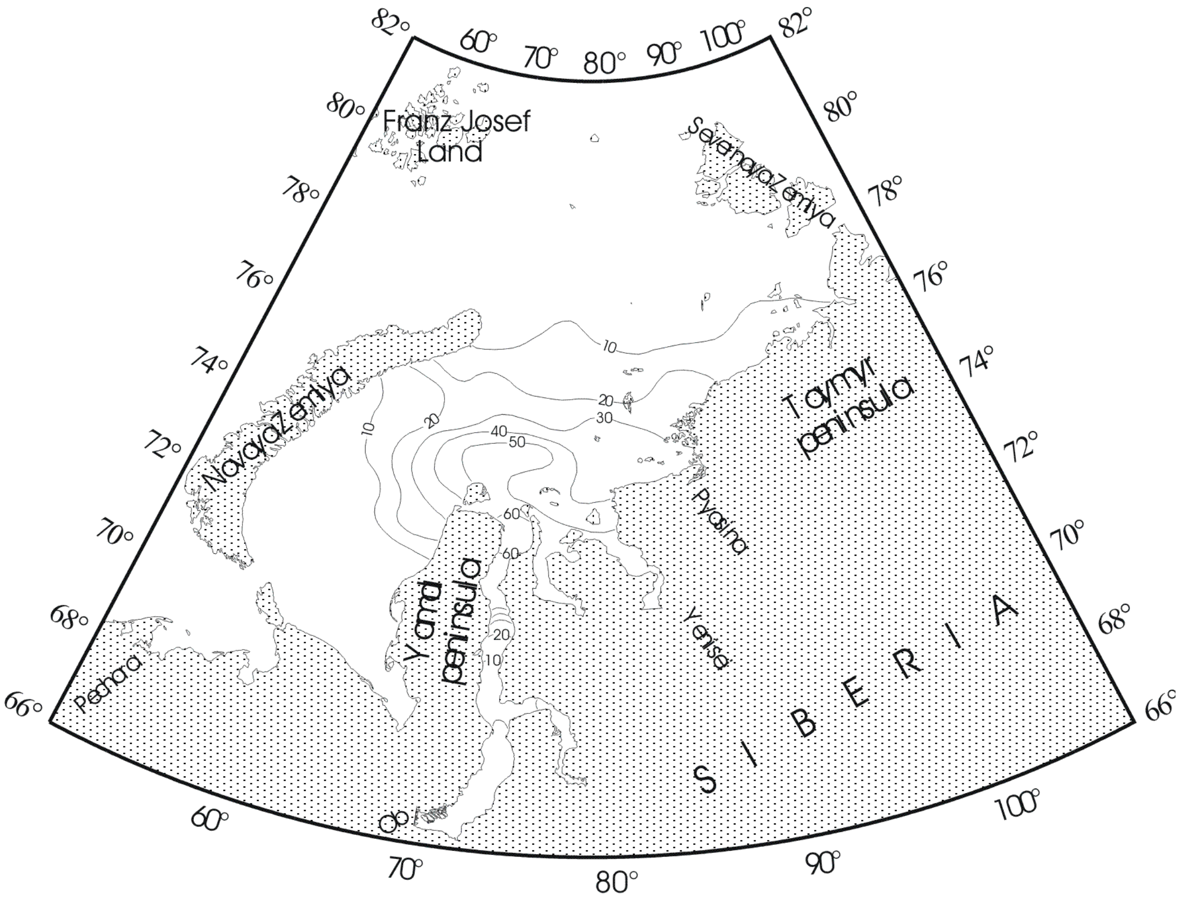


Fig. 3: An average silicate (µmol/l) distribution at the surface of the Kara Sea in summer (August-September). Ocean Data View software was used for averaging and gridding.

The river plume area constitutes as a matter of fact a vast frontal zone with a number of hydrological fronts, which change their locations according to hydrometeorological conditions. The main transformation of matters imported by rivers occurs in this area. Melting of ice adds same amount of matter into the river plume system. There are many water masses with small volume having different physical, chemical, and biological properties in the surface structural zone in summer. Differently high silicate concentrations can be used to distinguishing between the water masses.

In winter, the river plume area constitutes a narrow belt along the coastline, if the same criteria as used in summer are used to set the boundary (Figs. 4 and 5). The River Plume Winter Surface Water Masses have temperatures near the freezing points for given salinities. Phosphate concentrations increase and range from 0.5 to 1.0 µmol/l. The rest of the central part of the sea is occupied by the surface water masses having salinity higher than 30, and silicate concentrations less than 10 µmol/l (Figs. 4 and 5).

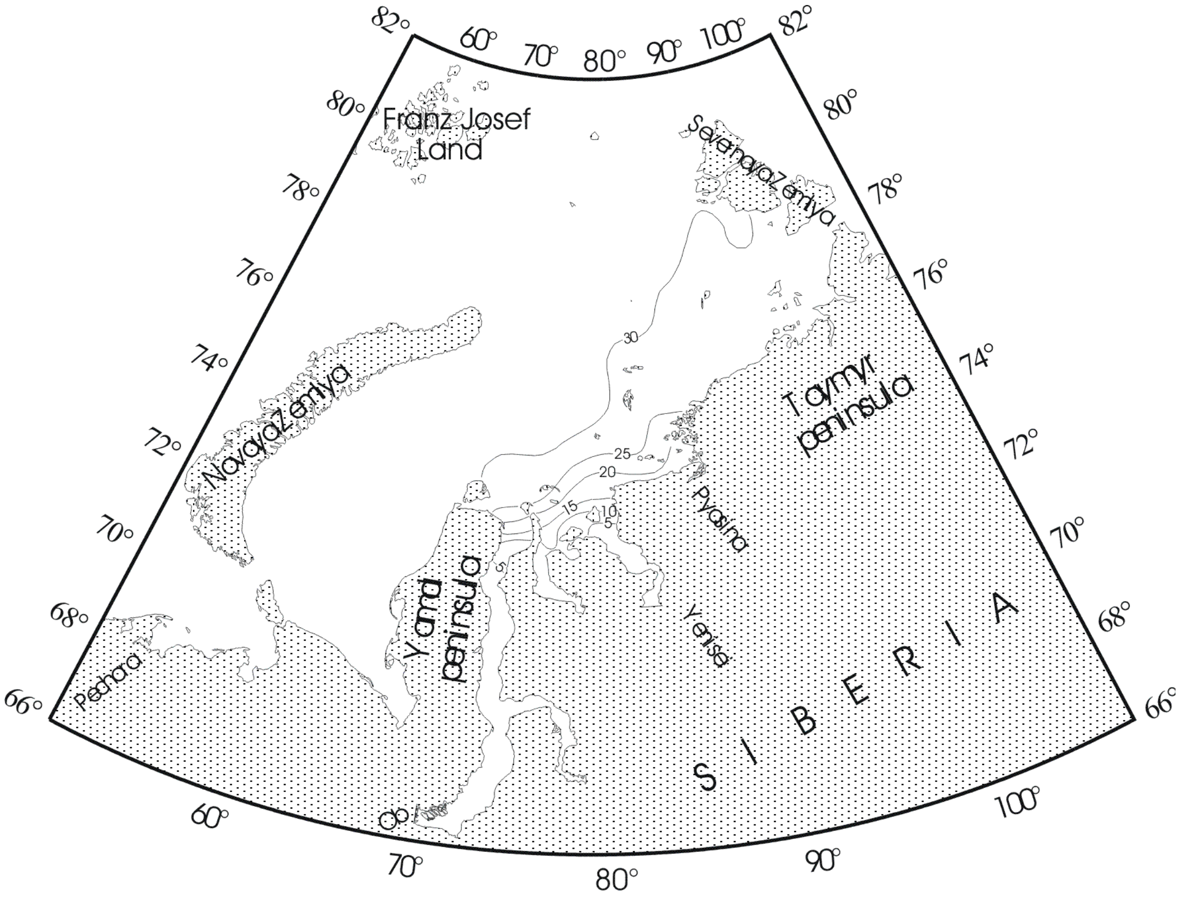


Fig. 4: An average salinity distribution at the surface (5 m depth) of the Kara Sea in winter (March-May). Ocean Data View software was used for averaging and gridding.

There are many intermediate water masses, which are differed by physical and chemical properties in this part of the sea both in summer and winter. As a rule, the water masses have negative temperatures that show their winter origin. Salinity, phosphate, and nitrate concentrations dramatically increase toward the bottom. However, silicate concentrations in the intermediate water masses are significantly less than they are in the surface water masses. It is possible to determine the places of formation, the hydrometeorological, ice and biological conditions at the time of the water masses formation. The water masses, which were formed under fast ice, are characterized by oxygen deficit and high nutrient concentrations. Well-ventilated water masses are formed in the polynyas. The water masses that are formed in the zone of drift ice are more homogeneous and occupy larger volumes. The most dense water masses accumulate and stagnate in small bottom depressions; they are characterized by deep oxygen deficit (hypoxia). The most complicated multilayered vertical structure is observed at the hydrological fronts.

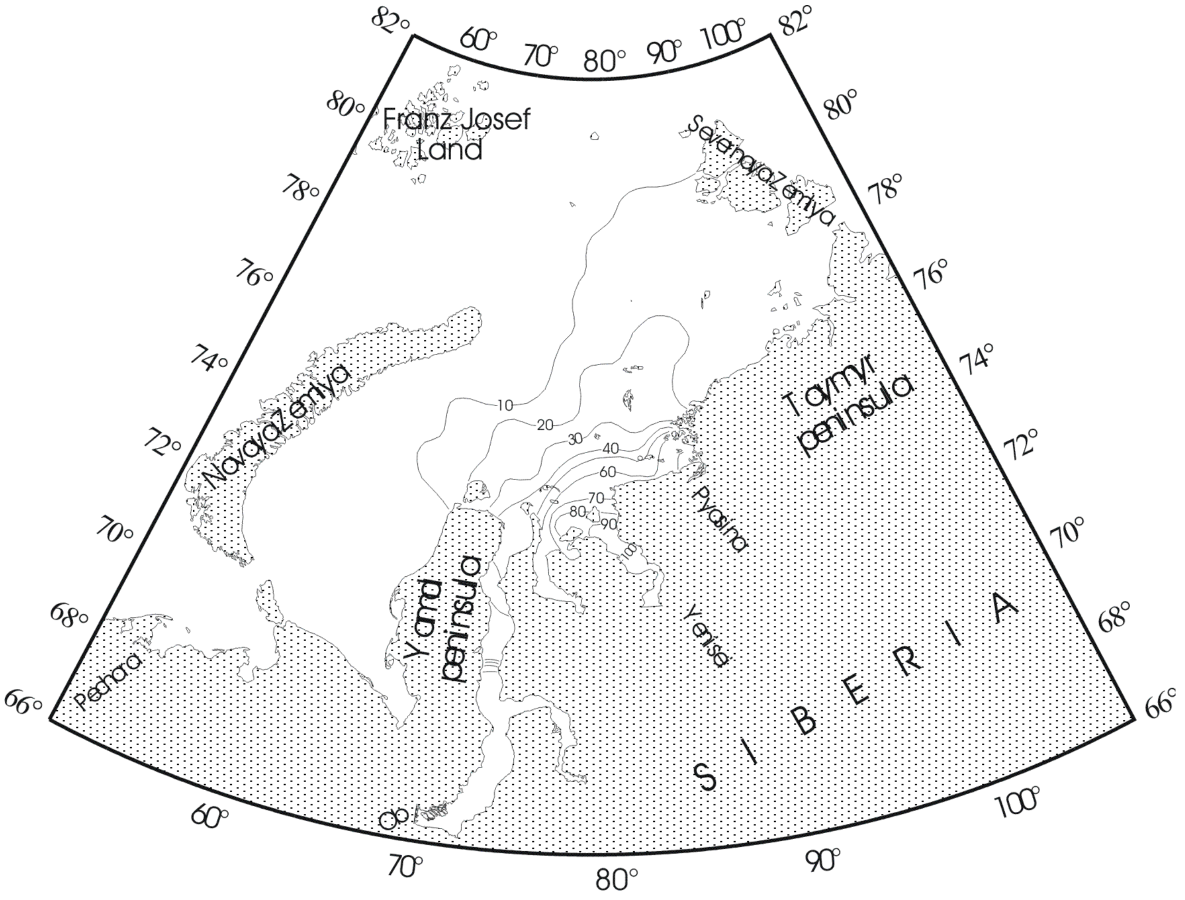
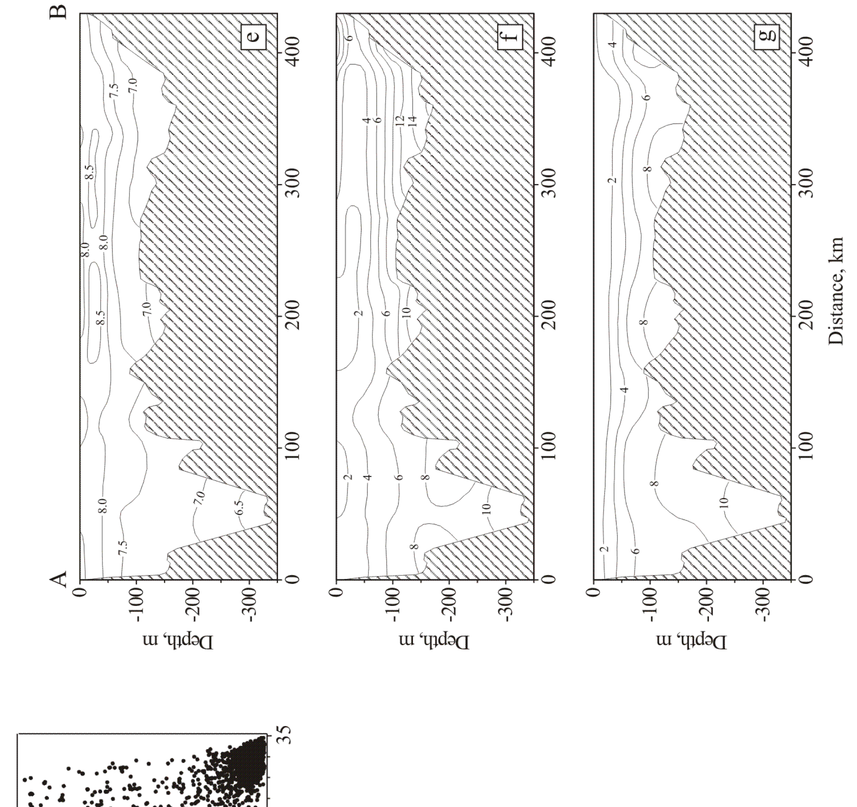


Fig. 5: An average silicate (µmol/l) distribution at the surface (5 m depth) of the Kara Sea in winter (March-May). Ocean Data View software was used for averaging and gridding.

3.4 Water masses of the southwestern part of the Kara Sea

The summer surface water masses in the southwestern part of the sea are freshened by melting of sea ice. Their salinity usually ranges from 28 to 32. In those regions near the Karskie Vorota (Kara Gates) where the influence of Pechora Sea waters is noticeable (70°25’-70°36'N, and 58°36’-59°20'E), salinities are 23 – 26. The surface water masses in the Baydaratskaya Bay have salinities from 20 to 25. Salinity of the surface mixed layer may be less than 3 near melting ice edges at the beginning of August. Temperature ranges from 0 up to 15 °C. Nutrients are almost absent in the surface structural zone in summer; even silicate concentrations are less than 5 µmol/l. Oxygen saturation ranges between 100 and 105%. Low values of alkalinity coefficient (Alk/S) confirm the absence of any noticeable influence of river run-off on the summer surface water masses in that part of the Kara Sea. River run-off influence is very weak even in the regions near the Karskie Vorota and Yugorsky Schar (strait) (69°45’-70°36'N, and 58°36’-61°10'E), through which the Pechora Sea water masses come into the Kara Sea.

In winter, the thickness of the surface structural zone as a rule increases up to 20 m, but near the Karskie Vorota it does up to 60 m. Temperatures of the winter surface water masses are approximately equal to freezing points. Salinity under drift ice ranges from 32.8 to 34.4 however salinities under fast ice in the shallow regions can be higher.


a
b
c
d
e
f
g
Novaya Zemlya
Yamal peninsula
A
B
50°
60°
70°
74°
72°
70°
60°
Temperature, °C
Salinity
Depth, m
Distance, km
0
100
200
300
400
-100
-200
-300
20
25
30
35
8
6
4
2
0
-2
2.0
0
-1.0
-1.5
34.0
34.5
33.0
31.0
30.0
8.0
8.5
7.5
7.0
6.5
2
4
6
8
10
12
14

Silicate concentrations are usually less than 10 µmol/l, oxygen concentrations range from 7.9 to 8.5 ml/l, those approximately correspond 92 – 100% of saturation with given temperatures and salinities.

The intermediate structural zone is stratified and has a well pronounced multilayered assemble of the water masses that has been formed in the Kara Sea in winter with some addition of the Barents Sea and Pechora Sea water masses (Fig. 6).

A striking peculiarity of the intermediate structural zone in summer is a 10 – 15 m thick layer super saturated in oxygen in the upper pycnocline (Fig. 6e). This cold, super saturated, and nutrient depleted waters are supposed to be formed in the southwestern part of the Kara Sea before intensive melting and so they are called the Spring Intermediate Water Masses.

Deeper, there are water masses having negative temperatures. But one can observe many weakly pronounced temperature and oxygen extremes at the vertical profiles of the parameters that indicate different origins and times of the water masses formation. Salinity and nutrient concentration increase with depth.

In winter, the Spring Intermediate Water Masses disappear. A remarkable feature of winter temperature profiles is a well-pronounced maximum at the depth from 40 to 100 m (Fig. 7). The maximum lies at different depths in the different regions of the sea. Water temperature in that layer is negative, as a rule, however sometimes positive values are observed. The formation of those water masses is not connected with a heat import from the Barents and Pechora seas because the winter water masses in those seas are colder than water masses in the Kara Sea. Probably, the warm layer remained in the intermediate structural zone since last summer or autumn.

Bottom water masses are various by physical and chemical properties in southwestern part of the Kara Sea. The bottom water masses in the Novozemelskaya depression (Fig. 6) usually have temperatures from -1.70 to -1.85 °C, salinities range between 34.70 to 34.95, silicate concentrations approach to 20 µmol/l, phosphate concentrations reach 1.2 µmol/l, nitrate concentrations – 13 µmol/l. Oxygen concentrations are usually rather low (form 5.5 to 6.5 ml/l) however occasionally the bottom structural zone is newly ventilated and oxygen concentrations increase up to 7.2 – 7.4 ml/l. Extensive mixing and flushing in the basin was explained by deep convection occurs in this region during some winters (Pavlov et al., 1994; Pavlov and Pfirman, 1995).

Water masses having properties similar to the bottom water masses of the Novozemelskaya depression can accumulate and stagnate in other shallower but more isolated depressions in the Kara Sea. In general, however, the bottom water masses in the remaining parts of the Kara Sea are well-ventilated and the range of their physical and chemical properties are very extensive.

3.5 Water masses of the northern part of the Kara Sea

Most of the sea located to the north of the river plume area is usually covered by drift ice in summer. Open water exists only in the western regions toward the Barents Sea.

A special type of water mass should be mentioned because of their abnormally high primary productivity, namely, the Ice Edge Summer Surface Water Masses. Those water masses are freshened by snow and ice melting and so their salinities show a wide range. Oxygen concentrations are very high; oxygen saturation often exceeds 120% due to photosynthesis. Nutrients are practically absent in the water. These kinds of water masses can also be observed in the southwestern part of the Kara Sea in August, but they subsist longer in the northern part and occupy a vast area along the ice margin.

The Northern Kara Sea Summer Surface Water Masses are found in the regions covered by sea ice. Salinity of the water masses range from 30 to 32, silicate concentration is less than 10 µmol/l. They are characterized by rather high phosphate concentrations (0.2 – 0.5 µmol/l). Warm Barents Sea waters influence the surface water masses in the region of Novaya Zemlya. The Arctic Basin Summer Surface Water Masses interact with the Kara Sea water masses in the area between Franz Josef Land and Severnaya Zemlya. The Laptev Sea water masses penetrate into the Kara Sea through the narrow and deep straits (Vilkitsky, Shokalsky, and Krasnoy Armii straits) from the east (Rusanov et al., 1979).

In winter, the salinity of surface water masses increases up to 34.5 especially under fast ice around the islands and over the Central Kara Plateau. Some local maxima in silicate concentrations of up to 15 µmol/l were recorded in the northeastern regions. The thickness of the surface mixed layer reach 75 m in places. A huge amount of dense and cold water is formed in the northern part of the Kara Sea in winter (Kazeeva, 1960). The water can spread into the Arctic Basin through the Saint Anna and Voronin troughs.

The intermediate structural zone consists of many different water masses in summer, namely: the Spring Intermediate Water Masses supersaturated in oxygen; nutrient rich Under Fast Ice Water Masses; transformed Arctic Basin surface and intermediate water masses and others. The most striking feature of the water column structure in the northern part of the sea is warm water masses of the Atlantic origin, which penetrate to the Kara Sea from the Arctic Basin through the Saint Anna and Voronin troughs at intermediate depth. Positive temperatures characterize the water masses. The 0 °C isotherm is used as a boundary of those water masses (Timofeev, 1962), however the criterion is disputed by many scientists (for example Stepanov, 1984). A more attentive analysis is needed for understanding the complex structure and dynamic of the Atlantic Warm Intermediate Water Masses in the troughs. The warm water has two cores in the northern regions in the Saint Anna Trough (Hanzlick and Aagaard, 1980). The warmest core is pressed to the western slope and another warm core located near the eastern slope of the trough but it is detached from the slope by water masses, which are less saline and colder (temperature ranges from -1.0 to -1.5 °C) and are formed in the Kara Sea.

The Warm Atlantic Intermediate Water Masses with positive temperatures can be observed in the northern regions of the Voronin trough only. Nevertheless the characteristic temperature maximum is well traced through the southern regions of the trough and there cannot be the slightest doubt of their origin.

Physical and chemical properties of the bottom water masses in the northern part of the Kara Sea are variable. They depend mostly on where and when the water masses were formed before their penetration or sinking into the bottom structural zone. Fresh surface water masses of the Arctic Basin, warm Atlantic water masses, cold Barents Sea winter water masses, and various Kara Sea winter water masses can appear in the bottom layer. Interaction between water and bottom sediments partly alters physical, chemical, and biological properties of the water masses but some distinguishing characteristics remain.

3.6 The Barents Sea water masses

Water exchange between the Barents and Kara seas occurs through the straits of Novaya Zemlya and through a vast passage between Novaya Zemlya and Franz Josef Land. While there is a continuous flow of Barents Sea water masses into the Kara Sea the physical and chemical properties and the flow rates change dramatically on seasonal and interannual time scales.

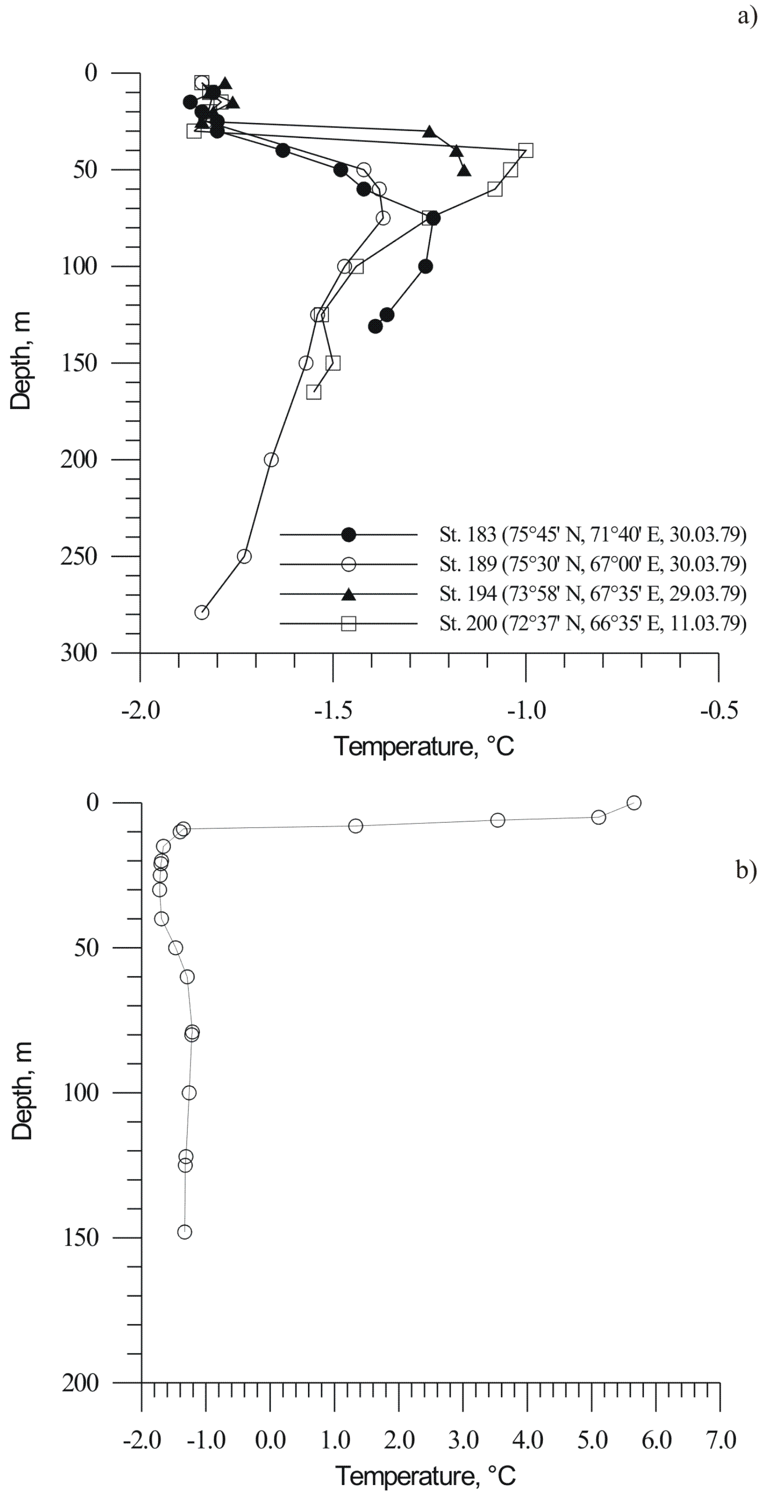


Fig. 7: Temperature profiles at some selected stations in the southwestern part of the Kara Sea where intermediate temperature maxima indicating complex structure of the pycnocline were observed in winter (a), and typical temperature distribution in the southwestern part of the Kara Sea in summer (b).

An average temperature, salinity, oxygen and silicate distributions on the transect between Zhelania (Desire) Cape and Salm island in summer (August – September) are shown in Figure 8. The Barents Sea Warm Summer Surface Water Masses are well recognized by relatively high temperature (0.5 to 2.5 °C) in the southern part of the transect. These waters are obviously transported by a rather narrow stream (salinities range from 33.5 to 34.6) along the northern coast of the Novaya Zemlya. The warm water masses can sink in the intermediate structural zone in the Kara Sea because of their relatively high salinity and density. The surface water masses at the other part of the transect are freshened by melting of sea ice. Nutrient concentrations are very low in the summer surface water masses; even silicate concentrations are less than 5 µmol/l.

The highest oxygen concentrations are found in the spring water masses in the intermediate structural zone (Fig. 8f). The temperature minimum layer (Fig. 8c, ca. 80 m depth) reflects the location of the winter water masses formed in the northern parts of the Barents and Kara seas. The temperature maximum (ca. 200 m depth) indicates the Atlantic water masses circulating and cooled in the Saint Anna Trough. It is possible to recognize the Barents Sea Intermediate Water Masses mainly of winter origin (negative temperatures) in the southern part of the transect.

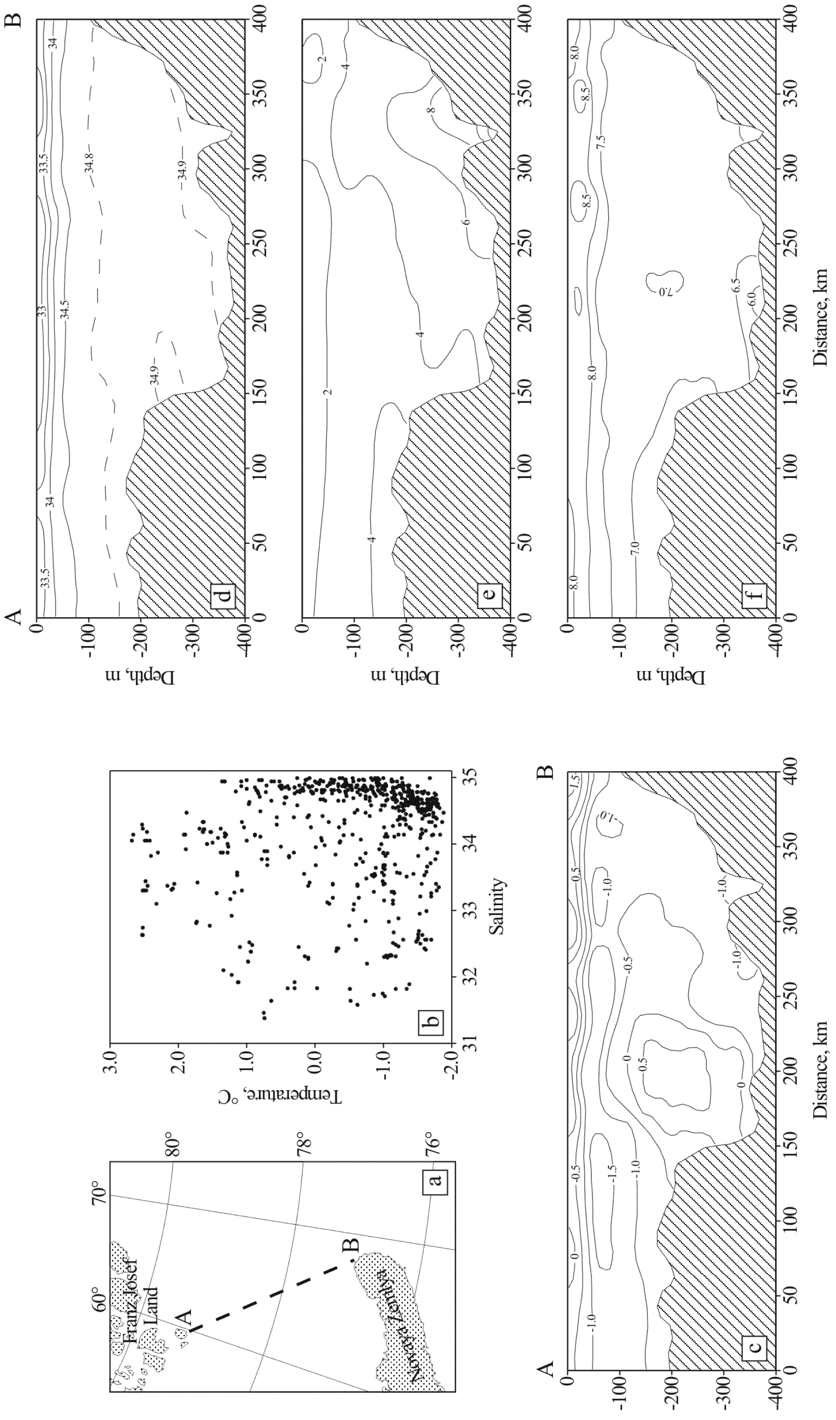
Different types of the bottom water masses on the transect are distinguished by temperature, ventilation rate, and nutrient concentration. The coldest bottom water masses in that region have temperature about –1.5 °C and salinity 34.95 while colder water masses, which are formed in the polynya adjacent to Novaya Zemlya, was found in the northeastern regions of the Barents Sea (Midttun, 1985).

4 Influence of River Run-Off on Water Mass Properties in the Kara Sea

The influence of river run-off on the sea manifests itself in different ways. The main influences are: thermal influx, salinity decrease (freshening), an additional import of dissolved and suspended organic and inorganic matters into the sea system, and pycnocline formation because strong stratification impedes energy and matter exchange between different layers of water.

If temperature and salinity are considered as the main distinguishing characteristics the Kara Sea water masses can be assumed as a result of mixing between ocean water and fresh (river) water. It means that all water masses in the Kara Sea are more or less diluted by river run-off because their salinities are less than the salinity of the Atlantic water, with the exception of the under fast ice winter water masses. The estuarine summer surface water masses constitute the main impact of river run-off. However, using only salinity is a primitive approach. The import of melted ice is not taken into account. Annual volume of melted ice (930 km^3) (Danilov et al., 1994) is commensurable with the volume of the annual river discharge. The summer surface water masses in the Kara Sea represent a complex mixture of seawater, river, and melted ice. The portion of river water can be approximately estimated by the isotope composition (Bauch et al., 1995).

The river signal (freshening) is transmitted into the intermediate and bottom structural zones with the formation of corresponding types of water masses. The overwhelming majority of those types of water masses are formed in winter when more than one thousand cubic kilometers of fresh water are extracted from the surface mixed layer for ice formation.


a
Franz Josef Land
Novaya Zemlya
A
B
60°
70°
80°
78°
76°
b
Temperature, °C
Salinity
3.0
2.0
1.0
0.0
-1.0
-2.0
31
32
33
34
35
c
d
e
f
A
B
Depth, m
Distance, km
0
-100
-200
-300
-400
0
50
100
150
200
250
300
350
400
33.5
34
33
34.5
34.8
34.9
2
4
6
8
-1.5
-1.0
-0.5
0
0.5
8.0
8.5
7.5
7.0
6.5
6.0

If an influence of river run-off upon water masses is estimated by salinity decreasing, that we can conclude that it is very scanty in the bottom structural zone to compare with upper layers.

Rivers bring more than 150 millions tons of organic and inorganic dissolved and suspended matters. This influx of matter directly influences the physical, chemical, and biological properties of the water masses in the river plume area. This influence is strong in the surface structural zone. However, riverine suspended matter is also dumped in the river plume area due to changes in the hydrodynamic conditions. Decomposition, oxidation, and dissolution of suspended matter continue in the intermediate layers and ends in the bottom water masses of the Kara Sea.

Additional nutrient influx plays an important ecological role, because it stimulates primary production. Silicate, phosphate, nitrate, and other nutrients are injected directly in the surface structural zone by river water, and disengaged from organic matters by oxidation in the whole water column and in the bottom sediments. Phosphate and nitrate are almost totally and very quickly consumed by phytoplankton in the surface structural zone in summer. Relatively high phosphate and nitrate concentrations were observed at the surface in the river plume some years at the end of July and at the beginning of August only. Usually their concentrations are very low (near the limits of the analytical methods) in the surface structural zone. Silicate concentrations, on the contrary, are unusually high in the river plume, which is the reason that silicate distribution is used as an indicator for river run-off influence (Rusanov et al., 1979; Ivanov et al., 1984). Nutrients are redistributed between structural zones during annual hydrological and biological cycles. Moreover, seasonal changes of silicate concentrations differ from seasonal changes of phosphate and nitrate in the river plume area. This is caused by particularity of the water column structure and variety of the factors (hydrometeorological, biological, geological), which control the nutrient variability.

An extremely important result of the river run-off influence on the Kara Sea is the maintenance of an extremely strong pycnocline. The pycnocline is a layer of water that has a complex structure and consists of water masses of different origin. It occupies utterly the intermediate structural zone in the river plume area in the Kara Sea. High vertical salinity gradients create a strong density stratification, which is not destroyed neither by autumn storms or winter convection. Mixing can penetrate up to the bottom only at shallow sites and in polynyas. At the remained regions of the sea, the pycnocline suppresses ventilation of bottom water masses and leads to a nutrient accumulation. The pycnocline exists almost everywhere in the Kara Sea in summer, it is not destroyed in winter in many regions despite the fact that the convection penetrate deeper, but its influence on the properties of bottom water masses in the river plume area is more evident. Suspended matters are separated by this density boundary. Organic matter can be accumulated there that leads to higher oxygen demand, pH and other physical and chemical properties change. Ventilation of bottom layers is possible only as a result of advection of water masses, which are formed in other regions of the sea. If the advection is restricted by bottom topography then stagnant water masses are formed, which are characterized by deep oxygen deficit. The oxygen depletion has influence on the benthos fatally.

5 Conclusions

The propounded enumeration of the main types of water masses in the Kara Sea accompanied by short characteristics of their physical and chemical properties, histories of formation, and their positions in the structural zones in the sea should be worked out in detail in further studies. Available data allows to determine typical winter and summer water column structures only. Sparse data can confirm our assumptions about the water column structure in the short transitional seasons – spring and autumn. However, spring as a period of extraordinary biological activity and autumn as a time of intensive mixing and new ice formation are very important for understanding the concept of formation and transformation of the water column structure in the Kara Sea.

It is important to note that the number of the main types of water masses is larger than it was considered earlier (Rusanov et al., 1979; Nikiforov and Shpaikher, 1980). Water masses in the Kara Sea have small volumes (from 1 to 10000 km^3) and are characterized by short life spans (from a few days to a few years). Water mass volumes and life spans increase with increasing depth. Numeric criteria for water mass determination are not constant and change seasonally and on multiyear scale, especially in the surface structural zone.

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