ISSN 1573-160X, *PHYSICAL OCEANOGRAPHY*, Vol. 30, Iss. 4, pp. 428-437 (2023)
Original Russian Text © A. A. Bukatov, E. A. Pavlenko, N. M. Solovei, 2023,
published in *Morskoy Gidrofizicheskiy Zhurnal*, 2023, Vol. 39, Iss. 4, pp. 467–477.

Original article

River Runoff Impact on the Density Vertical Stratification of the Eastern Arctic Chukchi and Beaufort Seas

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Abstract
Purpose. The aim of the study is to analyze the river runoff impact on density stratification in the Chukchi and Beaufort seas, and to identify the areas where the response to seasonal fluctuations in the river runoff volumes is the most pronounced.
Methods and Results. Based on the ECMWF ORAP5 reanalysis data on the monthly mean values of temperature and salinity for May – September of each year, the water density in the Chukchi and Beaufort seas was calculated. To study the river runoff impact on the density stratification of sea water, applied were the calculated maximum monthly average values of the Väisälä – Brunt frequency over depth at each grid node, and the monthly average water discharges in the closing gates of the Kolyma, Yukon and Mackenzie rivers for the period 1979–2013. The results of statistical analysis showed that density stratification of the Chukchi and Beaufort seas was most strongly affected by the Mackenzie and Yukon river runoffs for a previous month and also by the Kolyma river runoff for 3 and 6 previous months.
Conclusions. The impact of the Mackenzie runoff is found to be most pronounced from July to September. The areas of statistically significant correlation coefficients between the buoyancy frequency and the runoff volumes for the previous month are in the southeastern and central parts of the Beaufort Sea. The areas where the impact of the Yukon runoff is pronounced are in the Bering Strait area, in the northern region of the Chukchi Sea, and on the western periphery of the Beaufort gyre. The Kolyma runoff impact on the water density stratification is manifested near the western coast of the Chukchi Sea, in the Bering Strait area, the Kotzebue Bay, and on the southwestern periphery of the Beaufort gyre.

Keywords: Chukchi Sea, Beaufort Sea, water density stratification, buoyancy frequency, river runoff, rivers Mackenzie, Yukon and Kolyma

Acknowledgements: The investigation was carried out within the framework of the state assignment on theme FNNN-2021-0004.

For citation: Bukatov, A.A., Pavlenko, E.A. and Solovei, N.M., 2023. River Runoff Impact on the Density Vertical Stratification of the Eastern Arctic Chukchi and Beaufort Seas. *Physical Oceanography*, 30(4), pp. 428-437.

Introduction

Features of the Arctic Ocean hydrological regime are largely associated with a great continental runoff. The smallest of the oceans, the Arctic Ocean, receives the largest amount of fresh water inflowing along with the rivers of Eurasia and America [1]. The continental runoff layer in the Arctic Basin is 7 times greater than the runoff layer in the entire World Ocean [1]. Salinity and ice cover formation in

[1] Nikiforov, E.G. and Shpayher, A.O., 1980. [*Patterns of Formation of Large-Scale Fluctuations of the Hydrological Regime of the Arctic Ocean*]. Leningrad: Gidrometeoizdat, 270 p. (in Russian).

the seas of the Arctic Ocean are largely determined by the inflow of river waters [2].

In the process of interaction of river waters with more saline deep waters, significant vertical gradients of salinity and density are formed [3]. The layer of maximum density gradients and its depth affect vertical distribution of nutrients, suspended mineral and organic substances, pollution, as well as sea ice formation and distribution [4–6]. Vertical density stratification and its stability are characterized and can be represented by the vertical profile of buoyancy frequency (Brunt – Väisälä frequency), which is a fundamental quantity in the dynamics of a stratified fluid. In [7, 8], the regional features of the buoyancy frequency distribution in the Barents, Kara, Laptev, and East Siberian seas are considered, and the correlations between the Brunt – Väisälä frequency maximum in depth and climatic indices reflecting the state of the atmosphere and hydrosphere are assessed. In [9, 10], a study of the Arctic river runoff impact on the density stratification of the waters of the Barents, Kara, Laptev, and East Siberian seas is performed.

The purpose of this study is to analyze the river runoff impact on the density stratification of the waters of the Chukchi and Beaufort seas and to identify areas with the most pronounced response to seasonal fluctuations in river runoff.

Materials and methods

The ECMWF ORAP5 reanalysis arrays of monthly average temperature and salinity values at the nodes of 0.25° × 0.25° grid for the period of 1979–2013 were used as initial hydrological data [2] [11]. The study area is limited by the coordinates 65º–80°N, 125º–180°W. According to the monthly average values of temperature and salinity for May – September of each year, the water density was calculated [3]. The obtained data were tested for inversion and corrected by replacing them with values interpolated from neighboring horizons. For each grid node, the monthly average profiles of the Brunt – Väisälä frequency values (N, cycle/h) 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 density. The maximum of the Brunt – Väisälä frequency ($N_{max}(z)$, cycle/h) was determined by depth.

To study the river runoff impact on the density stratification of the waters of the Chukchi and Beaufort seas, we used the monthly average values of $N_{max}(z)$ at each grid node and the monthly average water discharges of the Kolyma, Yukon,

[2] Zuo, H., Balmaseda, M.A. and Mogensen, K., 2015. The *ECMWF-MyOcean2 Eddy-Permitting Ocean and Sea-Ice Reanalysis ORAP5. Part 1: Implementation.* Shinfield Park, Reading: ECMWF, 42 p. doi:10.13140/RG.2.1.3305.2248

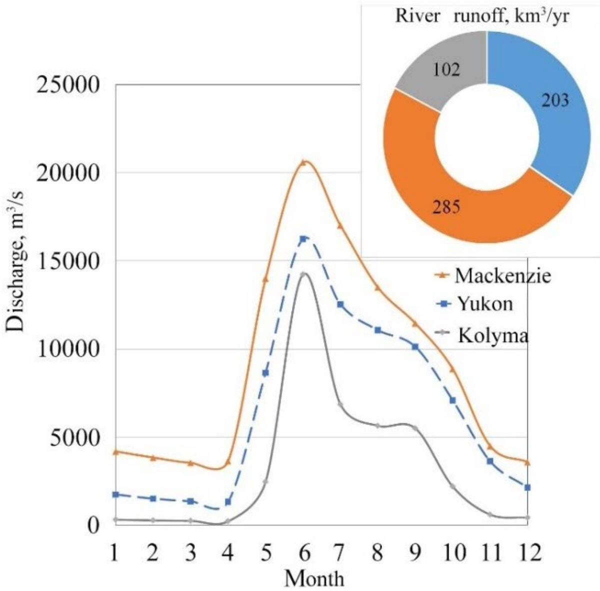
[3] Bezrukov, Y.F., 2006. [*Oceanology. Part I. Physical Phenomena and Processes in the Ocean*]. Simferopol: V.I. Vernadsky Taurian National University, 159 p. (in Russian).

and Mackenzie rivers in the outflow gates for 1979–2013 [4]. Based on the correlation analysis, the coefficients of pairwise linear correlation between $N_{max}(z)$ and water discharges for the previous month (R_1), as well as coefficients R_3, R_6 between the values of $N_{max}(z)$ and the total average monthly discharges for 3 and 6 previous months were obtained. Areas (S) of the regions of statistically significant coefficients R_1, R_3, R_6 (90% confidence interval) were calculated.

Analysis of results

The structure of the Chukchi Sea and the Beaufort Sea waters is formed under the effect of interaction of the surface Arctic waters, the Pacific waters entering through the Bering Strait, and the continental runoff waters. According to various estimates, the runoff of the **Mackenzie**, the largest river in the Arctic Basin in the Western Hemisphere, is 5–10% of the total inflow of fresh water into the Arctic Ocean; the average annual runoff for the period under consideration is 285 km^3 (Fig. 1); the average Mackenzie water discharge is 9053 m^3/s, the maximum is observed in June (20579 m^3/s).

The Yukon River flows into the Bering Sea (the Pacific Ocean Basin), but the Alaska coastal current carries the river runoff into the Arctic Ocean. The Yukon runoff ranks fifth after the Yenisei, Ob, Lena and Mackenzie in terms of fresh water inflow into the Arctic Ocean and is ~ 8% of the total inflow; the average annual volume of river runoff for the period under review is 203 km^3 (Fig. 1); an average water discharge at the Pilot Station gauging station is 6447 m^3/s, the maximum is observed in June (16237 m^3/s).

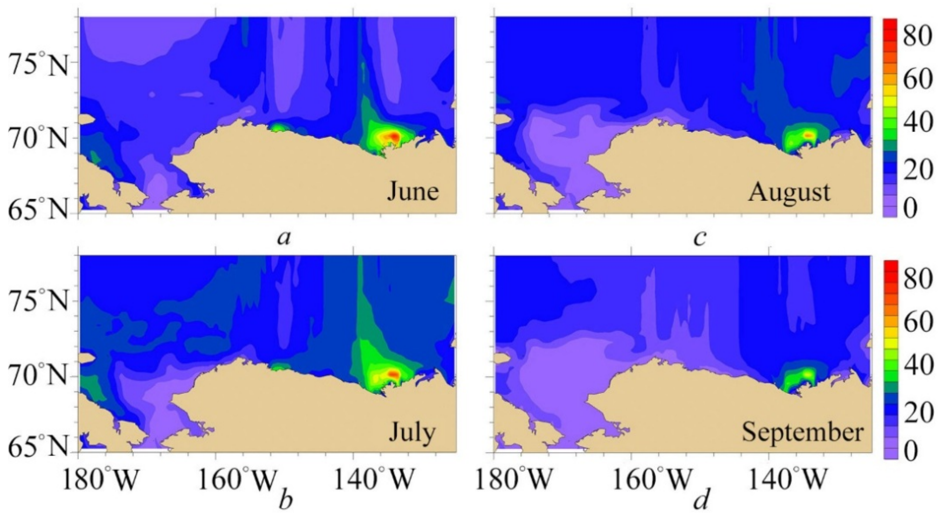


F i g. 1. Average long-term hydrograph of the Yukon, Kolyma and Mackenzie river runoffs calculated for the period 1979–2013

[4] McClelland, J.W., Tank, S.E., Spencer, R.G.M., Shiklomanov, A.I., Zolkos, S. and Holmes, R.M., 2023. *Arctic Great Rivers Observatory. Discharge Dataset, Version 20230810*. [online] Available at: https://arcticgreatrivers.org/discharge/ [Accessed: 20 June 2022].

The runoff of Siberian rivers also has a noticeable effect on the hydrological conditions of the Chukchi and Beaufort seas. The average annual runoff of the **Kolyma** River was 102 km^3 for 1979–2013 (Fig. 1); the average water discharge is 3247 m^3/s, the maximum is observed in June (14230 m^3/s). The lens formed by the runoff of Siberian rivers is the largest desalinated lens in the World Ocean in terms of area [12]. With an increase in atmospheric cyclonic circulation in the European part of the Arctic, freshened and cold waters of the lens enter the Chukchi Sea through the Long Strait with the alongshore Siberian Coastal Current, enter the Bering Strait and spread near its western coast. At a weak development of the Siberian Coastal Current, desalinated waters reach the northern regions of the Chukchi Sea and then are involved in the circulation of the Beaufort Sea, increasing the amount of fresh water in this area [13].

The maximum stability of waters in the Chukchi Sea occurs in July, in the Beaufort Sea – in June (Fig. 2, *a*, *b*). Near the western coast of the Chukchi Sea, in the area of impact of the Siberian Coastal Current desalinated waters, density stratification is the highest. River waters, due to their low density, spread over the surface of cold sea waters, and significant vertical density gradients are formed. The maximum values of the Brunt – Väisälä frequency reach 34 cycle/h in June and 37 cycle/h in July. The thickness of the upper homogeneous layer is ~ 7 m [14]. In the north, where the desalinated and cold waters of the East Siberian Sea, the Beaufort Sea, and the central part of the Polar Basin get, the density jump layer can be traced throughout the year. In summer, the pycnocline is located at 12–15 m depths; the maximum values of the Brunt – Väisälä frequency are 28–30 cycle/h in July near the Arctic coast of Alaska [14] (Fig. 2, *b*).



F i g. 2. Distribution of the Brunt – Väisälä frequency maximum values (cycle/h) in the Chukchi and Beaufort seas in June – September

The Pacific waters are one of the sources of heat, fresh water [15], and nutrients [16] for the Arctic Ocean. In summer, they almost completely fill the Bering Strait, and their surface layer is desalinated by the Yukon River runoff, and the deeper layers have a salinity characteristic of the Bering Sea waters. Passing through the Chukchi Sea shelf, the Pacific waters spread to the north and east in the form of a surface current. At the latitudes of the Kotzebue Bay (~ 66°N), they are connected with the waters of this bay, desalinated by the continental runoff. Salinity varies relatively little from the surface to the bottom, and only near the ice edge the cooled Pacific waters submerge under the less dense, although colder, surface Arctic waters[1]. As a result, stratification in the Chukchi Sea southern and central regions is less pronounced than in the northern and western regions. The maximum buoyancy frequency in the area of the Bering Strait is ~ 15 cycle/h, in the central region of the Chukchi Sea – 20 cycle/h (Fig. 2, *b*). The seasonal pycnocline occurs at a depth of ~ 11 m in the area of the Bering Strait and in the central part of the sea. In autumn, vertical stratification decreases mainly due to convective-wind mixing and salinization of surface waters during ice formation.

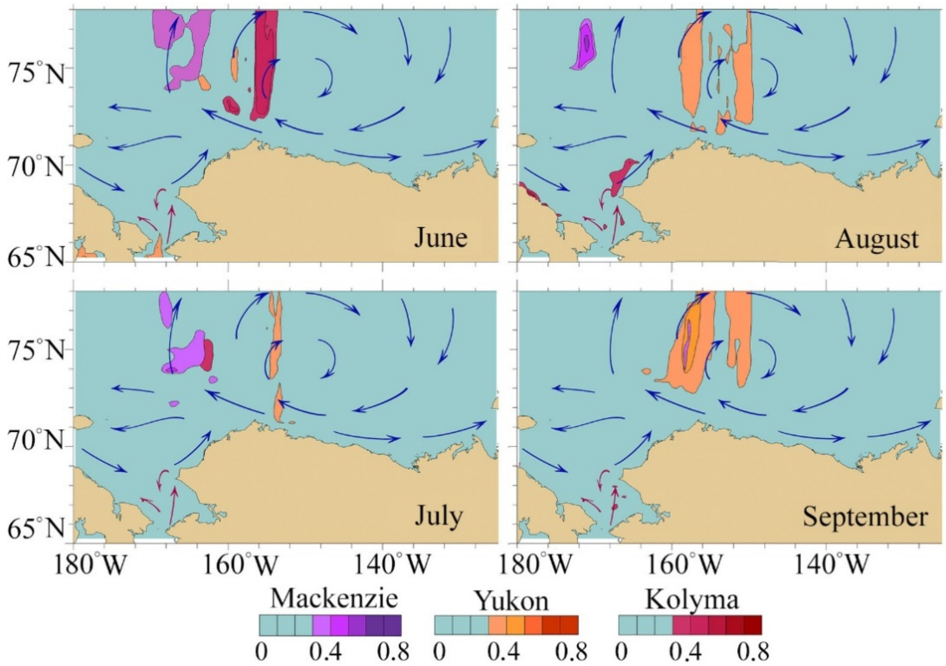
In the Beaufort Sea, as well as in the Chukchi Sea, Pacific waters play an important role in the formation of hydrological structure. Clearing from ice, the water area of the Beaufort Sea in summer is filled with warm Pacific waters, and in the marginal areas and in the area affected by the Mackenzie runoff, these waters submerge under fresh water, forming a depth temperature maximum [1]. An analysis of the spatial distribution of the buoyancy frequency maximum in June – September showed that its greatest values are determined in the influence zone of the Mackenzie runoff in June (~ 80 cycle/h) and in July (~ 74 cycle/h). In marginal regions, the values of this parameter reach 25–30 cycles/h with a maximum in July.

A Polar vortex of the Northern Hemisphere forms an anticyclonic distribution of the wind field over the Arctic Ocean surface [17]. As a result of the Ekman pumping, the wind causes convergence of waters of the near-surface layer. The waters of low salinity and low density are involved in this process, as a result of which an anomaly of desalinated waters is formed in the area of the Beaufort Sea Gyre [1] due to the inflow through the Bering Strait and the Mackenzie runoff, as well as due to intensification of atmospheric cyclonic circulation in the European part of the Arctic under effect of the inflow from Siberian rivers. The values of maximum buoyancy frequency in the area of the Beaufort Sea Gyre are small, ~ 10 cycle/h.

Analysis of the results revealed that the Beaufort Sea hydrological conditions are significantly affected by the Mackenzie runoff. In June, the areas of significant R_1 coefficients are located in the southeastern region and shift eastwards relative to the Mackenzie mouth under effect of easterly currents that are present in the area where the river flows into the sea. The maximum R_1 value at that time was 0.46, and the area of regions of significant correlation coefficients was 9700 km^2 (~ 2% of the total sea area).

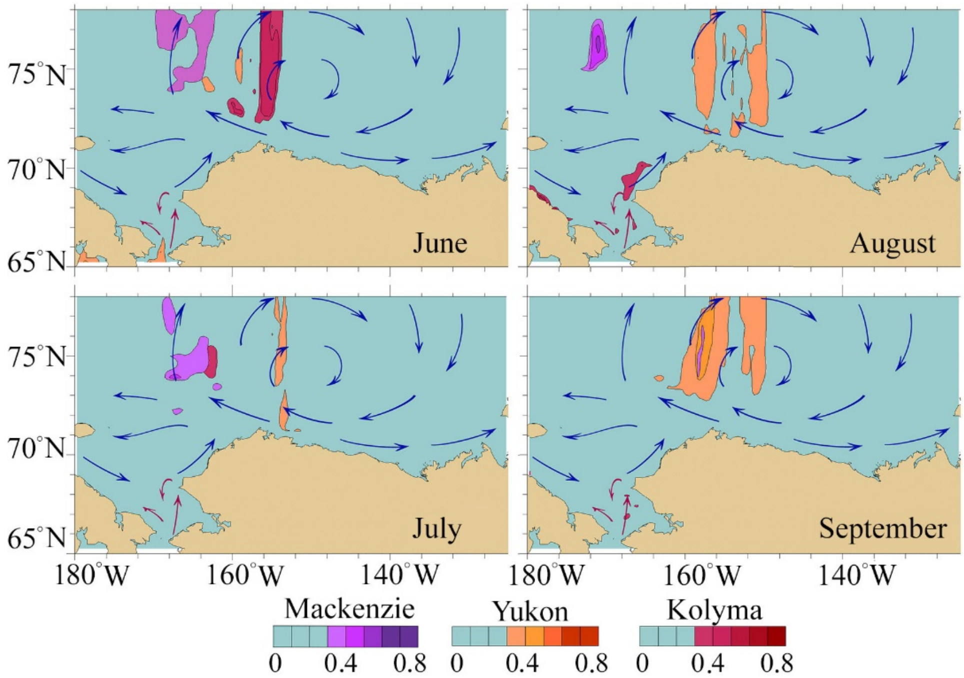
In July – September, the areas of significant R_1 coefficients shift towards the central part of the Beaufort Sea under the effect of anticyclonic gyre currents, directed mainly to the west or southwest. R_1 reaches its maximum value (0.60) in

September (Fig. 3), maximum S (~ 103700 km^2, ~ 22% of the total sea area) can be traced in July. The correlation coefficients R_3 between the maximum values of the Brunt – Väisälä frequency and the total monthly average Mackenzie discharges for the previous three months are statistically significant at the western periphery of the Beaufort Gyre. The maximum value of R_3 (0.54) can be traced in August (Fig. 4). An analysis of correlations between the maximum values of the Brunt – Väisälä frequency and the Mackenzie runoff volumes over the previous 6 months showed that R_6 is significant in August and reaches 0.52 (Fig. 5). The areas of significant R_6 are located in the north of the Chukchi Sea, S is ~ 2700 km^2.



F i g. 3. Distribution of the correlation coefficients R_1 between the Brunt – Väisälä frequency maximum values and the Yukon, Mackenzie and Kolyma river runoff volumes. Highlighted areas are the regions of statistically significant values of the R_1 coefficients. The surface circulation scheme is shown by arrows

From Fig. 3 it is obvious that the correlation coefficients R_1 between the Brunt – Väisälä frequency maxima in depth and the volumes of the Yukon runoff for the previous month are significant in the area of the Bering Strait in June and July and amount to 0.45. These coefficients are also statistically significant in the Chukchi Sea northeastern region and on the western periphery of the Beaufort Gyre, where the waters of the Alaska Coastal Current desalinated by the Yukon runoff get. In September, R_1 values are maximum (0.75), S is ~ 30400 km^2. The correlation analysis showed that the total Yukon discharges over the previous three months also affect variability of the Brunt – Väisälä frequency maximum, and the R_3 coefficients are statistically significant on the western and northwestern periphery of the Beaufort Gyre.

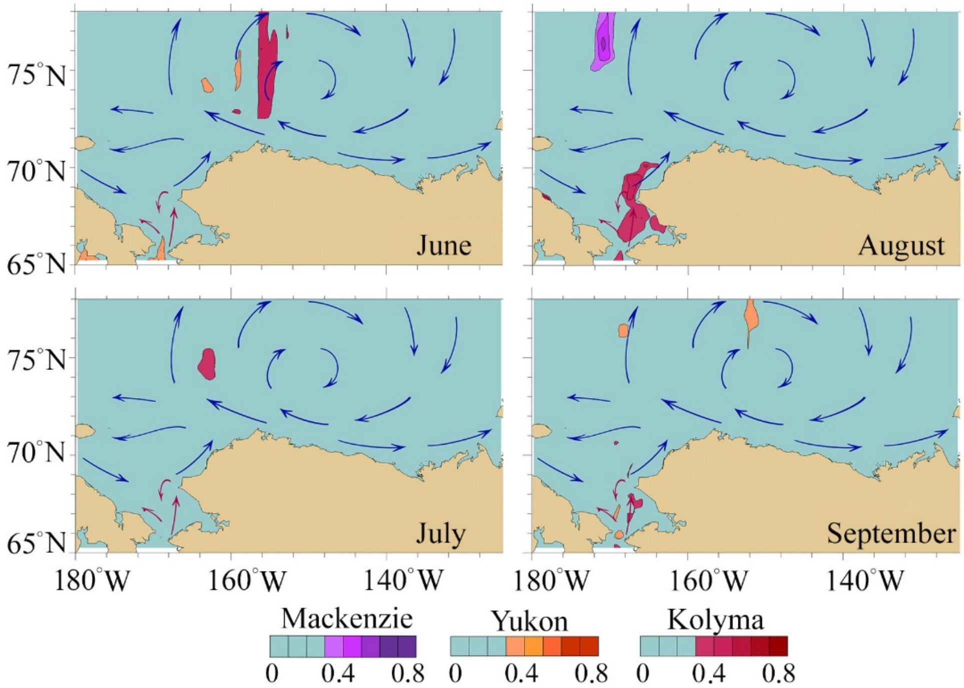


F i g. 4. Distribution of the correlation coefficients R_3 between the Brunt – Väisälä frequency maximum values and the Yukon, Mackenzie and Kolyma river runoff volumes. Highlighted areas are the regions of statistically significant values of the R_3 coefficients. The surface circulation scheme is shown by arrows

The R_3 values are the highest in September, reaching 0.55, and S is ~ 67100 km^2 (Fig. 4). The correlation coefficients R_6 between the maximum values of the Brunt – Väisälä frequency and the volumes of the Yukon runoff for the previous 6 months are significant in June and September, reaching 0.50 (Fig. 5). The areas of significant R_6 are located in the Bering Strait area, in the northeast of the Chukchi Sea and in the Beaufort Sea northern part.

The Kolyma runoff impact on the water density stratification is manifested near the western coast of the Chukchi Sea in the area of the effect of the Siberian Coastal Current desalinated waters. The correlation coefficients are also significant in the area of the Bering Strait, the Kotzebue Bay and at the southwestern periphery of the Beaufort Sea Gyre in June and July. The R_1 coefficients are maximum in June (~ 0.45), S is ~ 37200 km^2 (Fig. 3).

The correlation coefficients R_3 between the maximum values of the Brunt – Väisälä frequency and the total discharges of the Kolyma River over the previous three months are statistically significant at the western periphery of the Beaufort Gyre in June, July, and in August and September – near the Chukchi Sea western coast and in the Kotzebue Bay area. The R_3 coefficients reach their maximum in August (~ 0.51), and S – in June (~ 53300 km^2) (Fig. 4). The R_6 coefficients are also statistically significant. The areas in which they are recorded coincide with the ones for the R_3 coefficients. R_6 coefficients reach their maximum in August and September (~ 0.52), S – in August (~ 53300 km^2) (Fig. 5).



F i g. 5. Distribution of the correlation coefficients R_6 between the Brunt – Väisälä frequency maximum values and the Yukon, Mackenzie and Kolyma river runoff volumes. Highlighted areas are the regions of statistically significant values of the R_6 coefficients. The surface circulation scheme is shown by arrows

Conclusion

Based on ORAP5 reanalysis data over 1979–2013 period, a study of the impact of the Mackenzie, Yukon, and Kolyma river runoff on the density stratification of the Arctic Beaufort and Chukchi seas was carried out. The maximum stability of waters in the Chukchi Sea occurs in July, in the Beaufort Sea – in June. In the Chukchi Sea, the density stratification is most pronounced near the western coast, in the area of impact of the Siberian Coastal Current freshened waters. The Brunt – Väisälä frequency in the Chukchi Sea reaches its maximum value in June (34 cycle/h) and in July (37 cycle/h), in the Beaufort Sea – in the zone of the Mackenzie runoff impact in June (~ 80 cycle/h) and in July (~ 74 cycle/h), in the near-edge areas – in July (25–30 cycle/h).

The analysis of the results revealed that the Mackenzie and Yukon runoff for the previous month, and the Kolyma runoff for the previous 3 and 6 months, have the greatest impact on the density stratification of the Chukchi Sea and Beaufort Sea waters. It was determined that the Mackenzie runoff impact is most pronounced from July to September, the areas of significant R_1 coefficients are located in the southeastern and central parts of the Beaufort Sea. The R_1 coefficient maximum value is ~ 0.60. The areas of manifestation of the Yukon runoff impact are located in the Bering Strait region, in the Chukchi Sea northern region, and at the western periphery of the Beaufort Sea Gyre. The maximum values of the correlation coefficients are observed in September and amount to 0.75 for R_1. The Kolyma runoff impact on the density stratification of waters is manifested near the Chukchi Sea western coast, in the area of the Bering Strait, the Kotzebue Bay, and on the southwestern periphery of the Beaufort Sea Gyre. The maximum value of R_6 coefficients is observed in August and September and is ~ 0.52.

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Anton A. Bukatov – statement of the problem, analysis of the research data, analysis and revision of the text.

Ekaterina A. Pavlenko – development of the program algorithms, analysis and validation of results, preparation of graphic materials, preparation of the paper text, reviewing the literature

Nelya M. Solovei – development of the program algorithms, analysis of the results of numerical experiments, correction of the paper

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.