Original article

Study of Spatial-Temporal Variability in Density Stratification and Characteristics of Internal Waves in the Barents and Kara Seas

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Abstract

Purpose. The work aims to investigate the spatial-temporal variability of the vertical structure of the density field and characteristics of internal waves at the climatological scale in the Barents and Kara seas.

Methods and Results. Water density was calculated using the ORAS5 reanalysis data on monthly average potential temperature and salinity at the ~ 10 km grid nodes for the period 1958–2022. The resulting array of density data made it possible to determine the maximum values of buoyancy frequency and their depths. The amplitudes of the vertical component of the first-mode velocity of free internal waves were calculated, and the maximum amplitude values and their depths were defined for the Barents and Kara seas.

Conclusions. The performed analysis has revealed that during the considered time period, the sea-mean climatological maximum of buoyancy frequency had a tendency to decrease and deepen both in the Barents and Kara seas. The most manifested trends in the changes of buoyancy frequency maximum are noted in the warm half-year (June–November): positive trends occur in September–November in the southern Barents Sea where Atlantic water influence is significant, and negative ones occur in June–August in the Franz Josef Land and Svalbard region where there is an inflow of cold Arctic waters and ice from the Arctic Ocean. The most pronounced trends in changes in the maximum amplitude of the vertical component of internal wave velocity are observed in the cold half-year (December–May): positive trends occur in the northern regions of the Barents and Kara seas from January to April, and negative ones occur in the southern Barents Sea in November–January.

Keywords: Barents Sea, Kara Sea, buoyancy frequency, internal waves, amplitude of velocity vertical component, linear trend, interannual variability

For citation: Bukatov, A.A., Solovei, N.M. and Pavlenko, E.A., 2026. Study of Spatial-Temporal Variability in Density Stratification and Characteristics of Internal Waves in the Barents and Kara Seas. *Physical Oceanography*, 33(1), pp. 3-17.

Introduction

The Intergovernmental Panel on Climate Change, in its Sixth Assessment Report [1], concluded that global climate change is unequivocally established.

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[1] IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability. The Working Group II Contribution to the IPCC Sixth Assessment Report*. 2022. [online] Available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ [Accessed: 22 February 2025].

Analysis of contemporary research reveals that in the Arctic, climate change is occurring faster than the global average due to the Arctic amplification effect [1]. This manifests as a reduction in sea-ice area, increased heat accumulation in the upper layer, and consequently, changes in the thermohaline structure of the waters of the Arctic seas. Continued study of the variability of the vertical structure of waters is important not only for understanding current processes but also for predicting future changes and adapting to them [2–5].

Due to its geographical position, the Barents Sea holds a special place among the marginal seas of the Arctic Ocean. Due to the impact of the warm North Atlantic Current, positive water temperatures are observed year-round at the sea surface up to 75°N. Since the mid-2000s, an increase in temperature and salinity has been noted in the northern and northeastern parts of the Barents Sea [6]. This trend is associated with a decrease in the Barents Sea ice coverage, which leads to a weakening of density stratification, an intensification of convective mixing in the water column, and an increased influx of heat and salt from the depths to the sea surface. The result of such changes is a further reduction in sea-ice area, i.e. the realization of a "positive feedback" [7].

The Barents and Kara Seas are separated by the Novaya Zemlya archipelago. Warm Barents Sea waters enter the Kara Sea through the Yugorsky Shar, Karskie Vorota, and Matochkin Shar straits. Relatively warm and saline Atlantic waters enter the Kara Sea from the Central Arctic Basin via the St. Anna and Voronin Troughs, transforming as they move from north to south. The amount and characteristics of the Barents Sea and Atlantic waters vary from year to year [8–11]. However, the main components of the hydrological structure of the Kara Sea are surface Arctic waters and waters formed by mixing with fresh river waters. The average annual discharge of the largest Arctic rivers flowing into the Kara Sea (Yenisei, Ob) shows an increasing trend, especially noticeable in recent decades [12, 13]. "The annual runoff of Siberian and Far Eastern rivers into the Arctic seas of Russia has been steadily increasing since the 1980s" [14, p. 259].

Climate-forming processes that directly or indirectly, through a chain of interactions, affect the hydrological regime of the Arctic seas lead to the transformation of the thermohaline structure of waters. This results in changes in water dynamics, in particular, the characteristics of wave motion.

Internal waves (IW) affect the mixing of water masses and heat transport. Understanding of current trends in IW dynamics will improve the modeling of climate change and ensure the safe operation of underwater structures and ship navigation in the Arctic [15, 16].

This work is aimed at analyzing and assessing the climatological variability of the vertical structure of the density field and the characteristics of free short-period internal waves in the Barents and Kara Seas.

Materials and methods

Based on ORAS5 reanalysis data on monthly average potential temperature and salinity at the nodes of a ~ 10 km grid with non-uniform depth steps down to ~ 400 m for the period 1958–2022, the vertical structure of the density field in the Barents and Kara Seas was studied. The study area is bounded by the parallels 65° and 80°N and the meridians 16° and 120°E.

For each year of the considered period, at each grid node, monthly average profiles of the Brunt–Väisälä frequency (N, cycle/hour) were calculated using the formula

$$N^2(z) = \frac{g}{\rho}\frac{d\rho}{dz},$$

where z is depth; g is gravitational acceleration; ρ is potential density.

The maximum of the Brunt–Väisälä frequency with depth ($N_{max}(z)$, cycle/hour) and its depth ($HN_{max}(z)$, m) were determined.

The study of climatological variability in water dynamics involved examining the trend in the amplitude variability of the vertical velocity component of the first mode of free IWs. The system of linear equations of motion for a continuously stratified fluid in Fjeldstad form has a solution as a superposition of plane waves [17]. In particular, for the vertical velocity component $w(x, y, z, t)$ (x, y are horizontal coordinates, t is time), the representation is

$$w(x,y,z,t) = \sum_{n=1}^{\infty}\iint_{-\infty}^{\infty} W^{(n)}(k,z)\exp\left\{i\left[k_x x + k_y y - \omega^{(n)}(k)t\right]\right\}dk_x dk_y,$$

where $\omega^{(n)}(k)$ is the dispersion relation (eigenfrequency) for mode number n and wave number $k = \left(k_x^2 + k_y^2\right)^{\frac{1}{2}}$; $W^{(n)}(k, z)$ is the amplitude of this mode (eigenfunction). If we use the Boussinesq approximation, filter out surface waves, and neglect the Earth's rotation, then $W^{(n)}(k, z)$ becomes the solution to a Sturm–Liouville type boundary value problem with zero boundary conditions at the bottom and the free surface of the fluid (rigid-lid approximation):

$$d^2 W^{(n)}/dz^2 + \left(\lambda^{(n)}N^2 - k^2\right)W^{(n)} = 0, \quad W^{(n)}(H) = W^{(n)}(0) = 0,$$

where $\lambda^{(n)} = \left(k/\omega^{(n)}\right)^2$ is the eigenvalue; H is depth.

This spectral problem consists in determining the eigenvalues $\lambda^{(n)}$ and eigenfunctions $W^{(n)}(k, z)$ for each fixed wavelength. For the numerical implementation of the boundary value problem, its finite-difference approximation was constructed based on a given profile $N(z)$. The resulting system of linear algebraic equations was solved by finding the roots of the characteristic equation of its matrix [18].

When choosing the wavelength interval for calculating eigenvalues and eigenfunctions, the authors referred to works [19–21], which indicate that in high latitudes, IWs with wavelengths of 200–3000 m are observed on radar images. The first mode is dominant in the spectrum of a wave train [22]. This work presents, as an illustration, calculations of the first-mode characteristics of free IWs ($W^{(1)}(k, z)$) in dimensionless units for a wavelength (λ) of 1000 m.

Analysis of results

To analyze the climatological variability of the maximum buoyancy frequency and its depth, the time interval 1958–2022 was divided into two periods: 1958–1990

and 1991–2022. The World Meteorological Organization recommends using thirty-year averages for climatological calculations, as such an interval allows capturing the full cycle of most significant natural processes and identifying long-term trends, excluding the effect of short-term anomalies. Therefore, the 65-year period was divided into two ~ 30-year cycles to clearly illustrate the climatological trends in the variability of hydrological characteristics.

For each of these periods, the long-term average values of $N_{max}(z)$ and $HN_{max}(z)$ over the sea areas were found. From Fig. 1 it can be seen that the sea-average climatological maximum of the buoyancy frequency has a tendency to decrease and deepen in both the Barents and Kara Seas, which agrees well with the conclusions made in [23]. A decrease in the maximum Brunt–Väisälä frequency indicates a weakening of density stratification and an increase in vertical motion.
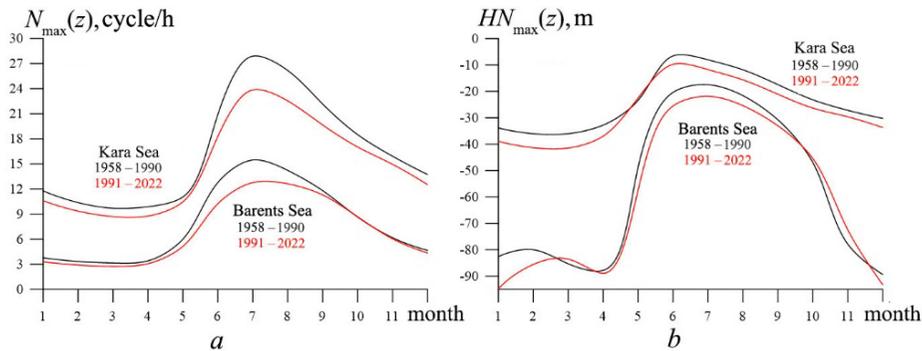

F i g. 1. Annual average values of the Brunt–Väisälä frequency maximum (*a*) and its depth (*b*) in the Barents and Kara seas

Regional features are observed in the $N_{max}(z)$ variability in the Barents and Kara Seas (Fig. 2), which are largely determined by the influx of waters from neighboring seas. Water exchange with adjacent seas depends on deep-water basins and straits through which waters enter or leave the sea. The widest and deepest channels for water penetration into the Barents Sea from adjacent seas are the Bear Island Trough in the west (Atlantic waters) and the strait between Franz Josef Land and Novaya Zemlya in the east (Arctic waters) [24]. It is in the zones of intense water exchange with the surrounding seas that the greatest variability of the maximum Brunt–Väisälä frequency is observed over the period 1958–2022 (Fig. 2). Negative trends of $N_{max}(z)$ are observed throughout the year in the water areas of the Barents and Kara Seas. The maximum values of linear trend coefficients reach –0.3 (cycle/hour)/year southwest of Franz Josef Land and in the region of the Central Kara Upland in July and August. Positive trends of $N_{max}(z)$ are observed during the warm half-year in the central and southern parts of the Barents Sea within the influence zone of the North Cape Current (Fig. 2), with a maximum coefficient value of ~ 0.06 (cycle/hour)/year in September in the Bear Island Trough area. The positive climatological trend of $N_{max}(z)$ in the zone affected by Atlantic waters may be associated with a weakening of the North Cape Current, as it is precisely the warm and saline waters of this current that reduce the density difference between layers with depth in this part of the Barents Sea [25].
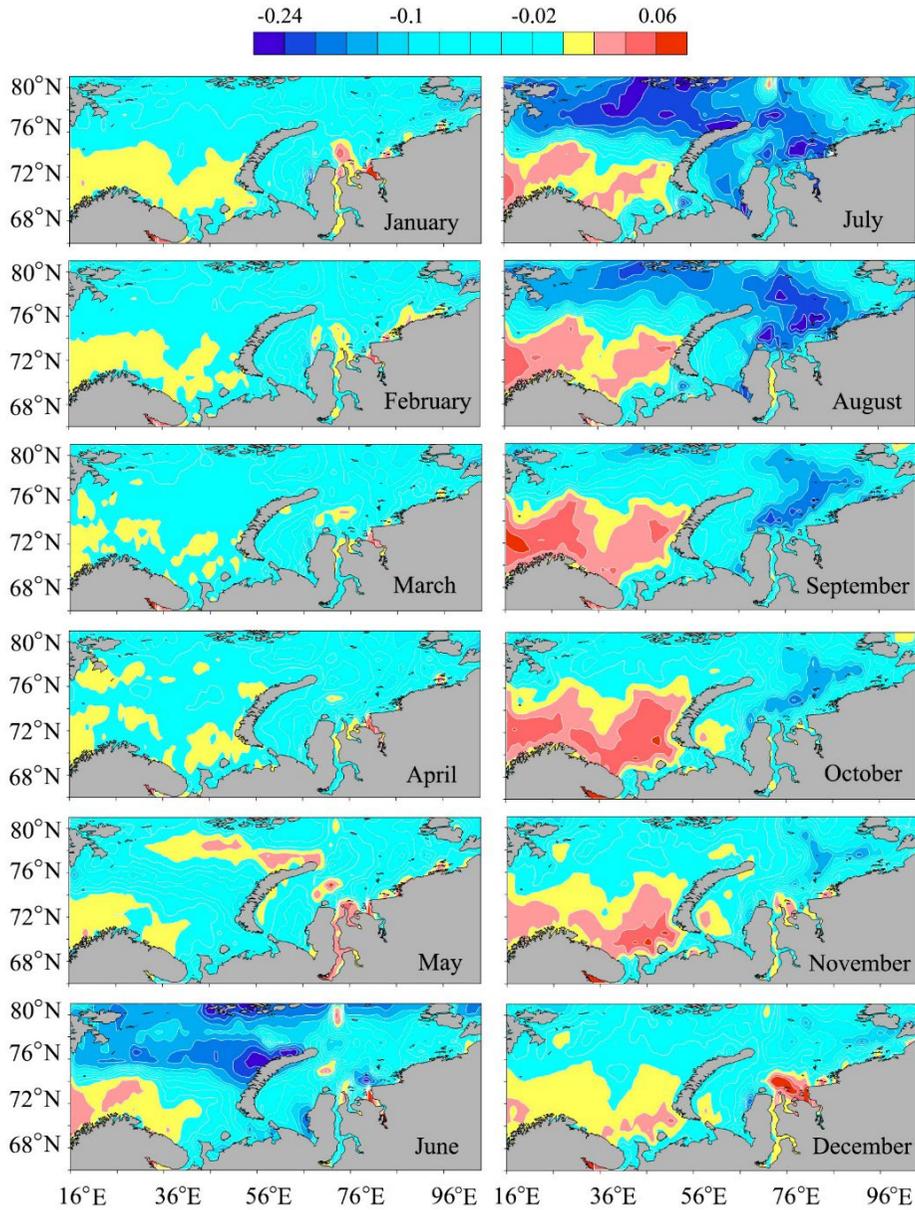
F i g. 2. Spatial distribution of the coefficients of linear trends of $N_{max}(z)$ ((cycle/hour)/year) in the Barents and Kara seas (1958–2022)

To assess the impact of global climatic processes on the stratification of the Arctic seas, the relationship between the maximum buoyancy frequency and atmospheric circulation indices NAO (North Atlantic Oscillation) [2], AO (Arctic

[2] Firenzemeteo. *North Atlantic Oscillation Index [NAO Index]*. [online] Available at: https://www.firenzemeteo.it/en/teleconnections/nao-north-atlantic-oscillation-index.php [Accessed: 22 February 2025].

Oscillation) [3], and GSNW (Gulf Stream North Wall) was studied. For each month of the period 1958–2022, at each grid node, the correlation coefficient between $N_{max}(z)$ and NAO, AO, and GSNW was calculated. Analysis of the results revealed that a significant correlation (95% confidence level) is observed between $N_{max}(z)$ and AO, and between $N_{max}(z)$ and GSNW in August (Fig. 3). The significant correlation coefficients (R) are negative and localized in areas of maximum negative linear trends of $N_{max}(z)$ (Fig. 2).
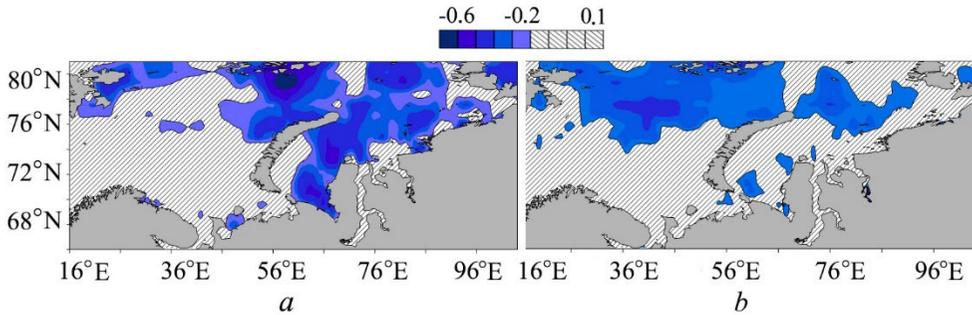

F i g. 3. Spatial distribution of correlation coefficients between $N_{max}(z)$ and AO (*a*), and $N_{max}(z)$ and GSNW (*b*) in August (1958–2022)

The Arctic Oscillation index indirectly characterizes the dependence of the hydrology of the Arctic seas on the penetration of warm Atlantic waters. During the positive phase of the AO, the central Arctic is occupied by a low-pressure area, which facilitates the inflow of Atlantic waters. During the negative phase of the AO, a high-pressure area is located over the Arctic, reducing the influx of Atlantic waters [4]. The negative R between $N_{max}(z)$ and AO in the region of negative trends of the maximum buoyancy frequency suggests that an increased inflow of Atlantic water into the Barents and Kara seas leads to a decrease in $N_{max}(z)$, and conversely, a decrease in the influx of Atlantic waters contributes to an increase in $N_{max}(z)$.

The GSNW values characterize the position of the Gulf Stream North Wall – the front of warm waters in the Atlantic Ocean. The higher the index value, the further north the current extends [26–28]. The significant negative correlation coefficients between $N_{max}(z)$ and GSNW in August in the region of negative trends of the maximum buoyancy frequency may indicate that an increase in the intensity of the Gulf Stream causes a decrease in $N_{max}(z)$, and conversely, a weakening of the current leads to an increase in $N_{max}(z)$.

No significant correlation was found between $N_{max}(z)$ and NAO.

Fig. 4 illustrates the spatial distribution of the coefficients of linear trends for the depth of the maximum Brunt–Väisälä frequency in the Barents and Kara seas. It can be seen that in July and August, over almost the entire water area of the seas,

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[3] Firenzemeteo. *Arctic Oscillation Index: Arctic Atmospheric Circulation Analysis*. [online] Available at: https://www.firenzemeteo.it/en/teleconnections/ao-arctic-oscillation-index.php [Accessed: 22 February 2025].

[4] Drozdov, O.A., Vasilyev, V.A., Kobysheva, N.V., Raevsky, A.N., Smekalova, L.K. and Shkolny, E.P., 1989. *Climatology*. Leningrad: Gidrometeoizdat, 568 p. (in Russian).

the values of the linear trend in $HN_{max}(z)$ are close to zero. From December to June, negative trends are noted in the Kara Sea in the zone affected by the runoff of the Ob and Yenisei rivers. The coefficient values do not exceed −0.5 m/year. From September to November, tendencies towards a decrease in $HN_{max}(z)$ prevail in the western, central, and eastern parts of the Barents Sea. The linear trend coefficients reach their greatest value ($\sim$ −3.5 m/year) in the Bear Island Trough area in November. From December to June, both positive and negative trends are observed. The coefficients of maximum positive trends do not exceed 2 m/year.
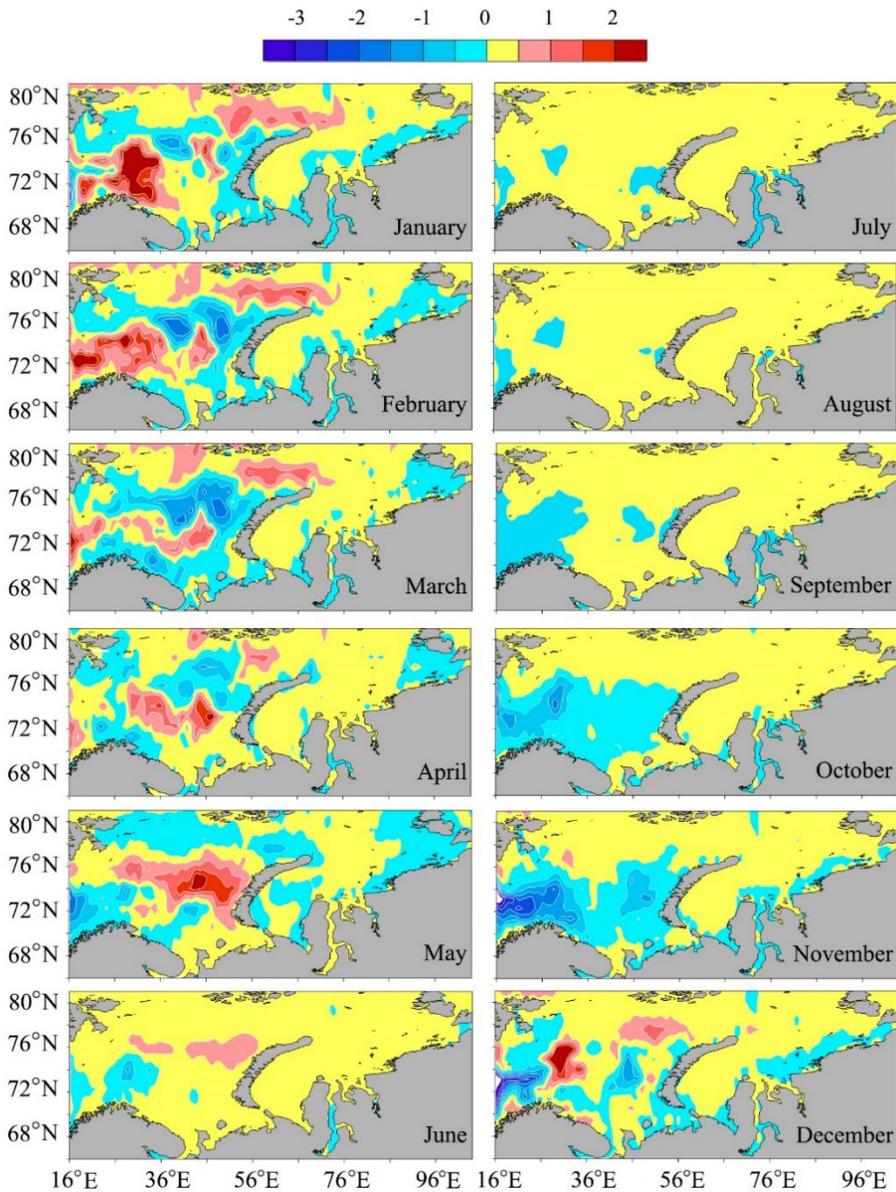
F i g. 4. Spatial distribution of the coefficients of linear trends in $HN_{max}(z)$ (m/year) in the Barents and Kara seas (1958–2022)

Analysis of the relationship between trends in the maximum Brunt–Väisälä frequency and its depth showed that, overall, these quantities changed in opposite phases over the period 1958–2022. In areas where a tendency for an increase in $N_{max}(z)$ is observed, the trend in $HN_{max}(z)$ is negative, and conversely, where $N_{max}(z)$ decreases, $HN_{max}(z)$ increases (Fig. 2, 4). The assertion that these two quantities vary in opposite phases means that an increase in $N_{max}(z)$ corresponds to a shift of the depth of maximum density gradients closer to the surface, while a decrease in $N_{max}(z)$ is accompanied by its deepening. The exceptions are January and February, when the value of R is close to zero. The correlation coefficient between the linear trends of $N_{max}(z)$ and $HN_{max}(z)$ reaches maximum values (R_{max}) of −0.62 (Barents Sea) and −0.38 (Kara Sea) in August (Fig. 5). The average correlation coefficient (R_{avg}) for the Barents Sea is ∼ −0.33, and for the Kara Sea ∼ −0.21. The calculated correlation coefficients are significant [5].
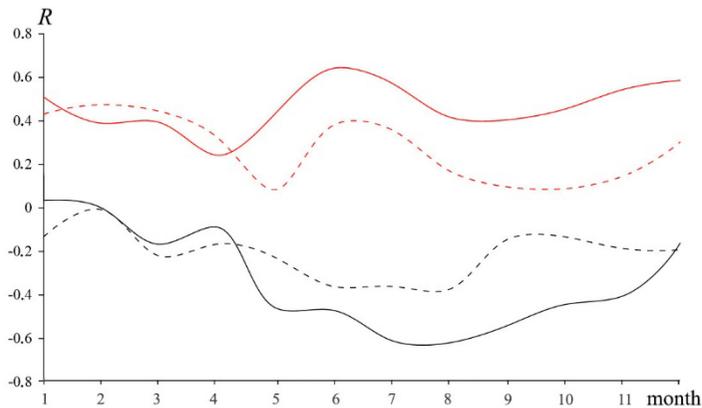

F i g. 5. R between the coefficients of linear trends: $N_{max}(z)$ and $HN_{max}(z)$ (black lines), and $W_{max}^{(1)}(z)$ and $HW_{max}^{(1)}(z)$ (red lines). The solid line shows the Barents Sea, and the dashed line the Kara Sea (1958–2022)
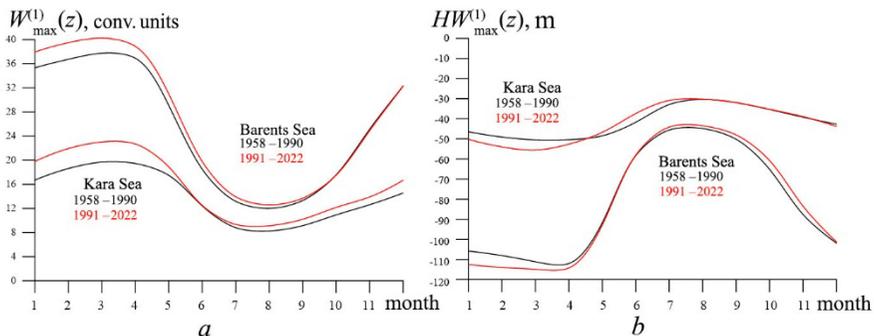

F i g. 6. Annual average values of $W_{max}^{(1)}(z)$ (a) and $HW_{max}^{(1)}(z)$ (b) in the Barents and Kara seas

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[5] Brooks, C.E.P. and Carruthers, N.B., 1953. *Handbook of Statistical Methods in Meteorology*. London: Her Majesty's Stationery Office, 412 p.
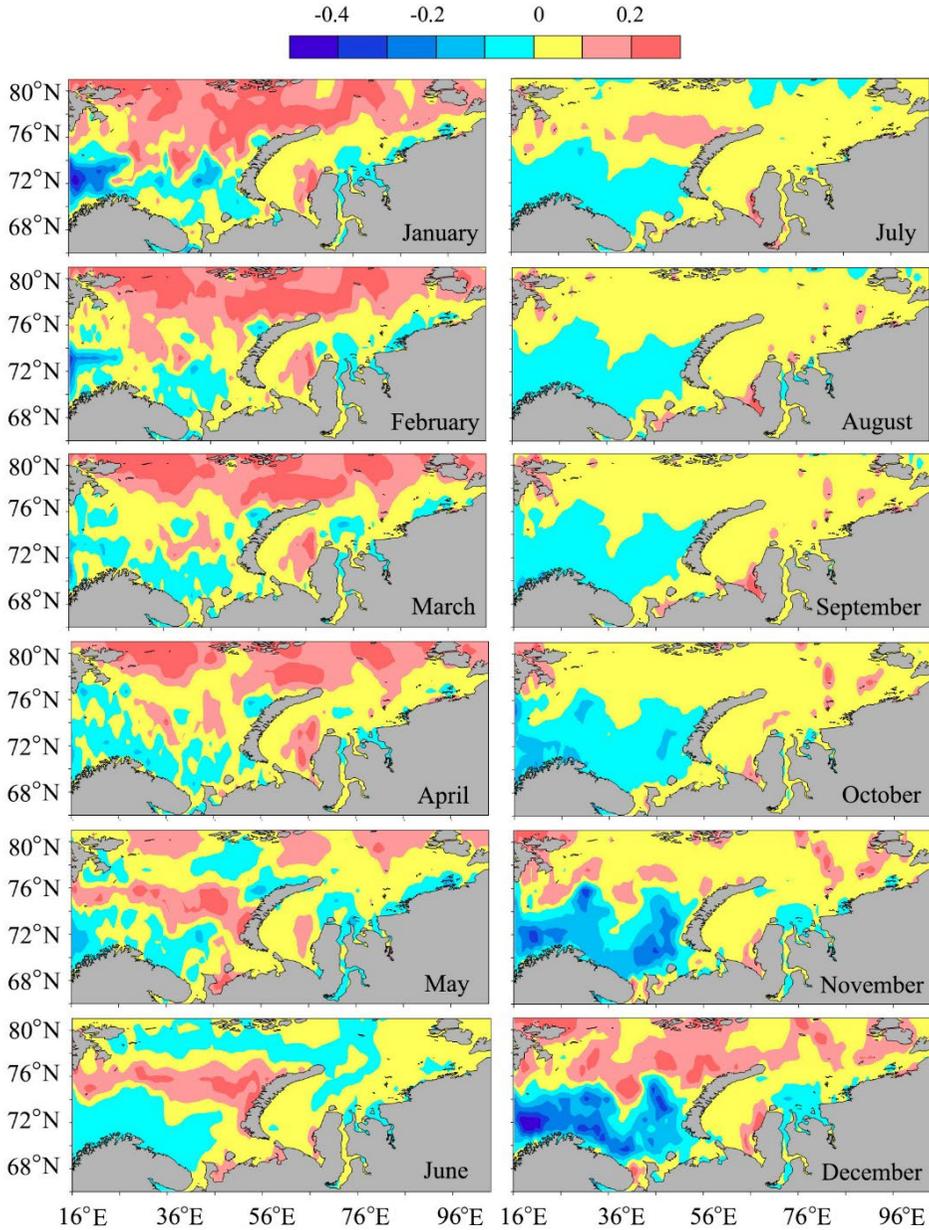
F i g. 7. Spatial distribution of the coefficients of linear trends in $W_{max}^{(1)}(z)$ (conv. units/year) in the Barents and Kara seas (1958–2022)

Long-term changes in the hydrological structure of waters inevitably lead to changes in the dynamic characteristics of IWs. The sea-average climatological maximum of the amplitude of the vertical velocity component of the first-mode IW $(W^{(1)}{}_{max}(z)_{avg})$ has a tendency to increase in both the Barents and Kara Seas during the cold half-year (Fig. 6, *a*). Thus, from January to May, the difference between

the values of $W^{(1)}_{max}(z)_{avg}$ averaged over 1958–1990 and those averaged over 1991–2022 reaches $\sim 25\%$ (Fig 6, *a*). In these same months, there is a trend towards deepening of $W^{(1)}_{max}(z)_{avg}$, but in the remaining months it is less than or equal to zero (Fig 6, *b*).
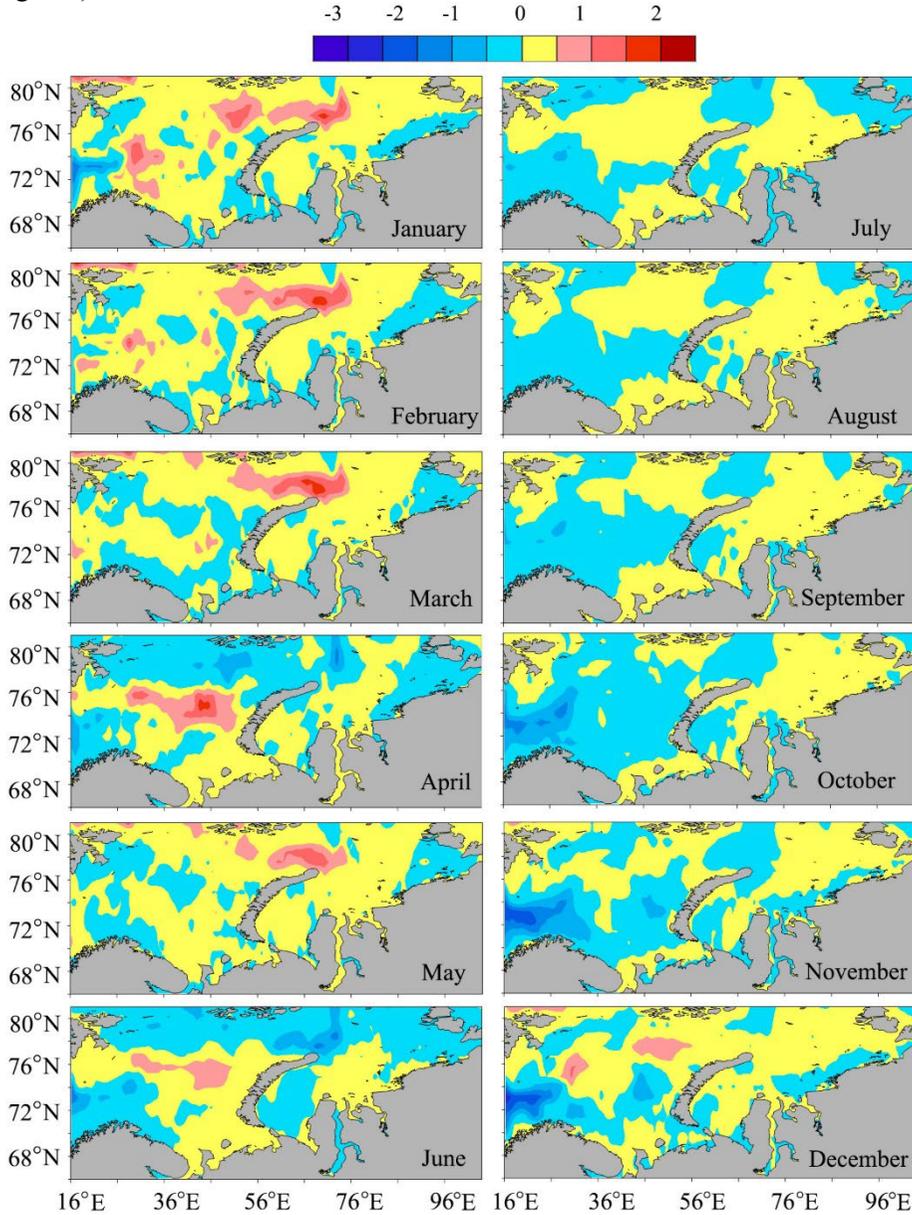

F i g. 8. Spatial distribution of the coefficients of linear trends in $HW^{(1)}_{max}(z)$ (m/year) in the Barents and Kara seas (1958–2022)

From December to April, positive trends of $W^{(1)}_{max}(z)$ are observed in the northern regions of the Barents and Kara Seas (Fig. 7). In May–July, positive trends are localized in the central part of the Barents Sea in the area between

the Persey and Central Uplands. Negative trends of $W_{max}^{(1)}(z)$ are observed throughout the year in the zone affected by Atlantic waters. The greatest values of negative coefficients of the linear trend in $W_{max}^{(1)}(z)$ do not exceed −0.5 conv. units/year in December in the area of the Bear Island Trough (Fig. 7).

Analyzing the geographical distribution of the coefficients of linear trends in $HW_{max}^{(1)}(z)$ (Fig. 8), we note that from May to November, tendencies towards a decrease in $HW_{max}^{(1)}(z)$ are observed over a significant part of the sea area (the north and south of the Barents Sea, and the north of the Kara Sea). The largest values of the linear trend coefficients of $HW_{max}^{(1)}(z)$ do not exceed −2 m/year in November in the area of the Bear Island Trough. From December to April, many small areas with positive and negative trends are located throughout the water area, where the values of the trends in $HW_{max}^{(1)}(z)$ are small. The coefficients of negative trends during this time do not exceed –0.5 m/year, and positive ones do not exceed 2 m/year.

The correlation coefficients between the trends of $W_{max}^{(1)}(z)$ and $HW_{max}^{(1)}$ are positive (Fig. 5): their average value is ~ 0.47 in the Barents Sea and ~ 0.28 in the Kara Sea. This means that the variability trends of $W_{max}^{(1)}(z)$ and $HW_{max}^{(1)}(z)$ coincide. Note that the R_{max} between the trends of $W_{max}^{(1)}(z)$ and $HW_{max}^{(1)}(z)$ is ~ 0.64 in the Barents Sea in June, and ~ 0.47 in the Kara Sea in February.

The variability trends of the maximum buoyancy frequency and the amplitude of the vertical velocity component of the first-mode IW have R_{avg} ~ −0.66 in the Barents Sea and R_{avg} ~ −0.51 in the Kara Sea, indicating a significant relationship between these characteristics (Fig. 9). The correlation coefficients between $N_{max}(z)$ and $W_{max}^{(1)}(z)$ reach their maximum values in November: in the Barents Sea R_{max} is ~ −0.73, and in the Kara Sea R_{max} is ~ −0.6.

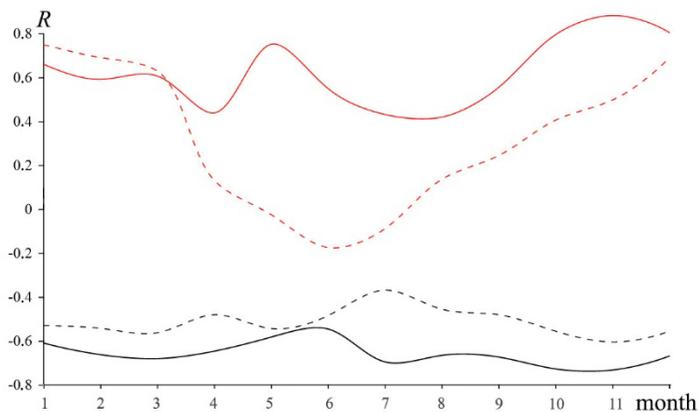**F i g. 9.** R between the coefficients of linear trends: $N_{max}(z)$ and $W_{max}^{(1)}(z)$ (black lines), $HN_{max}(z)$ and $HW_{max}^{(1)}(z)$ (red lines). The solid line shows the Barents Sea, and the dashed line the Kara Sea (1958–2022)

The relationship between the trends of $HN_{max}(z)$ and $HW_{max}^{(1)}(z)$ in the Barents and Kara Seas has significant differences (Fig 9). In the Barents Sea, the correlation

coefficients between $HN_{\max}(z)$ and $HW^{(1)}_{\max}(z)$ are positive throughout the year, with $R_{\max} \sim 0.88$ in November. In the Kara Sea, from April to August, the correlation coefficients are negative or close to zero, with $R_{\max} \sim 0.75$ in January.

Conclusion

Based on ORAS5 reanalysis data, this work investigates the spatial-temporal variability of the hydrophysical characteristics of waters in the Barents and Kara Seas on a climatological scale.

Atlantic water in the Arctic Ocean and Arctic seas is a layer of water with positive temperatures in the depth range of 150–900 m. The influence of Atlantic water on the ice cover is weakened by its isolation from the ocean surface by an intermediate high-gradient layer (the halocline), which hampers vertical heat transfer. This holds true for most of the Arctic Basin, except for areas where the upper boundary of Atlantic water is located close to the surface. The maximum Brunt–Väisälä frequency and its depth characterize the thickness and depth of the high-gradient layer that attenuates the impact of Atlantic water on ice. Understanding the trend in the development of the layer of maximum density gradients is important for predicting the impact of warm Atlantic water on the ice cover of the Arctic seas and the Arctic Ocean.

Changes in the vertical structure of the density field lead to the transformation of the IW properties, which play an important role in the dynamics of oceans and seas. Internal waves affect energy exchange processes and contribute to water mixing, which is essential for the life of marine organisms. Information on the spatial-temporal variability of IW characteristics in the Arctic seas can be used for planning fishing activities in commercial areas. This is based on known conclusions about the relationship between plankton biomass density and IW height, which is proportional to the amplitude of the vertical velocity component of the IW.

As a result of the performed research, it was found that over the time period 1958–2022, the sea-average climatological maximum of the buoyancy frequency has a tendency to decrease and deepen in both the Barents and Kara seas.

The largest positive trends of the maximum Brunt–Väisälä frequency are observed in the southern part of the Barents Sea in June – November, the largest negative trends are observed in June – August in the region of Franz Josef Land, Svalbard, and the Central Kara Upland.

From December to June, in the central part of the Barents Sea, positive trends in the depth of the maximum buoyancy frequency alternate with negative ones, while in July and August they are close to zero over the entire sea area. From September to November, tendencies towards a decrease in the layer depth of maximum density gradients prevail in the western and central parts of the Barents Sea. In the Kara Sea, in the zone affected by the runoff of the Ob and Yenisei rivers, from December to June negative trends are noted in the depth of the maximum Brunt–Väisälä frequency. In the remaining months, the climatological variability of the depth of the layer of maximum density gradients is close to zero.

It is shown that the sea-average climatological maximum of the amplitude of the vertical velocity component of the first-mode IW has a tendency to increase and deepen in both the Barents and Kara Seas during the cold half-year. The largest positive trends in the maximum amplitude of the vertical velocity component of

the first-mode IWs are observed from December to April in the northern regions of the Barents and Kara Seas. The largest negative trends are observed from November to January in the southern part of the Barents Sea.

From May to November, tendencies towards a decrease in the depth of the maximum amplitude of the vertical velocity component of the first-mode IW prevail over a significant part of the sea area (the north and south of the Barents Sea, and the north and east of the Kara Sea). In the remaining months, both positive and negative trends are observed in the Barents Sea water area, while in the Kara Sea climatological variability in the depth of the maximum values of the vertical velocity component of the first-mode IW is practically absent.

The maxima of the buoyancy frequency and the amplitude of the vertical velocity component of the first-mode IW vary in opposite phases in both the Barents and Kara Seas. The correspondence between the climatological variability of the depths of the maximum buoyancy frequency and the amplitude of the vertical velocity component of the first-mode IW differs markedly in the Barents and Kara Seas: in the Barents Sea, the correlation coefficients are positive throughout the year, while in the Kara Sea, from April to August, they are negative or close to zero.

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The authors declare that they have no conflict of interest.