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Influence of Thermohaline Stratification on the Evolution of Coastal Upwelling on the Northeastern Shelf of Sakhalin

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Abstract—Satellite data on sea surface temperature and temperature and salinity profiles in the northeastern shelf of Sakhalin showed that during the periods of advection of warm and low-salinity water to the eastern shelf of Sakhalin, intensive coastal upwelling did not develop, even under favorable wind conditions. Regular deepening of the thermocline/halocline has prevented the rise of cold and salt water to the sea surface. Numerical experiments with the INMOM-JRA55-do model showed a significant deepening of the thermocline/halocline accompanied by the increasing density stratification, which prevented the elevating of the Sea of Okhotsk water to the sea surface. It is assumed that the joint monitoring of wind conditions and hydrology on the eastern shelf of Sakhalin in the second half of the year will significantly clarify the features of its development and more accurately assess the biological productivity of water in this area of the Sea of Okhotsk.

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INTRODUCTION

The eastern shelf of Sakhalin (the Sea of Okhotsk) is the area of intensive fishery and fattening of marine mammals. The monsoon change in the second half of the year leads to the development of coastal upwelling on the shelf [4, 11]. Southern winds responsible for the rise of the cold and salt water of the Sea of Okhotsk, which is rich in biogenic elements, make this region a unique place for studying the coastal upwelling and its influence on the biological productivity of shelf water.

Some studies [7, 8] based on instrumental observations in northeastern Sakhalin provided incontrovertible proofs of routine manifestations of coastal upwelling associated with the emergence of the cold and salt water on the sea surface. The analysis of satellite data on sea surface temperature (SST) and wind speed revealed a direct relationship between the intensity of coastal upwelling (the emergence of cold water on the sea surface) and wind forcing, which is characterized by the prevalence of the northward alongshore component and the spatial inhomogeneity (a positive wind stress curl) [3]. However, the peculiarities of the thermohaline stratification can have a significant effect on the evolution of coastal upwelling, even under favorable wind conditions.

A typical feature of hydrological fields on the northeastern shelf of Sakhalin is their strong dependence on river runoff. The warm and desalinated water of the Amur River forms the thermohaline stratification typical of this sea area [6, 11]. The authors of [7, 8] pointed out the formation of the frontal zone whose boundary is highly dependent on river runoff, as well as on the processes related to the dramatic change in the wind direction to the northern one along the eastern coast of Sakhalin. The thermohaline stratification formed by the advection of the warm and desalinated water can significantly complicate the pattern of intensive coastal upwelling, despite favorable wind conditions. The studies of the phenomenon in the Aegean and South China seas [12, 18] showed that river runoff in the coastal zone forms the subsurface barrier layer, which suppresses the intensive rise of deep water to the sea surface. In view of this, it is important to reveal the influence of the thermohaline stratification on the development of intensive coastal upwelling on the eastern shelf of Sakhalin, in particular, to improve the quality of forecasting/assessing the biological productivity of water in this area of the Sea of Okhotsk.

The objective of the present paper is to develop concepts of the influence of the thermohaline stratification formed by the advection of warm and low-salinity water on the formation of intense coastal upwelling on the eastern shelf of Sakhalin: based on the numerical modeling, possible scenarios of its evolution in case of low and high desalination of water are provided. The intensity of the subsurface barrier layer and its effect on the coastal upwelling intensity in August during 2008–2017 are quantified. Along with hydrological and wind conditions, the distributions of chlorophyll *a* (*Chl-a*) are analyzed, and the interannual variability of its concentration in the distinguished area is presented. The conclusions are made on the need in hydrological measurements to improve the quality of forecasting the consequences of coastal upwelling.

DATA AND METHODS

The data on SST from the dataset of the Institute of Automatics and Control Processes of the Far Eastern Branch of Russian Academy of Sciences (IACP FEB RAS) were used to analyze the spatial features of coastal upwelling manifestations on the eastern shelf of Sakhalin [5]. The analysis of the wind speed field was based on the CCMP (Cross-Calibrated Multi-Platform) gridded data [13] with a spatial resolution of 1/4° in latitude and longitude and a temporal resolution of 6 hours.

The GOFS3.1 ocean reanalysis data [14] with a spatial resolution of 1/12 in longitude and 1/24 in latitude and a temporal resolution of 3 hours were used to characterize the thermohaline stratification. Based on this reanalysis, the zonal density gradient / (is the conditional density, is the longitude on the eastern shelf of Sakhalin) characterizing the barrier layer intensity in August during 2008–2017 was estimated. The profiles of temperature T and salinity S in northeastern Sakhalin were obtained for 2008–2019, in particular, using the MIDAS-CTD+500 autonomous combined profiler with the permission of Exxon Neftegas Limited. The scheme of the stations where the profiling was provided can be found in [7, 8].

The experiments with the INMOM numerical ocean circulation model [1] with a spatial resolution of 1/32° in latitude and longitude and atmospheric forcing based on the JRA55-do dataset [20] were held to demonstrate the scenarios of coastal upwelling evolution under conditions of different thermohaline stratification. The INMOM has been successfully used for studying upwelling in different areas of the ocean [9]. The present paper provides the model configuration that was previously used for modeling the circulation in the Sea of Okhotsk with a high spatial resolution [2, 19], but unlike [2], not taking tidal forcing into account. Initial conditions for potential temperature and salinity corresponded to their January climatology values taken from the WOA2013 database, and initial fields of the velocity and level were specified equal to zero. In the area of liquid boundaries, the zones with a width of ~1 from the surface to the bottom were reserved, where potential temperature and salinity were "attracted" to the monthly climatology taken from the WOA2013 dataset. Subgrid processes were parameterized in accordance with [2]. The integration was carried out continuously from 1997 to 2013, and the spin-up included the first 5 years.

The upwelling index (hereinafter, TPI) was used to estimate the coastal upwelling intensity and was evaluated in accordance with the following relationship [18]:

$$\mathrm{TPI}(\ ,\ )\qquad \frac{1}{N^2}\ {}_{i}^{n}\ {}_{n\,j}^{n}\ {}_{n}\ (\mathrm{TPI}(\ ,\ )\qquad \mathrm{TPI}(\qquad i,\qquad j))$$

where is longitude, is latitude, $n = (N - 1)/2$; N is the size of the neighborhood (the number of points) around the cell, N was taken equal to 21. The TPI was estimated using the gridded SST data from the GHRSST (Group for High Resolution SST) dataset [15] with a spatial resolution of 1/10 in latitude and longitude and a temporal resolution of 1 day for the period of 2008–2017. The grid cells where TPI is negative indicate a manifestation of coastal upwelling. The smaller TPI is, the lower sea surface temperature is, the more intense coastal upwelling is. According to instrumental observations [7, 8], due to intense and stable southern winds, upwelling fronts are formed along the eastern coast of Sakhalin. Their width exceeds

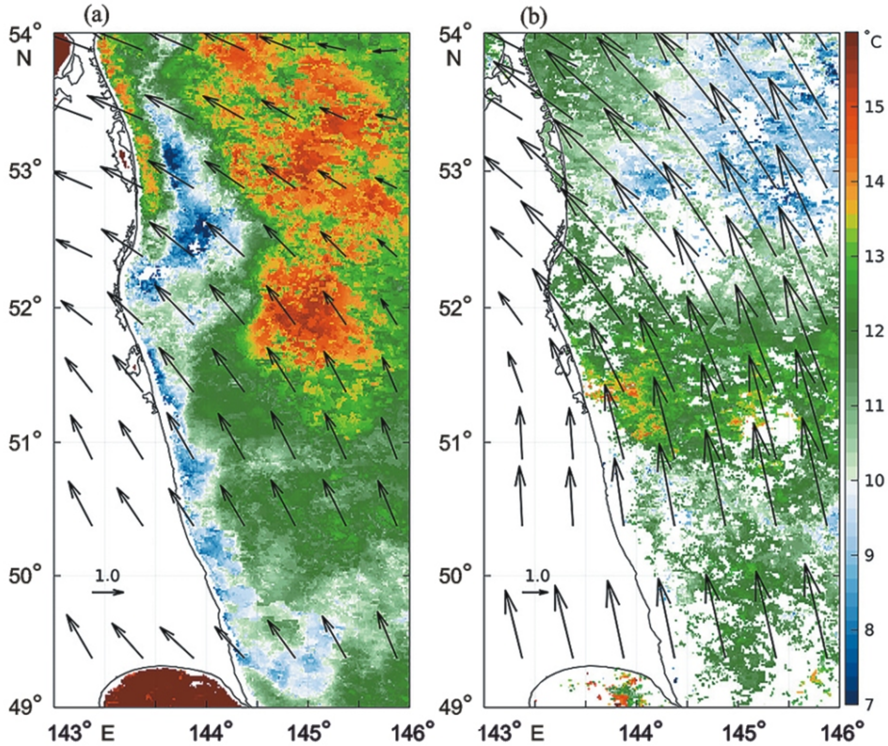

Fig. 1. Sea surface temperature (color scale; IACP FEB RAS database) and 10 m wind speed (the arrows, m/s; CCMP database) averaged over the period of August 8–14 in (a) 2009 and (b) 2013.

the first baroclinic Rossby deformation radius, therefore, the spatial resolution of the GHRSST dataset is sufficient to take into account the peculiarities of coastal upwelling.

Coastal upwelling affects the biological productivity of shelf water, since deep water rising to the sea surface is rich in biogenic elements, which are necessary for the algae development. A possible quantitative characteristic of the biological productivity is the concentration of chlorophyll *a*. The changes in chlorophyll *a* under conditions of coastal upwelling were analyzed using the MODIS-Aqua 2, 3 level data for cloudless scenes in August during 2008–2017, which were obtained at the Goddard Space Flight Center [16, 17]. The data processing was performed with the SeaDAS version 7.4 software. The analysis was based on the 8-day values averaged over the zonal section (52.0 N) in the area of 36 36 km, which were subsequently averaged for August.

RESULTS

Since the hydrological conditions characterized by the presence of warm and desalinated water off the eastern coast of Sakhalin caused by the Amur River runoff were of interest, two patterns of the coastal upwelling evolution corresponding to the first half of August in 2009 and 2013 were considered for comparison. The spatial distribution of SST averaged over the period of August 8–14, 2009 (Fig. 1a) demonstrates that its values almost along the entire eastern coast of Sakhalin are 5–6 C lower than in the offshore part. Southern and southeastern winds with an average speed of 5–6 m/s dominated in the wind field. In accordance to the Ekman’s theory, these winds form an intensive eastward quasizonal transport, which is accompanied by the intensive rise of the salt and cold Sea of Okhotsk water to the sea surface. At the same time, north of 52.5 N, despite the presence of the northward alongshore wind component, no low SST was observed.

According to [10], the extreme (as compared to the previous years) spring flood was registered on the Amur River in 2013. The spatial pattern of SST, as well as wind speed in August 2013 are presented in Fig. 1b. Despite more intense (as compared to August 2009) southern winds with a speed up to 10 m/s, SST along the entire eastern coast of Sakhalin did not drop below 10 C, which is 5 C higher than in August 2009. Such significant differences in the intensity of the coastal upwelling evolution in August in 2009 and

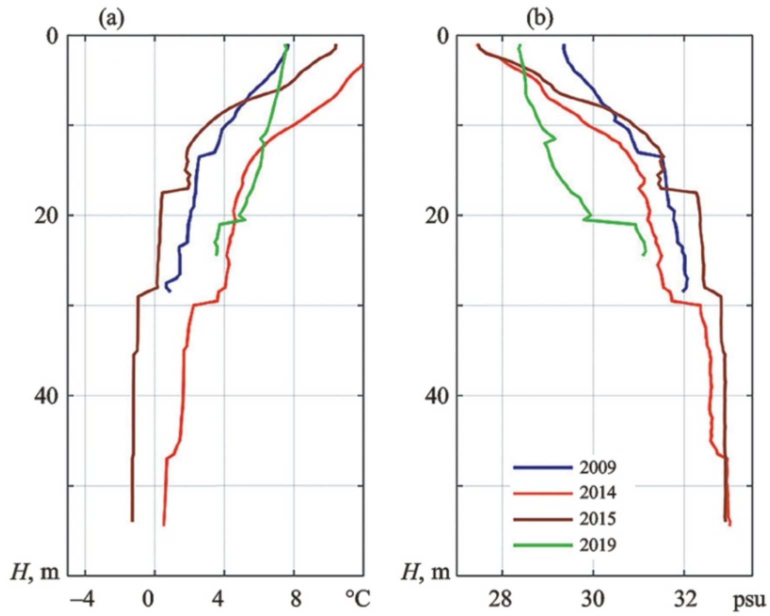

Fig. 2. The typical profiles of (a) temperature and (b) salinity obtained in different years on the northeastern shelf of Sakhalin. The average profile for August in the coastal area between 52.5 and 53 N is presented for every year.

2013 with the prevalence of southern winds point out that southern winds and wind stress curl [3] on the eastern shelf of Sakhalin are not the only factors responsible for the intensity of the elevating of the cold and salt Sea of Okhotsk water to the surface.

It is supposed that the background thermohaline stratification on the eastern shelf of Sakhalin may be a factor that impedes or facilitates the development of intense coastal upwelling. To confirm this supposition, the vertical structure of water in northeastern Sakhalin was analyzed using instrumental observations, which were carried out on the northeastern shelf of Sakhalin in the second half of the year from 2008 to 2019. Figure 2 presents the monthly mean profiles of temperature T and salinity S obtained in August in the coastal zone between 52.5 and 53 N. As follows from the analysis of the profiles, in some years, for example, in 2014, there was a noticeable deepening of the thermocline/halocline as compared to its long-term position. In particular, the 5 C isotherm in August 2009 was located at a depth of 8 m, while it dropped to 18 m in August 2014. These peculiarities of the vertical structure are also manifested (not so clearly though) in the salinity profiles (Fig. 2b). In particular, the isohaline of 31.8 psu was registered at a depth of 12 m in August 2009, whereas it dropped almost to 30 m in August 2014. The typical wedging-out of isotherms/isohalines to the surface was registered in August 2015, when the 5 C isotherm was found at a depth of 8 m, and the isohaline of 31.8 psu was registered at 12 m. A still more pronounced pattern of the deepening of isotherms/isohalines was observed in August 2019, when the 5 C isotherm was registered at a depth of 20 m, and the isohaline of 31.8 psu deepened to 25 m. These features of the thermohaline stratification indicate a regular occurrence of the surface barrier layer characterized by high temperature and low salinity off the eastern coast of Sakhalin [12]. This layer is formed by the advection of warm and low-salinity water of the Sakhalin Gulf, which, in its turn, is caused by the Amur River runoff. In addition, the transport of this water was contributed by intense northern winds, which are routinely observed in the analyzed period [7, 8]. The presence of this layer, despite intense southern winds, indicates a less intensive development of coastal upwelling as compared with the periods when the layer was absent.

The series of numerical experiments with the INMOM ocean circulation model was held to confirm the supposition about the contribution of the barrier layer to the coastal upwelling evolution. The simulated variations in wind speed, temperature T and salinity S at the station with the coordinates of 52.28 N, 143.3 E in August in 2009 and 2013 were considered.

According to the JRA55-do atmospheric reanalysis, southern winds prevailed in the wind speed variations in August 2009 (Fig. 3a). During the periods of August 1–7 and 12–20, the speed of southeastern wind reached 8–12 m/s; on August 25–28, the wind changed its direction to southwestern with a speed of 12 m/s. Such long domination of southern winds should have favored the development of coastal upwelling

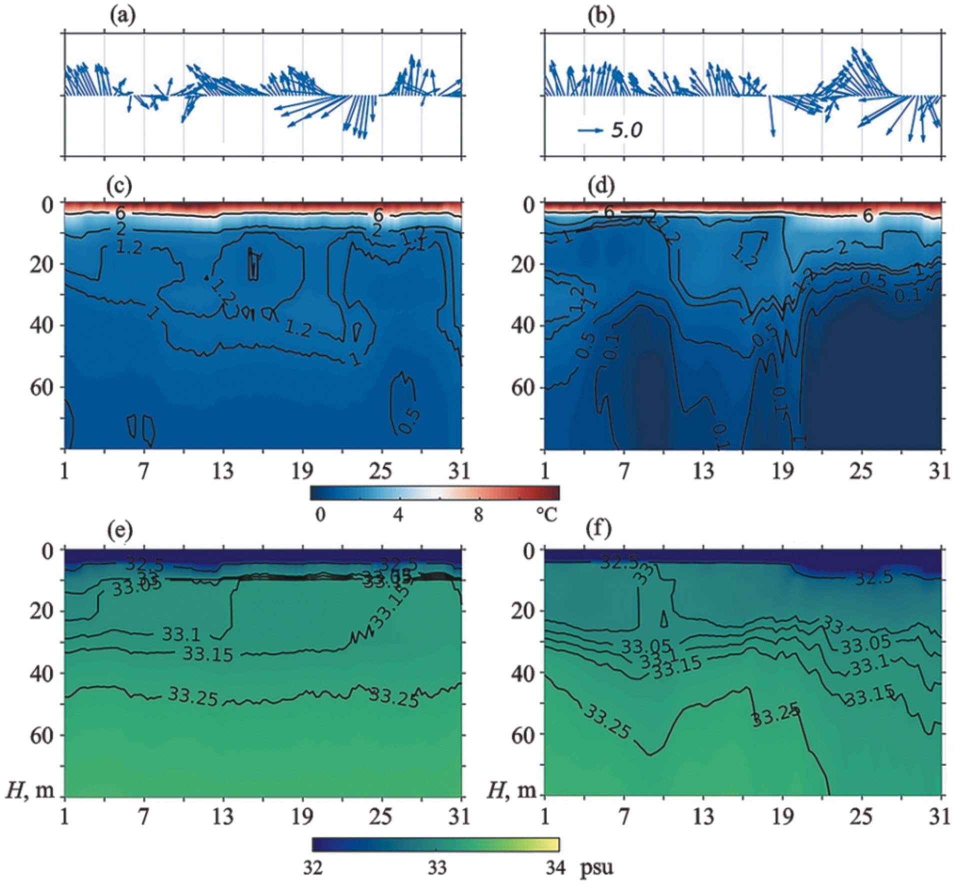

Fig. 3. (a, b) Wind speed (m/s; JRA55-do atmospheric reanalysis) and depth–time plots for (c, d) potential temperature and (e, f) salinity obtained with the INMOM at the station (143.3 E; 52.28 N): (a, c, e) August 2009, (b, d, f) August 2013.

in these periods. A dramatic veering of wind to the northwestern direction on August 20–25 should be noted, when its speed reached 13 m/s. During that period, the termination of wind-induced upwelling and the development of downwelling could be expected.

The depth–time plots for *T* and *S* in August 2009 (Figs. 3c and 3e) demonstrated a strongly pronounced dependence of the coastal upwelling intensity on wind. For all time intervals when southern winds dominated (see Fig. 3a), there was a noticeable decrease in *T* and an increase in *S* in the sea surface layer with a thickness of ~40 m, which indicates the development of intense coastal upwelling. The position of the 1.2 C isotherm changed most significantly: it wedged out from a depth of 40 m almost to the surface. In addition, there was a clear wedging-out of isohalines to the surface: for example, the isohaline of 33.1 psu moved up almost by 20 m. It should be noted that the short event (August 20–25) associated with a dramatic change in the wind direction was manifested in the typical deepening of the 1.2 C isotherm. This confirms once more the prevalent influence of wind conditions on the coastal upwelling evolution in August 2009 [8].

In August 2013 (Figs. 3b, 3d, and 3f), the pattern of the coastal upwelling evolution changed. According to the JRA55-do reanalysis (Fig. 3b), due to the prevalence of southern winds, which reached 7–8 m/s on August 1–18 and strengthened up to 10–12 m/s on August 25–28, the development of intense coastal upwelling was expected in northeastern Sakhalin. The depth–time plots (Figs. 3d and 3f) demonstrated that the wedging-out of the 1.2 C isotherm and the 32.5 psu isohaline to the sea surface was observed only in the first half of August, which indicates the development of coastal upwelling. However, since August 11, despite the prevalence of southern winds, temperature started rising and salinity started decreasing. A dramatic change of wind direction to northwestern on August 18–22 was accompanied by the termination of wind-induced upwelling and the advection of warm and salt water from the north, which led to the deepening of the thermocline/halocline. Subsequently, even if the wind changed, the coastal upwelling was not almost manifested. The thermohaline stratification suppressed the rise of the cold Sea of Okhotsk water to the

Table 1. The TPI, zonal gradient of conditional density (averaged in the surface 100 m layer), chlorophyll *a* concentration, and anomalies of meridional wind speed component with respect to its monthly mean value averaged over the territory of 51.75 –52.25 N, 143.0 –144.5 E for August

Parameter	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
TPI	–0.26	**–0.46**	–0.39	–0.23	–0.27	–0.10	–0.001	**–0.73**	–0.32	**–0.58**
/ 10^{-6} kg/(m^3 m)	5.96	4.50	6.22	7.46	9.39	8.83	9.61	4.94	6.82	6.93
Chl-a, mg/m^3	1.93	1.43	4.94	2.53	3.11	3.01	3.37	1.57	2.78	4.14
V, m/s	–0.86	0.80	–1.41	0.10	1.65	0.36	–1.14	–0.16	0.13	0.89

The most intensive upwelling events are bolded.

sea surface. The presented patterns of the upwelling evolution in the presence of the barrier layer were also observed in August for the other years (from 2008 to 2017).

Thus, it may be concluded that the evolution of coastal upwelling on the eastern shelf of Sakhalin depends not only on wind forcing but also on hydrological conditions. Moreover, even in case of strong southern winds, the coastal upwelling may not be formed if hydrological conditions on the shelf are not favorable for that.

DISCUSSION

The analysis of the thermohaline stratification on the northeastern shelf of Sakhalin in different years revealed that the advection of the water with high temperature *T* and low salinity *S* leads to the formation of the barrier layer that impedes the development of intensive coastal upwelling. In particular, the typical feature of this layer is the deepening of isopycnic lines to the bottom off the coast.

For more detailed investigation of the dependence of the coastal upwelling intensity on the thermohaline stratification, two parameters were estimated: TPI and the zonal gradient of conditional density (/). The TPI characterizes the coastal upwelling intensity more qualitatively accurately as compared to SST, since the index takes into account the large-scale interannual SST variations [18]. Since the advection of desalinated and warm water to the eastern shelf of Sakhalin leads to the deepening of isopycnic lines to the bottom off the coast, the gradient / was used to characterize the intensity of this deepening. High values of the parameter indicate the presence of the barrier layer off the eastern coast of Sakhalin, which according to the results of numerical modeling, impedes the rise of the cold Sea of Okhotsk water to the surface. Small values imply the absence or presence of the weak barrier layer, and the coastal upwelling evolution will depend on wind forcing.

Table 1 presents the above parameters averaged for northeastern Sakhalin, as well as the values of chlorophyll *a* and the anomalies of the alongshore wind component (*V*) averaged for this part of the shelf. As follows from the table, the coastal upwelling intensity over the period of 2008–2017 exhibits strongly pronounced interannual variations. The most intensive coastal upwelling was developed in August in 2009, 2015, and 2017. During these periods, TPI reached the minima of –0.46, –0.73, and –0.58, respectively. At the same time, the gradient / was characterized by the minimal (as compared to the other years) values, which points out a weakness of the barrier layer and a leading role of wind (the alongshore component) in the intensity of the coastal upwelling evolution. For example, in the analyzed periods, the values of *V* (except for August 2015) were maximal, which indicates the prevalence of southern winds facilitating the development of coastal upwelling.

On the other hand, in August in 2011, 2013, and 2014, despite the positive anomalies of the alongshore wind speed component *V* (except for 2014), the coastal upwelling did not almost develop, and TPI demonstrated the minima of –0.23, –0.1, and –0.001, respectively. Such small absolute values of TPI are caused by the presence of the strong barrier layer off the coast, which was confirmed by the maximum values of the zonal gradient of conditional density / , namely, 7.46, 8.83, and 9.61 (10^{-6} kg/(m^3 m)). Such high values of / in August in 2013 and 2014 were caused by the increased Amur River runoff.

Thus, the Amur runoff increase can lead to the formation of the barrier layer, which, in its turn, will result in the suppression of upwelling on the eastern shelf of Sakhalin. It should be noted that an essential factor of the presence of desalinated water on the eastern shelf of Sakhalin is also northern winds, which enhance the advection of this water. In addition, the coastal upwelling intensity in the northern and southern parts of the eastern shelf will noticeably differ. This difference will be determined by the presence of low-salinity water in the northern part and their increasingly smaller influence on the upwelling development in the southern part of the eastern shelf.

The interannual variations in chlorophyll *a* at the 95% significance level depended on TPI (with the correlation coefficient R equal to 0.81) and the gradient / (with $R = 0.97$), with two outliers in the sample (in 2010 and 2017). There was no correlation between chlorophyll *a* and V ($R = 0.1$). Despite the fact that the variations in chlorophyll *a* depended on TPI, this index depended on the parameter / ($R = 0.76$), i.e., on the propagation of low-salinity and warm water on the eastern shelf of Sakhalin, and did not depend on V. These results indicate that the interannual variations in chlorophyll *a* are highly affected by the propagation of the Amur River runoff, which is richer in biogenic elements as compared to surrounding water. The lowest values of chlorophyll *a* were recorded for the smallest values of / (in 2009 and 2015). The highest values of chlorophyll *a* were observed for the medium values of / (in 2010 and 2017), but the absolute value of V was higher in this case (see Table 1). Therefore, the maxima of chlorophyll *a* in 2010 may be caused by the increased advection of the Amur River water and those in 2017 may be explained by the development of coastal upwelling with the increased wind forcing.

CONCLUSIONS

Based on different sources of satellite and instrumental observations, as well as on the results of numerical modeling, the influence of the thermohaline stratification on the coastal upwelling evolution was analyzed for the northeastern shelf of Sakhalin in August from 2008 to 2017. It was found that in some years, the coastal upwelling was poorly developed, despite the intensive wind forcing. The analysis of the thermohaline stratification of water demonstrated that it is formed, in particular, due to the advection of warm and desalinated water from the north, which, in its turn, may depend on many factors: the Amur runoff, the large-scale circulation, and the intensity of northern winds. It was found that the presence of river water is accompanied by the deepening of the pycnocline (that is accompanied by the deepening of the thermocline/halocline) and impedes the elevating of the cold and salt Sea of Okhotsk water to the surface, despite intensive southern winds. In particular, during the periods of the significant Amur runoff, despite the predominance of southern winds, the coastal upwelling intensity was much lower than, for example, in August 2009, when the desalinated water was not detected on the shelf. Thus, in addition to the wind forcing, an important factor of the development of intense coastal upwelling in northeastern Sakhalin is the thermohaline stratification, which is formed, in particular, by the advection of warm and low-salinity water from the north. The coastal upwelling is an important factor for the development of biological productivity of water on the eastern shelf of Sakhalin. Therefore, its prediction, along with the monitoring of wind conditions requires routine profiling to improve the forecast quality. The obtained data on the interannual variability of chlorophyll *a* in August for 10 years for the northeastern shelf of Sakhalin and on their correlation with wind conditions also indicate a need in further, more detailed upwelling studies based on instrumental observations.

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