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Original article

Variability of Decadal Horizontal Thermohaline Gradients on the Surface of the Barents Sea during Summer Season in 1993–2022

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Abstract
Purpose. The paper is aimed at comparative analysis of the decadal horizontal gradients of thermohaline fields in the Barents Sea during the summer periods in 1993–2022 derived from the reanalysis and satellite measurements with the aim to select the most suitable data array for studying the surface manifestations of frontal zones.
Methods and Results. The fields of decadal and background thermohaline gradients on the Barents Sea surface were calculated for the summer periods in 1993–2022 based on the monthly mean temperature data from GHRSST OSTIA, MODIS/Aqua, and VIIRS/Suomi NPP, as well as on the monthly mean temperature and salinity data from CMEMS GLORYS12V1 and MERCATOR PSY4QV3R1. The quantitative estimates of temperature and salinity gradients were obtained for certain decades using different data arrays, and a comparative analysis of these estimates was performed along with a description of the physical and geographical characteristics of frontal zones. Maximum thermohaline gradients on the surface were observed in July. Based on the data from all the sources, the background horizontal thermal gradient has been increasing over three decades. During a summer period, the Polar Frontal Zone was identified on the surface of the Barents Sea in all the data arrays, whereas the Coastal and Arctic Frontal Zones were observed in the salinity field based on the CMEMS GLORYS12V1 and MERCATOR PSY4QV3R1 data.
Conclusions. The difference between the calculated estimates of horizontal temperature gradient can exceed 0.01°C/km that is comparable to the magnitude of the average climate gradient in the Barents Sea. The thermal gradient values obtained from the CMEMS GLORYS12V1 and MERCATOR PSY4QV3R1 reanalysis data are the closest to this estimate. This fact makes it possible to classify these data arrays as the most preferable ones for the analysis of the surface manifestations of frontal zones in the Barents Sea.

Keywords: frontal zones, temperature gradient, satellite data, reanalysis, Barents Sea, sea surface temperature

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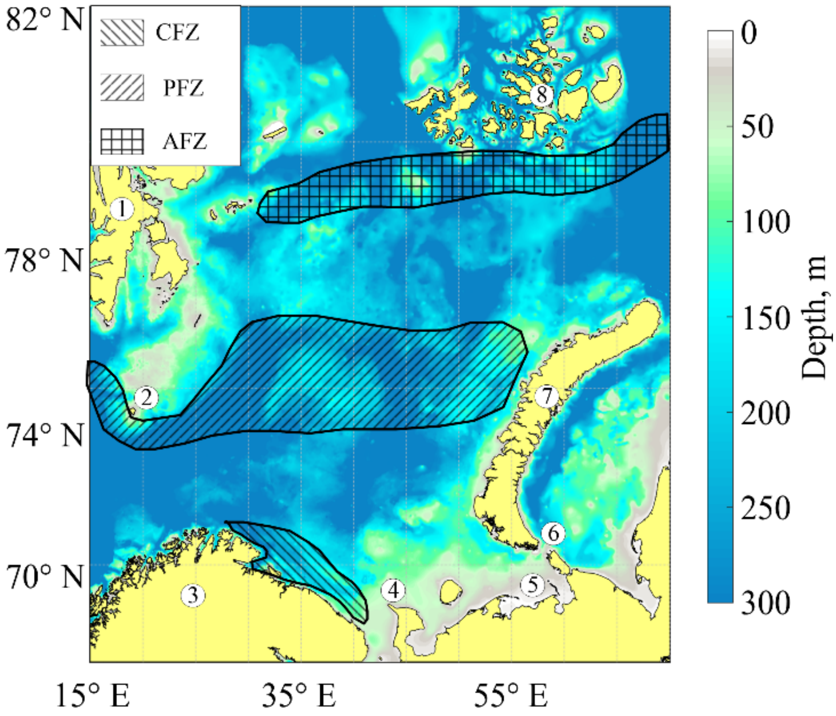
Introduction

Frontal zones in the seas and oceans represent a complex geophysical phenomenon that affects the formation of small eddy structures and internal waves as well as the variability of biogeochemical cycles [1–3]. Baing formed at the boundary of areas where waters with different hydrological characteristics interact, frontal zones are distinguished by their complex internal structure and dynamics.

One of the most significant problems associated with frontal zones in the World Ocean is the methodology of their determination. According to the work [1], frontal zone is a region of sharpened spatial gradients of thermodynamic characteristics compared to the average uniform distribution between steadily existing extrema, and the main frontal section (front) inside the frontal zone is the surface inside it which coincides with the maximum gradient surface of the characteristic.

There is a large variety of works [4–8] studying the spatial variability and features of frontal zones based on *in situ* data, satellite measurements or reanalysis using various methods and approaches. Taken together, most of these studies are united by a single criterion for determining the frontal zone for the World Ocean [1] – a tenfold excess of the gradient of hydrophysical parameters over the background (mean value of the gradient over space). At the same time, compared to other parts of the World Ocean, the Arctic seas represent a relatively inert system for most period of the year which leads to a much smaller value of primarily horizontal hydrophysical gradients and complicates the process of identifying frontal zones.



F i g. 1. Composite scheme of large-scale frontal zones in the Barents Sea based on [4–10]: *1* – Svalbard; *2* – Bear Island; *3* – Scandinavian Peninsula; *4* – Kanin Nos; *5* – Pechora Sea; *6* – Kara Gate; *7* – Novaya Zemlya; *8* – Franz Josef Land. CFZ – Coastal Frontal Zone; PFZ – Polar Frontal Zone; AFZ – Arctic Frontal Zone

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[1] Fedorov, K.N., 1983. *The Physical Nature and Structure of Oceanic Fronts*. New York: Springer, 333 p.

The Barents Sea (Fig. 1) belongs to the Arctic Ocean basin and is characterized by a complex system of surface and subsurface frontal zones combined into the largest Coastal, Polar and Arctic Frontal Zones [5, 9–11]. These frontal zones are an important part of the Barents Sea hydrological regime affecting its thermohaline characteristics, ice conditions and distribution of nutrients [4, 8]. According to the general concept accepted by a large number of researchers (see work [2] and [7, 8]), it is sufficient for the hydrophysical feature gradient to exceed its background value twice to determine the frontal zone on the Barents Sea surface. A number of works [5, 7–8] give estimates of the value of the Barents Sea background gradient on the basis of which the criterion for recording the position and features of frontal zones is then determined. Such estimates can vary within 0.005–0.01 °C/km for temperature and 0.005 PSU/km for salinity. However, hydrological features of the sea (negative water temperature, ice cover) and climate changes [12–14] affect thermohaline fields which ultimately affects the value of the background horizontal gradient and leads to the need to refine its assessments.

Determining the background horizontal gradient of the Barents Sea therefore currently remains an urgent problem which solution would help to improve the quality of assessment of the frontal zones variability in this region. Thus, the main purpose of this work is a comparative analysis of horizontal gradients of thermohaline fields in the Barents Sea calculated over decades from 1993 to 2022 for summer periods using satellite and model (reanalysis, forecast and assimilation) data.

Data and methods

To calculate the gradients, various reanalysis and satellite measurement data on the temperature and salinity of the Barents Sea were used with a spatial step of latitude and longitude from 4 to 25 km for June–August periods over three decades from 1993 to 2022. Fig. 2 shows clearly the difference in the grid scales that are included in each of the data arrays used.

Thermal characteristics were analyzed using L3 processing level monthly mean sea surface temperature (SST) data (http://oceancolor.gsfc.nasa.gov) obtained from visible and infrared surveys with a spatial resolution of 0.05° by MODIS (Moderate Resolution Imaging Spectroradiometer) satellite spectroradiometer installed on board Aqua satellite for warm periods of 2003–2022 and VIIRS (Visible Infrared Imaging Radiometer Suite) radiometer on board Suomi NPP for 2013–2022 [15].

GHRSST OSTIA product (The Group for High Resolution Sea Surface Temperature Operational Sea Surface Temperature and Sea Ice Analysis) contains data fields averaged using optimal interpolation on a global grid with a resolution of 0.054° in latitude and longitude [16]. GHRSST OSTIA is based on satellite SST data from high-resolution sensors (AVHRR, AMSR-E and AATSR) and data from buoys. The daily OSTIA data for June–August 2013–2022 previously averaged to a monthly interval were used for the calculations.

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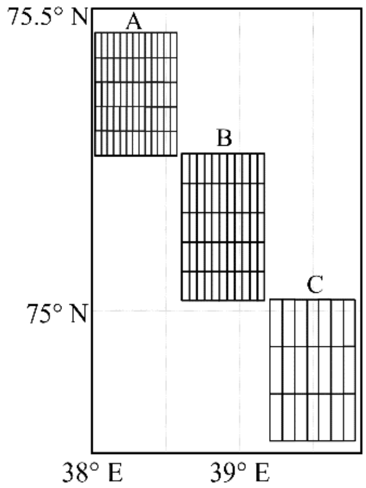
[2] Ozhigin, V.K., Ivshin, V.A., Trofimov, A.G., Karsakov, A.L. and Antsiferov, M.Yu., 2016. *The Barents Sea Water: Structure, Circulation, Variability*. Murmansk: PINRO, 260 p. (in Russian).



F i g. 2. Schematic representation of grids for each data array: a – MODIS/Aqua and VIIRS/Suomi NPP; *b* – GHRSST OSTIA; *c* – GLORYS12v1 and PSY4QV3R1

The Global Ocean Physics Reanalysis [3] product (CMEMS GLORYS12v1) contains monthly and daily average hydrophysical fields with global coverage at a resolution of 0.083° in longitude and latitude for 50 horizons. The model component of GLORYS12v1 is the ECMWF (European Center for Medium-Range Weather Forecasts) ERA-Interim reanalysis system which uses a Kalman filter to assimilate [17] data on temperature, salinity, currents, sea level and ice surface. To calculate horizontal gradients, monthly averages of surface water temperature and salinity for the summer period from June to August 1993–2020 were used.

A product based on a predictive model was also used. Global Ocean 1/12° Physics Analysis and Forecast updated Daily [4] (MERCATOR PSY4QV3R1) is a CMEMS GLORYS12v1 continuation. It provides simulation of mean daily hydrophysical fields for the entire World Ocean with a resolution of 0.083°. MERCATOR PSY4QV3R1 contains daily data on sea level, salinity, temperature, mixed layer depth and ice extent. MERCATOR PSY4QV3R1 contains the NEMO numerical model [18] with 50 unevenly spaced horizons for most hydrophysical characteristics. Monthly average data on surface water temperature and salinity for the periods from June to August 2021–2022 were used within the study.

The quality of the satellite data used depends both on the type of sounding systems and on the state of the surface waters of the considered water area. The error of the satellite data used in the work (VIIRS/Suomi NPP and MODIS/Aqua) on SST does not exceed 0.15°C, while the reanalysis data error (GHRSST OSTIA, CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1) is 0.1 °C. The reanalysis data error (CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1) on surface salinity is on average less than 0.1 PSU.

Surface decadal gradient fields were calculated identically for all data arrays. The first stage included monthly averaging of temperature and salinity fields for each decade. The second stage consisted of calculating horizontal gradients of temperature and salinity according to a method repeatedly tested for the Barents Sea [8, 19]. At the third stage, the module of the ten-year horizontal gradient was determined. First, the step along the parallel and meridian in kilometers was

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[3] Global Ocean Physics Analysis and Forecast. *E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS).* doi:10.48670/moi-00016

[4] Global Ocean Physics Reanalysis. *E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS).* doi:10.48670/moi-00021

calculated, then the zonal and meridional components of the gradient were calculated for each grid node. The final ten-year module of the horizontal gradient was calculated as the sum square root of the squares of zonal and meridional components.

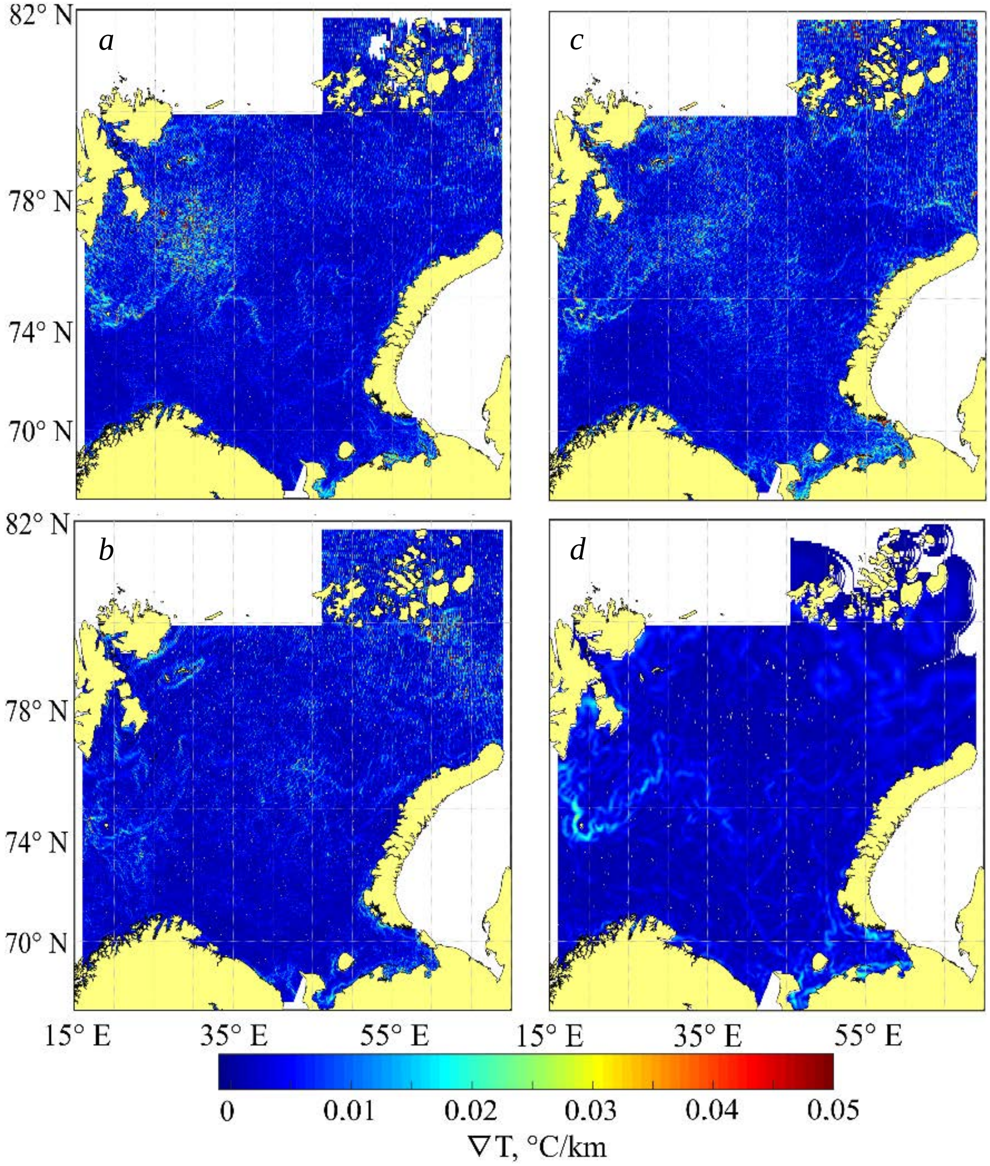
Research results

Temperature gradients from MODIS/Aqua and VIIRS/Suomi NPP data.

Fig. 3 shows maps of the surface distribution of horizontal temperature gradients based on satellite data for July 1993–2022.

According to MODIS/Aqua data, in June the maximum thermal gradient reaching 0.03–0.04 °C/km is observed in the central and western Barents Sea near the Svalbard and Bear Island. In the first decade (2003–2012), in June, the main frontal section of the Polar Frontal Zone can be observed throughout the central Barents Sea, while from 2013 to 2022 – only in the western part of the sea in the region of 15°–35°E. At the same time, in the southern part of the sea, the values of thermal horizontal gradients are not large and average 0.01–0.015 °C/km, and the front in the Coastal Frontal Zone is not traced. From 2013 to 2022, more pronounced surface gradients are observed in the north of the sea. Its values on average reach 0.02–0.03 °C/km, which correlates with the ten-year position of the Arctic Frontal Zone [11]. Two decades of June showed the temperature gradient of 0.03–0.04 °C/km in the Pechora Sea. The maximum temperature gradient is observed in July. In both decades (see Fig. 3, *a*, *b*), maximum values of 0.03–0.05 °C/km are recorded around Bear Island and in the Pechora Sea. In August, thermal gradient decrease is observed over the first and second decades. Thus, this is reflected in the Polar Frontal Zone with its main frontal section appearing to the south of Bear Island and further in the central Barents Sea in 2003–2012, while in 2013–2022 in the area 20°–45°E its position is difficult to track. In addition, in August 2003–2012 near the Scandinavian Peninsula coast a strip of large thermal gradient values (> 0.03 °C/km) is observed, which correlates with the Coastal Front position, and in the Pechora Sea individual areas with a thermal gradient not exceeding 0.05 °C/km are registered. A comparative analysis by decade shows that the maximum surface temperature gradients are recorded in July 2003–2012 according to MODIS/Aqua data. The mean value of the horizontal thermal temperature gradient in the Barents Sea has decreased by 0.01 °C/km over the past two decades.

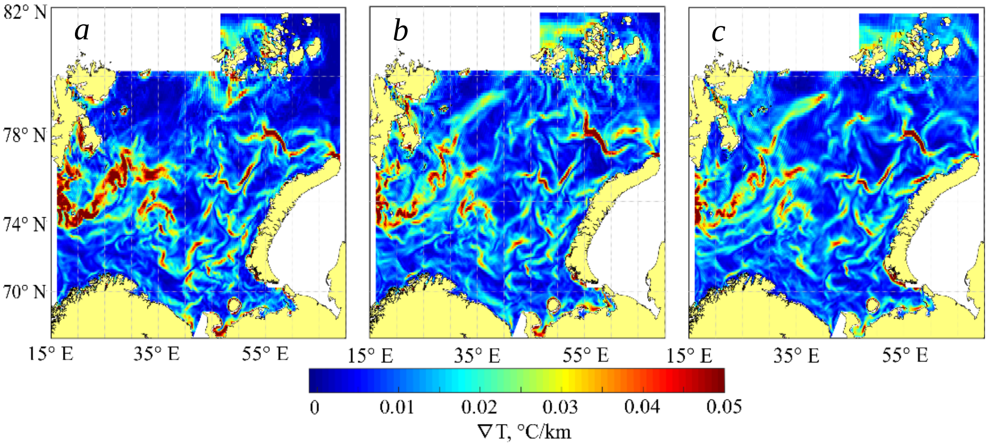
Analysis of VIIRS/Suomi NPP satellite products for 2013–2022 showed the correlation of thermal gradient value according to data from this database with its values from MODIS/Aqua array. Fig. 3, *c* gives a map for July as an example. Thus, the Polar Frontal Zone appears also in the area of Bear Island only, where the SST gradient value from June to August varies within 0.04–0.05 °C/km, and in the Pechora Sea its value of 0.03–0.04 °C/km for the warm season is comparable to the SST gradient value according to MODIS/Aqua data. At the same time, separate high-gradient areas that can be attributed to the Arctic Frontal Zone are observed near the Novaya Zemlya and the Franz Josef Land. Position of the Coastal Frontal Zone for 2013–2022 is not traceable according to SST data.



F i g. 3. Distribution of decadal horizontal temperature gradients in the Barents Sea in July based on the satellite data: a – MODIS/Aqua, 2003–2012; *b* – MODIS/Aqua, 2013–2022; *c* – VIIRS/Suomi NPP, 2013–2022; *d* – GHRSST OSTIA, 2013–2022

Temperature gradients according to GHRSST OSTIA data. According to GHRSST OSTIA data, the maximum value of the temperature gradient in summer in the Barents Sea does not exceed 0.03 °C/km. Such gradients are most often observed in June and July (see Fig. 3, *d*); in August their magnitude decreases. High-gradient areas can be observed in the Polar Frontal Zone and the Pechora Sea. According to GHRSST OSTIA data, the position of the main front of the Polar Frontal Zone is more pronounced than according to satellite data, especially near the Svalbard and Bear Island. In addition, the Arctic Frontal Zone is traced in the northern Barents Sea, where the gradient can reach 0.025 °C/km. In the southern part of the sea, the gradient value does not exceed 0.01 °C/km. It is worth noting that according to OSTIA data, in July the Coastal Front can be traced with a gradient not exceeding 0.02 °C/km. In general, the surface gradient values from GHRSST OSTIA reanalysis data are lower by 0.02 °C/km than those from MODIS/Aqua and VIIRS/Suomi NPP satellite data.

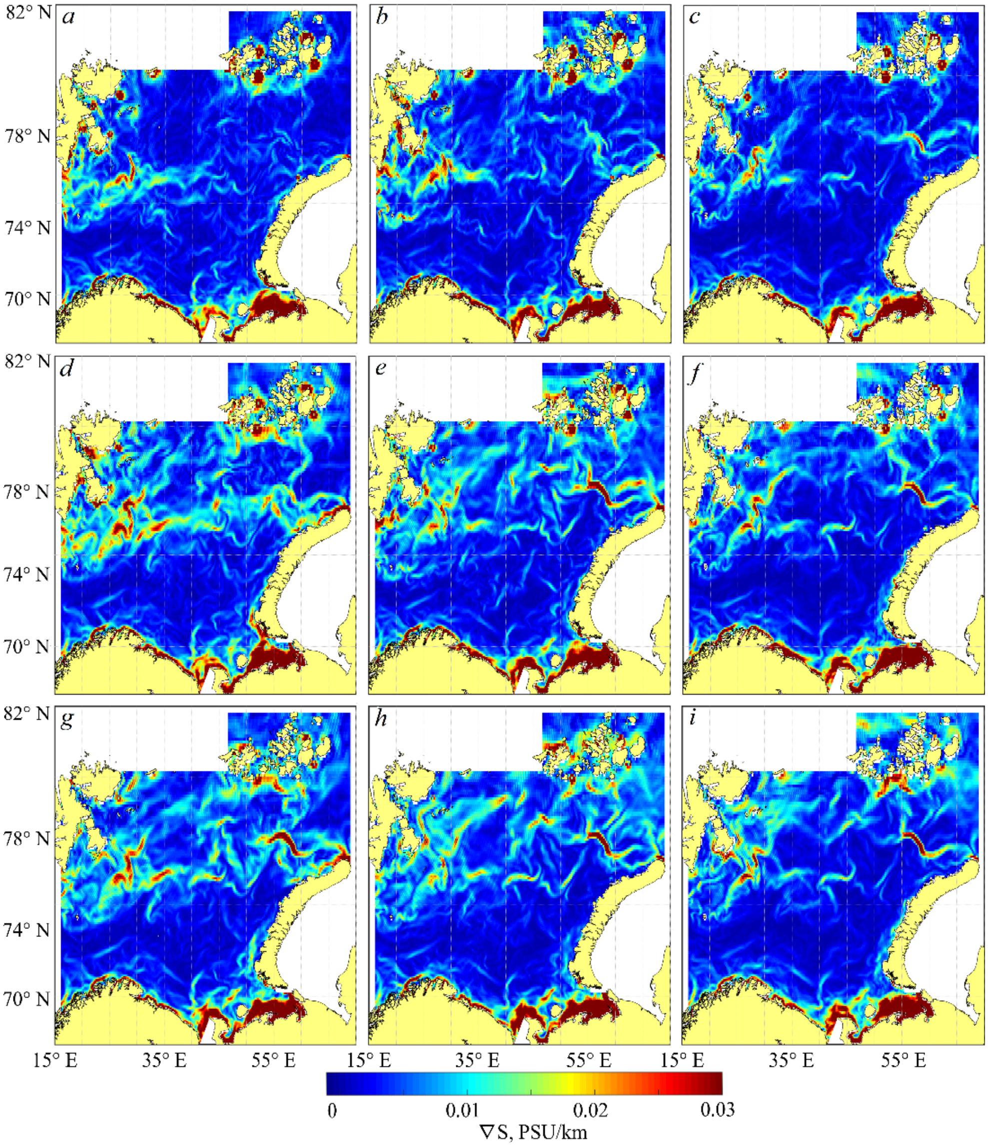
Temperature and salinity gradients from CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data. Fig. 4 shows maps of the surface distribution of horizontal temperature gradients according to reanalysis data for July 1993–2022.



F i g. 4. Distribution of decadal horizontal temperature gradients in the Barents Sea in July based on the reanalysis data: *a* – CMEMS GLORYS12v1, 1993–2002; *b* – CMEMS GLORYS12v1, 2003–2012; *c* – CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1, 2013–2022

According to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 reanalysis data, in all the months high-gradient zones (> 0.07 °C/km) corresponding to the quasi-stationary western part of the Polar Frontal Zone are observed.

A comparison of SST gradient fields in June over three decades showed that the areas of maximum gradients almost coincided. The eastern part of the Polar Frontal Zone is less pronounced in the first decade (smaller gradients) than in the other two. June 2003–2012 is characterized by high gradient values near the Franz Josef Land. In July, in each decade (see Fig. 4), maximum Polar Frontal Zone gradients (> 0.07 °C/km) are also clearly visible. The western part of the frontal zone is clearly expressed in July 2013–2022, while the values of the gradients in its eastern part do not change significantly. Unlike June, in July high-gradient (> 0.07 °C/km) areas are observed already near the Kara Gate and in the Pechora Sea, where maximum gradients are also observed in the third decade. In August, for all three decades, the maximum values of surface temperature gradients (> 0.07 °C/km) are observed in the western and eastern parts of the Polar Frontal Zone. The areas near the northern part of the Novaya Zemlya, the Svalbard and the Franz Josef Land are worth noting individually as there the thermal gradient magnitude has increased significantly compared to other months.



F i g. 5. Distribution of decadal horizontal salinity gradients in the Barents Sea based on the CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data: in June (*a*, *b*, *c*), in July (*d*, *e*, *f*), in August (*g*, *h*, *i*), 1993–2002 (*a*, *d*, *g*), 2003–2012 (*b*, *e*, *h*), 2013–2022 (*c*, *f*, *i*)

Analysis of summer SST data for three decades showed that in the field of temperature gradients the Polar Frontal Zone and the frontal zone in the Pechora Sea were best identified, and maxima (up to 0.15 °C/km) were most often observed in the third decade. It is also worth noting that the Coastal Frontal Zone on the surface for 1993–2022 could not be identified according to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data.

Fig. 5 shows maps of the horizontal distribution of the salinity gradient according to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 reanalysis data. There is no significant variability in the characteristics over all three months under study. In June, small high-gradient areas (> 0.03 PSU/km) are observed in the western part of the Polar and Coastal Frontal Zones, near the shores of the Svalbard and the Franz Josef Land. Maximum haline gradients (> 0.07 PSU/km) are recorded in the Pechora Sea. In July 2003–2012, gradients are minimal (> 0.02 PSU/km) in contrast to other decades, especially in the western part of the Polar Frontal Zone and in the Kanin Nos region. The gradient values in the Pechora Sea and in the region of the Coastal Frontal Zone are close. In August, the trends of July continue – in the second decade, the western region of the Polar Frontal Zone is less pronounced than in the first and third ones; maxima are observed in the Pechora Sea and in the region of the Coastal Frontal Zone.

Comparative analysis of thermohaline gradients in the Barents Sea. The table below presents quantitative estimates of the spatially mean temperature and salinity gradient variability in the summer seasons for three decades under consideration.

Horizontal gradient of temperature and salinity in the Barents Sea in 1993–2022

Data source	1993–2002			2003–2012			2013–2022		
	June	July	August	June	July	August	June	July	August
∇S, PSU/km									
CMEMS GLORYS12v1	0.008	0.010	0.009	0.008	0.009	0.009	0.007	0.009	0.008
MERCATOR PSY4QV3R1									
∇T, °C/km									
CMEMS GLORYS12v1	0.013	0.014	0.013	0.014	0.014	0.013	0.014	0.014	0.014
MERCATOR PSY4QV3R1									
MODIS/Aqua	–	–	–	0.005	0.005	0.004	0.006	0.005	0.004
VIIRS/Suomi NPP	–	–	–	–	–	–	0.006	0.006	0,005
GHRSST OSTIA	–	–	–	–	–	–	0.002	0.003	0.003

The obtained estimates show that the data source affects the magnitude of the area-averaged decadal surface gradient significantly. According to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data, the maximum values of the background thermal gradient (> 0.014 °C/km) are observed in the first decade in July, and the minimum values are observed in the third decade in June (0.003 °C/km) according to GHRSST OSTIA. The temperature gradient value according to satellite measurements is on average 0.005 °C/km lower than according to the reanalysis results. The difference among the estimates of the background gradient based on the data used in this paper can be more than 0.01 °C/km which is comparable to the value of the mean climate gradient in the Barents Sea [1]. At the same time, the smallest difference was recorded between the background decadal gradients calculated using CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data, and the climatic temperature gradient from work [1], which permits to classify these arrays of satellite measurements as the most preferred data source for analyzing the surface manifestations of the Barents Sea frontal zones on climatic time scales. According to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data, the maximum values of salinity gradients are recorded in the first decade in July (0.1 PSU/km), and the minimum ones – in the third decade in July (< 0.08 PSU/km).

The interdecadal variability analysis of the data from all sources showed a slight increase of the background horizontal thermal gradient over three decades. This situation results from the changes in the Atlantic water transport volume which can be associated with a record warm period observed in the Barents Sea in the last decade [20]. The thermal gradient increase in the Barents Sea is monitored in July as a result of surface currents weakening and pycnocline formation leading to significant instability in the surface layer [21]. August is characterized by a temperature gradient decrease associated with a decrease in the number of heterogeneity areas as a result of an increase in temperature to a seasonal maximum and stable stratification in the Barents Sea.

The magnitude of surface salinity gradients has significantly decreased over the past three decades, with a maximum recorded in July. Such interdecadal variability can appear from the reduction of ice cover in the Barents Sea [22, 23] which affects the intensity of interaction between the ocean and the atmosphere and, ultimately, the magnitude of the surface horizontal gradient of not only salinity, but also temperature. It is important to note that the significant difference in the values of thermohaline gradients obtained from different arrays data could be influenced by hydrometeorological (cloudiness, wind) and ice processes which were not taken into account in the present study.

Conclusion

Based on a set of reanalysis data and satellite measurements, a comparative analysis of horizontal decadal gradients of thermohaline fields in the Barents Sea was carried out for the summer period of 1993–2022. Analysis of surface gradients showed a high degree of variability in space and time, both within the warm season and between decades.

In all summer months and in all data sets, the position of the large-scale Polar Frontal Zone is observed on the surface. According to CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data, it is possible to determine the position of the Coastal and Arctic Frontal Zones in July and August. It has been established that according to data from all presented arrays the maximum background gradients on the Barents Sea surface are recorded in July (0.014 °C/km and 0.01 PSU/km), and in August the magnitude of the gradients decreases. It is shown that increased Atlantic water transport and decreased ice cover in the Barents Sea can be the main factors in increasing the background thermal gradient and decreasing the salinity gradient.

The difference between the calculated estimates of background horizontal temperature gradients can reach more than 0.01 °C/km, which is comparable to the value of the mean climatic temperature gradient in the Barents Sea. The thermal gradient value is closest to this value according to data from CMEMS GLORYS12v1 and MERCATOR PSY4QV3R1 data which could potentially be the most preferable tool for determining and analyzing long-term variability of the surface manifestations of frontal zones in the Barents Sea.

Thus, the choice of data source from various reanalysis arrays or satellite measurements for calculations can have a significant impact on the resulting value of the horizontal gradient of temperature and salinity which should be taken into consideration when obtaining the final estimate of the background gradient.

REFERENCES

1. Johannessen, O.M., Johannessen, J.A., Svendsen, E., Shuchman, R.A., Campbell, W.J. and Josberger, E., 1987. Ice-Edge Eddies in the Fram Strait Marginal Ice Zone. *Science*, 236(4800), pp. 427-429. doi:10.1126/science.236.4800.427
2. Small, R.J., deSzoeke, S.P., Xie, S.P., O'Neill, L., Seo, H., Song, Q., Cornillon, P., Spall, M. and Minobe, S., 2008. Air-Sea Interaction over Ocean Fronts and Eddies. *Dynamics of Atmospheres and Oceans*, 45(3-4), pp. 274-319. doi:10.1016/j.dynatmoce.2008.01.001
3. Boeckel, B. and Baumann, K.-H., 2008. Vertical and Lateral Variations in Coccolithophore Community Structure across the Subtropical Frontal Zone in the South Atlantic Ocean. *Marine Micropaleontology*, 67(3-4), pp. 255-273. doi:10.1016/j.marmicro.2008.01.014
4. Våge, S., Basedow, S.L., Tande, K.S. and Zhou, M., 2014. Physical Structure of the Barents Sea Polar Front near Storbanken in August 2007. *Journal of Marine Systems*, 130, pp. 256-262. doi:10.1016/j.jmarsys.2011.11.019
5. Oziel, L., Sirven, J. and Gascard, J.-C., 2016. The Barents Sea Frontal Zones and Water Masses Variability (1980–2011). *Ocean Science*, 12(1), pp. 169-184. doi:10.5194/os-12-169-2016
6. Atadzhanova, O.A., Zimin, A.V., Svergun, E.I. and Konik, A.A., 2018. Submesoscale Eddy Structures and Frontal Dynamics in the Barents Sea. *Physical Oceanography*, 25(3), pp. 220-228. doi:10.22449/1573-160X-2018-3-220-228
7. Artamonov, Yu.V., Skripaleva, E.A. and Fedirko, A.V., 2019. Seasonal Variability of Temperature Fronts on the Barents Sea Surface. *Russian Meteorology and Hydrology*, 44(1), pp. 53-61. doi:10.3103/S1068373919010060

8. Ivshin, V.A., Trofimov, A.G. and Titov, O.V., 2019. Barents Sea Thermal Frontal Zones in 1960–2017: Variability, Weakening, Shifting. *ICES Journal of Marine Science*, 76(suppl. 1), pp. i3-i9. doi:10.1093/icesjms/fsz159

9. Moiseev, D.V., Zaporozhtsev, I.F., Maximovskaya, T.M. and Dukhno, G.N., 2019. Identification of Frontal Zones Position on the Surface of the Barents Sea According to in Situ and Remote Sensing Data (2008-2018). *Arctic: Ecology and Economy*, (2), pp. 48-63. doi:10.25283/2223-4594-2019-2-48-63 (in Russian).

10. Konik, A.A., Zimin, A.V. and Kozlov, E.I., 2021. Spatial and Temporal Variability of the Polar Frontal Zone Characteristics in the Barents Sea in the First Two Decades of the XXI Century. *Fundamental and Applied Hydrophysics*, 14(4), pp. 39-51. doi:10.7868/S2073667321040043 (in Russian).

11. Konik, A.A. and Zimin, A.V., 2022. Variability of the Arctic Frontal Zone Characteristics in the Barents and Kara Seas in the First Two Decades of the XXI Century. *Physical Oceanography*, 29(6), pp. 659-673. doi:10.22449/1573-160X-2022-6-659-673

12. Callaghan, T.V., Bergholm, F., Christensen, T.R., Jonasson, C., Kokfelt, U. and Johansson, M., 2010. A New Climate Era in the Sub-Arctic: Accelerating Climate Changes and Multiple Impacts. *Geophysical Research Letters*, 37(14), L14705. doi:10.1029/2009GL042064

13. Overland, J.E., Wang, M., Walsh, J.E. and Stroeve, J.C., 2014. Future Arctic Climate Changes: Adaptation and Mitigation Time Scales. *Earth's Future*, 2(2), pp. 68-74. doi:10.1002/2013ef000162

14. Yamanouchi, T. and Takata, K., 2020. Rapid Change of the Arctic Climate System and Its Global Influences – Overview of GRENE Arctic Climate Change Research Project (2011–2016). *Polar Science*, 25, 100548. doi:10.1016/j.polar.2020.100548

15. Liu, Y. and Minnett, P.J., 2016. Sampling Errors in Satellite-Derived Infrared Sea-Surface Temperatures. Part I: Global and Regional MODIS Fields. *Remote Sensing of Environment*, 177, pp. 48-64. doi:10.1016/j.rse.2016.02.026

16. Stark, J.D., Donlon, C.J., Martin, M.J. and McCulloch, M.E., 2007. OSTIA: An Operational, High Resolution, Real Time, Global Sea Surface Temperature Analysis System. In: *OCEANS 2007 – Europe*. Aberdeen, UK: IEEE, pp. 1-4. doi:10.1109/oceanse.2007.4302251

17. Poli, P., Healy, S.B. and Dee, D.P., 2010. Assimilation of Global Positioning System Radio Occultation Data in the ECMWF ERA-Interim Reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 136(653), pp. 1972-1990. doi:10.1002/qj.722

18. Mathiot, P., Jenkins, A., Harris, C. and Madec, G., 2017. Explicit Representation and Parametrised Impacts of under Ice Shelf Seas in the z∗ Coordinate Ocean Model NEMO 3.6. *Geoscientific Model Development*, 10(7), pp. 2849-2874. doi:10.5194/gmd-10-2849-2017

19. Chvilev, S.V., 1991. Frontal Zones in the Barents Sea. *Meteorologiya i Gidrologiya*, (11), pp. 103-110 (in Russian).

20. Trofimov, A.G., Karsakov, A.L. and Ivshin, V.A., 2018. Climate Changes in the Barents Sea over the Last Half Century. *Trudy VNIRO*, 173, pp. 79-91 (in Russian).

21. Pnyushkov, A.V., 2008. The Investigations of Barents Sea Water Circulation Structure. *Arctic and Antarctic Research*, (1), pp. 27-37 (in Russian).

22. Zhichkin, A.P., 2012. Climatic Variations of Ice Conditions in Different Regions of the Barents Sea. *Russian Meteorology and Hydrology*, 37, pp. 624-630. doi:10.3103/S1068373912090063

23. Ivanov, V.V., Arkhipkin, V.S., Lemeshko, Ye.M., Myslenkov, S.A., Smirnov, A.V., Surkova, G.V., Tuzov, F.K., Chechin, D.G. and Shestakova, A.A., 2022. Changes in Hydrometeorological Conditions in the Barents Sea as an Indicator of Climatic Trends in the Eurasian Arctic in the 21st Century. *Vestnik Moskovskogo Universiteta. Seriya 5, Geografiya*, 1, pp. 13-25 (in Russian).

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