ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2021, Vol. 57, No. 12, pp. 1680–1689. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2016, published in Issledovanie Zemli iz Kosmosa, 2016, No. 1–2, pp. 105–115.

USE OF SPACE INFORMATION ABOUT THE EARTH STUDYING SEAS AND OCEANS FROM SPACE

Seasonal and Inter-Annual Variability of Wind-Driven Upwelling near the East Coast of Sakhalin Island Based on QuikSCAT/SeaWinds Scatterometer Data

I. A. Zhabin[a, *] **and E. V. Dmitrieva**[a]

[a] *Ilyichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences, Vladivostok, 690041 Russia*

**e-mail: zhabin@poi.dvo.ru*

Received August 25, 2014; revised June 18, 2015; accepted July 12, 2015

Abstract—In this paper, seasonal and interannual upwelling variability in the Sea of Okhotsk off the eastern coast of Sakhalin Island based on wind data obtained using the QuikSCAT/SeaWinds scatterometer (1999–2009) were studied. The upwelling strength was estimated from the magnitude of the wind-induced Ekman transport directed away from the coast (upwelling index). The obtained results show that upwelling near the eastern coast of Sakhalin Island is mainly associated with summer southerly monsoon winds over the Sea of Okhotsk. In the northern and central parts of the East Sakhalin shelf, upwelling is observed in July–August. In the southern part of the region, off the coast of Cape Patience, it begins in August and continues until September. The variability in the duration and strength of upwelling is due to regional features of the wind forcing. Ekman transfer and pumping contribute approximately equally to the upwelling generation. This shows that upwelling associated with the spatial inhomogeneity of the wind stress vorticity can affect the decrease in water temperature off the eastern coast of Sakhalin Island. The seasonal variability of the southern monsoon winds favorable for the development of upwelling is largely determined by the summer Okhotsk anticyclone (atmospheric center of high pressure over the Sea of Okhotsk). The latter is characterized by significant interannual variability. Its interannual variations correlate well with the upwelling strength near the eastern coast of the island. Upwelling decreases in years with negative atmospheric pressure anomalies in the Okhotsk anticyclone, while enhanced upwelling is associated with a well-developed positive anomaly of this regional high-pressure center.

Keywords: wind-driven upwelling, seasonal and interannual variability, surface wind, SeaWinds/QuikSCAT, Ekman transport, summer monsoon, Okhotsk anticyclone, Sea of Okhotsk, Sakhalin Island

DOI: 10.1134/S000143382112029X

INTRODUCTION

Coastal upwelling develops under the impact of two main physical factors: alongshore wind stress and the Earth's rotation (the Coriolis effect). In the Northern Hemisphere, it is caused by wind blowing along the coast so that the coast is on the left. In this case, the Ekman transport directed away from the coast leads to a divergence of currents near the coast, which causes a compensatory rise and the release of colder waters from the underlying layers to the surface. Another physical mechanism plays a significant role in the upwelling dynamics. This process known as Ekman pumping is associated with the horizontal inhomogeneity of the wind field. Positive (negative) vorticity of the tangential wind stress leads to divergence (convergence) of wind currents and subsequent rise (lowering) of waters. Upwelling is affected by seasonal and synoptic variability of the wind field, density stratification, coastline indentation, and shelf morphology. Upwelling waters are characterized by a high content of biogenic elements; therefore, coastal upwelling significantly affects the bioproductivity of the shelf zone of oceans and seas.

In the Sea of Okhotsk, wind upwelling in summer is known to be observed off the eastern coast of Sakhalin Island. Coastal upwelling in this area is associated with steady southerly and southeasterly winds typical of the summer monsoon period. The existence of upwelling off the eastern coast of Sakhalin Island was confirmed by hydrological and hydrochemical measurements (*Gidrometeorologiya*..., 1988; Gruzevich et al., 1996; Rutenko et al., 2009) as well as instrumental observations of currents (Popudribko et al., 1998). Upwelling was usually observed in late July–August when the outflow of cold water near the coast is clearly visible in the sea surface temperature (SST) field. According to observations, it is most clearly expressed in a narrow coastal strip with a width of 10–20 km. Thermal contrasts between cold upwelling waters and warm waters of the shelf zone can reach 5°C. Upwelling has a negative impact on the regional climate (fogs and low water temperatures near the coast). On the other hand, it produces conditions for high biological productivity of the Sakhalin shelf zone. The waters of the coastal upwelling zone are characterized by a high content of phosphates, nitrates, and silicic acid. The calculated values of primary production in the upwelling zone exceed the values obtained for the open part of the Sea of Okhotsk in summer (Gruzevich et al., 1996). The upwelling strength is noted to vary along the eastern coast of Sakhalin Island. Upwelling is more pronounced in the northern part of the East Sakhalin shelf. In the central part of the shelf, the cold waters of the upwelling zone occupy a larger area with smaller thermal contrasts (Krasavtsev et al., 2000).

Satellite data show (Fig. 1) that the East Sakhalin upwelling is well expressed in the SST field. An analysis of archives of satellite data on the SST distribution (AVHRR NOAA, http://www.satellite.dvo.ru and MODIS Aqua, http://coastwatch.pfeg.noaa.gov/erddap/index.html) showed that upwelling is observed along the eastern coast of Sakhalin Island from Cape Patience in the south to Cape Elizaveta in the north (the coastline length is approximately 700 km). Episodic upwelling was recorded off the southeastern coast of Sakhalin Island in Patience Bay and at the eastern coast of the Tonino-Anivsky Peninsula. According to satellite data, two main regions of stable and intensive upwelling can be distinguished. One of the upwelling zones is formed off the northeastern coast of Sakhalin Island in the area adjacent to Piltun Bay (52°15′–53°45′ N), the second is between Cape Patience and 51° N. Upwelling on satellite maps of the SST distribution was observed from the beginning of July to September. In September, its well-defined zone is usually located in the region of Cape Patience. The width of the coastal upwelling zone with minimal values of surface temperature ranged from 10 to 60 km. In some cases, the effect of upwelling (a region of low SST values) was traced at a distance of 100–120 km from the coast of Sakhalin Island. In reality, water rise occurs in a narrow coastal strip, the horizontal scale of which is determined by the Rossby deformation radius (~10 km for the study area). The width of the upwelling strip in our study was determined from the actual decrease in surface temperature associated both directly with the upwelling zone and with transfrontal exchange processes through upwelling fronts. The possibilities of using satellite information on the SST distribution to study the spatiotemporal variability of upwelling near the eastern coast of Sakhalin Island are significantly limited by unfavorable cloudiness. Upwelling can be studied using surface wind data obtained on a regular basis using satellite scatterometers (microwave radars). In this case, the upwelling strength is estimated from the magnitude of the wind-induced offshore Ekman transport (upwelling index). The data of the SeaWinds scatterometer fully reflect the regional wind enforcing leading to upwelling (monsoons and the passage of cyclones/anticyclones), which allows using them to study such a phenomenon as seasonal upwelling. In the last decade, this approach was used to study coastal upwelling in various regions of the World Ocean (e.g., Alvarez et al., 2008; Castelao and Barth, 2006). Based on this, the main tasks of the study were determined: based on the analysis of satellite wind data, to study the seasonal variability of upwelling off the eastern coast of Sakhalin Island, to estimate the relative contribution of the Ekman transfer and Ekman pumping to the upwelling generation, and to consider the interannual variability of the upwelling strength in this region.

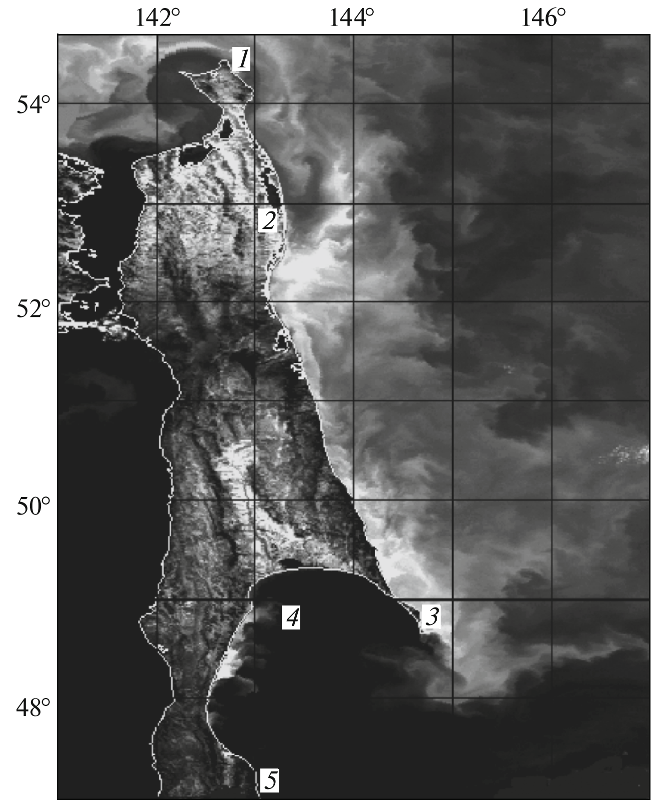

Fig. 1. Satellite IR image of the coastal upwelling zone off the east coast of Sakhalin Island taken on August 31, 2008. Legend: (*1*) Cape Elizabeth, (*2*) Piltun Bay, (*3*) Cape Patience, (*4*) Patience Bay, and (*5*) Tonino-Anivsky Peninsula. Light tones in the satellite image correspond to cold upwelling waters, and dark tones correspond to warm waters of the adjacent part of the Sea of Okhotsk.

DATA AND CALCULATION METHODS

The surface wind speed and direction data were obtained using the SeaWinds scatterometer installed on the QuikSCAT satellite. The scatterometer operated in orbit from July 1999 to November 2009. The spatial resolution of the initial data array is 0.25° × 0.25°. The wind speed measurement range is from 3 to 20 m/s with an accuracy of 2 m/s, while the wind direction measurement accuracy is 20° (Freilich and Dunbar, 1999). Satellite scatterometers have certain limitations: information about the wind cannot be obtained in the coastal strip of the sea with a width of ~25 km.

To study the seasonal variability of upwelling, the upwelling index used was based on the calculation of the Ekman transport directed away from the coast. Ekman transport (m^3/s/100 m of coastline) was calculated for selected coastal points using the equation: $M = \tau_y/\rho f$, where τ_y is the alongshore component of the shear wind stress, ρ is the density of sea water (1025 kg/m^3), and f is the Coriolis parameter at the corresponding latitude (Bakun, 1973). The upwelling index quantitatively characterizes the volume of water that rises (positive values of the index) or sinks (negative values) near the coast through the base of the Ekman layer. Thus, the upwelling index shows the amount of Ekman transport in the direction from the coast (upwelling) or to the coast (downwelling) caused by wind variability. The "upwelling index" term was introduced in the widely known and frequently cited study of Bakun (1973) and is used as a quantitative characteristic of Ekman transport.

The calculations were performed for the ice-free period (June–October) using the long-term monthly average values of the alongshore shear wind stress (http://numbat.coas.oregonstate.edu/scow/google_earth.html) for the northern, central, and southern regions of the main upwelling zone. Information about the accuracy of this data set is given in Craig and Dudley, 2008. The general conclusion made by the authors is that the accuracy of the climatological data of the SeaWinds scatterometer of the QuikSCAT satellite exceeds the accuracy of other existing global wind data arrays. At the same time, the authors do not provide quantitative estimates of the accuracy of the data, arguing that the array is constantly replenished, including by merging data from various scatterometers that have operated in orbit in different years or continue to operate at present.

For the northern and southern regions, where the shelf edge is oriented in the meridional direction, the meridional component of the tangential wind stress was used in the calculations. For the central part of the shelf, the projection of the meridional component of the tangential wind stress onto the coastline was calculated. To estimate the relative contribution of the two main processes involved in upwelling generation off the east coast of Sakhalin Island, Ekman transport and Ekman pumping were calculated (Pickett and Paduan, 2003). Ekman transport values for the northern and central regions of the upwelling zone were obtained at each of the selected coastal points with allowance for the coastline orientation. The Ekman pumping velocity was calculated at each point of the computational domain using the following equation: $W = \mathrm{rot}(\tau)/\rho f$, where $\mathrm{rot}(\tau)$ is the shear stress vorticity of the wind. For the northern and central regions, the Ekman pumping velocities were integrated in the direction from the coast along five zonal lines, starting from coastal points (seven points, a distance is ~100 km). At the next stage of calculations, the obtained values of the Ekman transfer and Ekman pumping were averaged within each of the two considered regions. To obtain commensurate values, the value of the Ekman transport was reduced to 1 m of the coastline. In this case, the dimensions of the Ekman transport and the Ekman pumping coincide (m^3/s/1 m of the coastline). The average long-term array of satellite wind data cannot be used to calculate the Ekman pumping since the points with values of wind shear stress vorticity are mainly located outside the area of the island shelf and slope. Therefore, to estimate the relative contributions of the Ekman transport and pumping, we used the monthly average wind data set obtained in 2008 (http://coastwatch.pfeg.noaa.gov/erddap/index.html). The developers define the accuracy of the initial data on the tangential wind stress as 0.1 Pa. In this case, the spatial resolution of the data array was 0.125° × 0.125°. In 2008, according to satellite data on the SST distribution near the eastern coast of Sakhalin Island, a well-developed and stable upwelling was observed in summer (Fig. 1).

To study the interannual variability of upwelling for three points (52°37.5′ N, 144°07.5′ E; 51′ N, 144′ E; 50°15′ N, 145′ E) for the period from 2000 to 2008, the accumulated (cumulative) upwelling index was calculated from the 3-day values along the coastal component of the shear wind stress. The cumulative upwelling index is used to study interannual and interannual upwelling variability. The accumulated index is useful in that it allows one to smooth out the synoptic variability of the wind, which affects the development of upwelling. When calculating the accumulated upwelling index for the period from July 1 to August 31 of each year, 3-day values of the upwelling index were sequentially summed up. The initial array of daily wind data has gaps, so the accuracy of the 3-day shear wind stress values used for calculations is currently not defined. When analyzing data on the interannual variability of upwelling, the anomalies of its accumulated index normalized to the standard deviation were considered.

As additional information, hydrological data from the US National Oceanographic Data Center (NODC, http://www.nodc.noaa.gov/) and monthly mean surface atmospheric pressure fields (Reanalysis 2 NCEP/DOE, http://www.esrl.noaa.gov/psd/) were used.

The obtained quantitative estimates allow considering the seasonal and interannual variability of upwelling near the eastern coast of Sakhalin Island and estimating the contributions of Ekman transport and pumping to the generation of wind upwelling in this region.

SEASONAL VARIABILITY OF UPWELLING OFF THE EAST COAST OF SAKHALIN ISLAND

An analysis of satellite data on the SST distribution showed that two main stable upwelling zones, one of which is located off the northeastern coast of the island and the other is located in the central part of the Sakhalin shelf, are formed off the eastern coast of Sakhalin Island in summer (July–early September). Upwelling in the southern section of the shelf adjacent to the Cape Patience was observed in July–September. The average monthly values of the upwelling index are usually used as a quantitative criterion for studying the seasonal variability of the upwelling strength. The upwelling index was calculated for three regions located in the northern, central, and southern parts of the East Sakhalin shelf (Fig. 2a). Figures 2b–2d show the average monthly values of the upwelling index for each of these regions during the ice-free period (from June to October). In general, according to long-term average satellite wind data, the upwelling season off the east coast of Sakhalin Island begins in July and ends in September. The calculation results show that the most enhanced upwelling is observed in the central part of the shelf in the period from July to August. In August, the values of the upwelling index in this area are maximum for the entire East Sakhalin shelf. In the main part of the studied area, upwelling develops in August and September under average wind conditions. Less favorable wind conditions for its development were observed off the northeastern coast of Sakhalin Island. In this part of the shelf, upwelling is well pronounced in July and August, and the Ekman transport is less than that in the central part of the shelf.

Thus, the most favorable conditions for the development of wind upwelling near the eastern coast of Sakhalin Island are observed in July–August. Off the coast of the Cape Patience, it continues in September. Differences in the length of the upwelling season in these areas of the main upwelling zone may be due to features of the wind enforcing of the Sea of Okhotsk. In general, upwelling is associated with the period of the summer monsoon (south and southeast winds). The intensity of monsoon development is determined by large-scale atmospheric processes associated with the state of the main regional centers of atmospheric action that regulate the wind enforcing over the Sea of Okhotsk (*Gidrometeorologiya*..., 1988; Nakamura and Fukamachi, 2004). The interaction of the Asian depression with the Okhotsk anticyclone leads to the development of the summer monsoon with two stages: from May to June and from July to September. Each of these stages corresponds to a different dynamic state of the Okhotsk anticyclone, which is associated with large-scale zonal and meridional thermal gradients between the Asian mainland, the Sea of Okhotsk, and the adjacent part of the Pacific Ocean.

An analysis of long-term average satellite data on a surface wind showed that upwelling off the eastern coast of Sakhalin Island is associated with the second stage of the development of the summer monsoon over the Sea of Okhotsk. The upwelling season begins at the maximal values of the zonal temperature gradient between land and the Sea of Okhotsk (July) and continues until the thermal contrasts equalize (September). This monsoon stage corresponds to the baroclinic mode of atmospheric circulation associated with the Okhotsk anticyclone (Nakamura and Fukamachi, 2004). In autumn, arctic cold air intrusions contribute to the development of anticyclonic forms of circulation, which leads to a gradual transition to the winter wind mode. In September, the northern part of the sea begins to experience the influence of the mainland in the form of air currents of the northeast and north directions. This leads to the end of the upwelling season in the northern and central parts of the East Sakhalin shelf. In the southern part of the Sea of Okhotsk, at this time, the summer wind mode is preserved with the predominance of winds with a southern component. Therefore, upwelling continues off the southeastern coast of the Cape Patience in September. The prevailing monsoon character of the wind circulation over the Sea of Okhotsk is significantly disturbed when continental and marine cyclones enter the water area of the sea (*Gidrometeorologiya*..., 1988). When cyclones pass off the Sakhalin Island coast, a sharp increase in southerly winds (up to 20 m/s or more), which produces favorable conditions for the development of fast-flowing intense coastal upwelling, can be observed. During the summer monsoon period, the release of such cyclones usually occurs in August and September (from one to four cyclones), with a maximal frequency occurring in September. In October, a winter wind mode is established with a predominance of strong northern and northwestern winds over the entire water area of the Sea of Okhotsk.

The results obtained from the analysis of long-term average satellite data on surface wind are in good agreement with the results of direct oceanographic observations. Figure 3 shows the monthly mean surface temperature-distribution fields off the eastern coast of Sakhalin Island plotted using the long-term dataset of the US National Oceanographic Data Center (NODC, 0.5° spatial resolution). In July (Fig. 3a), the outflow of cold water near the coast was observed in the northern and central parts of the shelf zone. In August, the main upwelling zone is located in the central part of the shelf zone. In September, signs of upwelling (lower temperatures) were observed near the Cape Patience, while the general temperature background of the northern and central parts of the East Sakhalin shelf remained lower than that in the open part of the Sea of Okhotsk.

The main differences noticeable when comparing the results of calculating the upwelling index and direct measurements of surface temperature are associated with different time periods of data averaging and uneven distribution of oceanographic stations. Besides, the

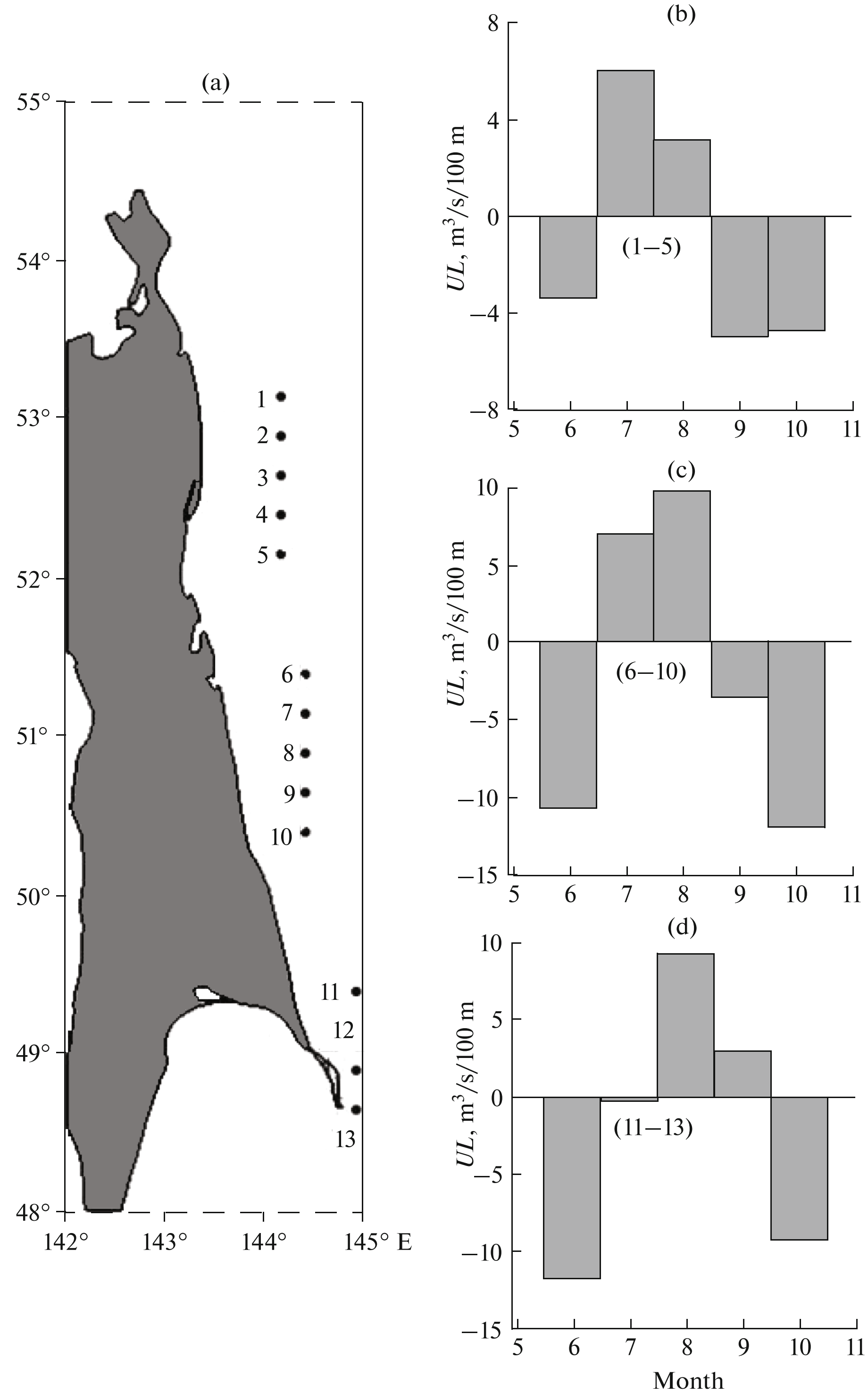

Fig. 2. Map showing (a) the position of the computational grid nodes and the monthly average values of the upwelling index in the (b) northern, (c) central, (d) and southern parts of the upwelling zone near the eastern coast of Sakhalin Island.

results of calculating the Ekman transfer showed that upwelling near Cape Patience should develop in August and September. However, according to direct oceanographic observations, an area with reduced SST values near Cape Patience was observed in July–September. As a rule, in the area of capes, the orientation of the coastline changes sharply, and upwelling can develop with various wind directions. Besides, in the area of capes, an increase in the alongshore orographic wind, which is not recorded by satellite scat-

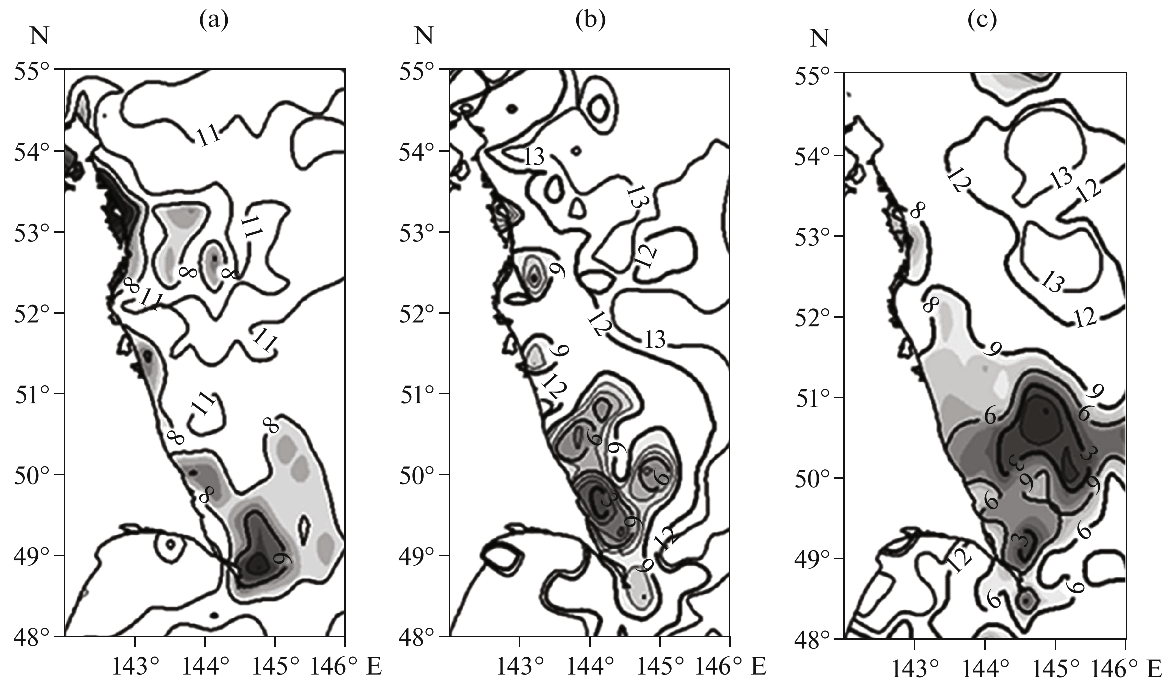

Fig. 3. Long-term average distribution of sea surface temperature near the Sakhalin Island coast in (a) July, (b) August, and (c) September.

terometers, is usually observed in a narrow coastal strip. According to archival satellite data on the SST distribution, upwelling signs in the region of Cape Patience were steadily observed throughout the entire upwelling season (July–September). The second difference noticeable when comparing the results of the upwelling index calculations with ship observations was observed in September and, according to hydrological data, signs of upwelling (reduced SST values near the coast) continued to be observed along the entire eastern coast of Sakhalin Island and not only in the area of Cape Patience. This may be due to both residual traces of summer upwelling and cases of intense rapid upwelling that occurs when continental and marine cyclones pass through the Sea of Okhotsk, which can cause a sharp increase in southward alongshore wind off the coast of Sakhalin Island.

ESTIMATING THE CONTRIBUTIONS OF EKMAN TRANSFER AND EKMAN PUMPING TO UPWELLING OFF THE EAST COAST OF SAKHALIN ISLAND

Wind upwelling can be caused by two processes: offshore Ekman transport and Ekman pumping caused by the divergence of surface wind currents. The relative contribution of each of these two processes to the upwelling generation in the northeastern and central parts of the Sakhalin shelf was calculated using the monthly average wind data obtained in 2008. The calculations were performed for the northern and central regions of the upwelling zone (Fig. 4a).

The calculation results showed that upwelling develops off the coast of Sakhalin Island both due to the Ekman transport and as a result of the Ekman pumping associated with the positive vorticity of the wind stress field. In 2008, upwelling on satellite maps of SST distribution was observed in the northern part of the shelf from late June to early September. Positive average monthly values of the upwelling index corresponded to the specified period (July–August, Fig. 4b). In the central part of the shelf zone, according to satellite data on SSTs, cold waters near the coast were clearly traced from late June to late September. The results of the upwelling index calculation showed that the upwelling season in 2008 lasted from June to September (Fig. 4c). The observed differences in the duration of the upwelling season compared to the long-term average data are explained by the interannual variability of the upwelling strength off the eastern coast of Sakhalin Island.

Comparison of estimates of water transport in the East Sakhalin upwelling system (Fig. 4) shows that the contribution of the Ekman pumping can be comparable with the contribution of the Ekman transport. Due to the latter, the cold bottom layer of waters comes to the surface off the coast of Sakhalin Island. Ekman pumping is associated with an increase in the vertical component of the current velocity at the base of the upper mixed layer. This causes water to rise in areas where positive values of wind field vorticity are observed. Thus, the Ekman pumping can provide rise of waters of the cold winter layer with low temperatures and a high content of biogenic elements in the area of the slope and shelf, which will lead to increased coastal upwelling.

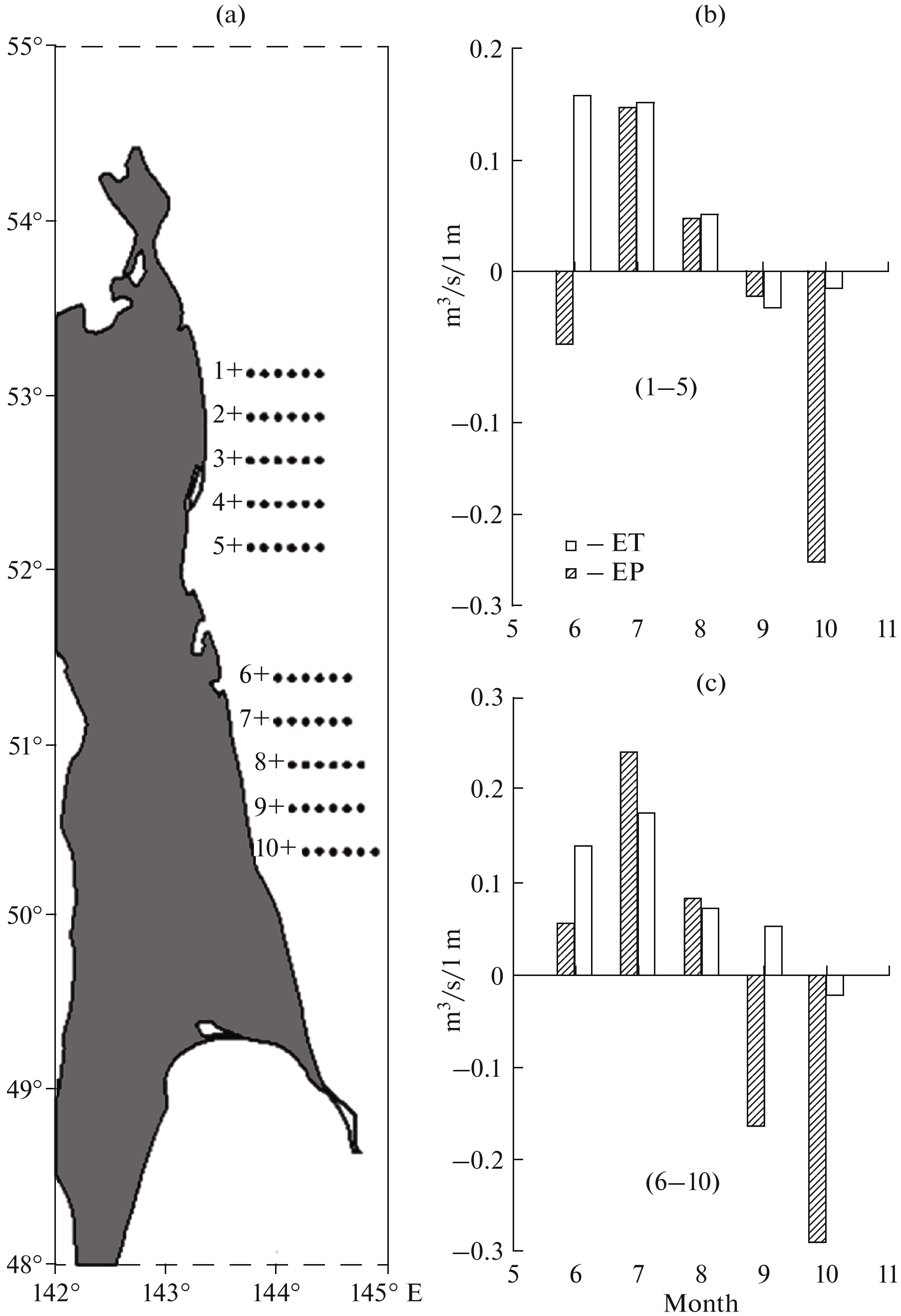

Fig. 4. (a) Map showing the position of the computational grid nodes and the monthly average values of the Ekman transport and pumping in the (b) northern and (c) central parts of the upwelling zone off the eastern coast of Sakhalin Island. Conditional symbols: crosses are the points for which the Ekman transfer (ET) was calculated, and the dots are the grid nodes used in the calculation of water transfer caused by Ekman pumping (EP).

INTERANNUAL UPWELLING VARIABILITY OFF THE EAST COAST OF SAKHALIN ISLAND

Wind conditions over the Sea of Okhotsk during the summer monsoon, which is associated with the predominance of southerly and southeasterly winds, are determined by the location and interaction of the main high-pressure centers and temperature contrasts between the eastern part of the Asian continent and the adjacent regions of the Pacific Ocean. The main regional baric formations that determine the circulation of the atmosphere and the nature of the transport of air masses in this region are the Okhotsk anticyclone and the Far East depression (one of the troughs of the summer large-scale Asian depression directed to northeastern China and the Amur River basin). During the summer monsoon, the greatest contributor to the formation of the baric field in this region is the anticyclogenesis over the Sea of Okhotsk. On the climatic summer maps of the distribution of surface atmospheric pressure, the Okhotsk anticyclone can be traced in the form of a crest of the North Pacific anticyclone, which belongs to the main large-scale centers of atmospheric impact. At the same time, the Okhotsk anticyclone has a completely independent circulation significance as a regional seasonal center of atmospheric impact (*Gidrometeorologiya*..., 1988; Popudribko et al., 1998; Nakamura and Fukamachi, 2004). On the synoptic scale of variability, the anticyclonic field over the Sea of Okhotsk is periodically observed from May to September, with a continuous duration from several days to a week. The developed Okhotsk anticyclone blocks the exit of continental cyclones to the Sea of Okhotsk and leads to the development of the Far Eastern depression. In this situation, stable southerly and southeasterly winds should produce more favorable conditions for the upwelling development off the coast of Sakhalin Island. When the Okhotsk anticyclone is weakly expressed, cyclones reach the Sea of Okhotsk, which leads to a significant change in wind conditions. When atmospheric cyclones pass over the Sea of Okhotsk off the eastern coast of Sakhalin Island, a successive change in wind direction occurs, which creates conditions for the development of both upwelling (strong winds with a southern alongshore component) and downwelling (northern wind). Such conditions are less favorable for the upwelling development off the eastern coast of Sakhalin Island. To test this assumption, we performed a joint analysis of the interannual variability of the index characterizing the state of the Okhotsk anticyclone and the accumulated (cumulative) upwelling index off the eastern coast of Sakhalin Island. The Okhotsk anticyclone index (Ogi et al., 2004) was calculated using the NCEP/DOE reanalysis-2 data as the average atmospheric pressure in July–August in the area located between 50°–60° N and 140°–160° E. The interannual variability of the Okhotsk anticyclone indices normalized to the standard deviation of anomalies and the accumulated upwelling index is shown in Fig. 5a. The figure shows that the Okhotsk anticyclone is characterized by significant interannual variability. A well-developed Okhotsk anticyclone was observed in 2002 and 2006, while 2004 and 2007 belong to years with weak anticyclonic activity. Correspondingly, in years with a well-developed Okhotsk anticyclone, a pronounced tendency to intensification of upwelling was observed near the eastern coast of Sakhalin Island, and the upwelling intensity noticeably decreased in years with a weakly expressed anticyclone. This shows that the interannual upwelling variability largely depends on the Okhotsk anticyclone, which is the main regional center of atmospheric impact that determines wind conditions over the Sea of Okhotsk. In turn, the Okhotsk anticyclone and the Far East depression are parts of large-scale centers of atmospheric impact, which include the North Pacific anticyclone and the Asian minimum of atmospheric pressure. Average maps showing the distribution of surface atmospheric pressure in 2004 (weak upwelling) and 2006 (active upwelling) that are built based on the NCEP/DOE reanalysis-2 are shown in Figs. 5b and 5c. The maps show that 2006 (high values of the accumulated upwelling index) was characterized by a developed North Pacific maximum of atmospheric pressure and a weakened Asian depression. This situation corresponds to an increase in the summer monsoon winds of the southern and southeastern directions over the Sea of Okhotsk, which are favorable for the development of upwelling. In 2004 (minimal values of the upwelling index), an increase in the Asian depression and a weakening of the North Pacific anticyclone were observed. In this case, the wind conditions over the Sea of Okhotsk are largely determined by the emergence of atmospheric cyclones in the water area of the Sea of Okhotsk. The successive change of upwelling and downwelling events near the eastern coast of Sakhalin Island that is associated with cyclonic activity reduces the values of the accumulated upwelling index. Constant, steady summer monsoon winds cause intense upwelling of cold waters in a relatively narrow coastal strip adjacent to the eastern coast of Sakhalin Island. In this case, coastal upwelling leads to a significant decrease in water temperature and the appearance of fog, which has a negative impact on regional climatic conditions. On the other hand, when the upwelling and downwelling events change associated with atmospheric cyclonic activity, an increase in the advection of cold waters in the direction across the shelf that is associated with the restructuring of the coastal zone circulation is observed (Send et al., 1987). This significantly increases the area of the shelf zone affected by upwelling, which must lead to an increase in the bioproductivity of the East Sakhalin shelf.

CONCLUSIONS

Long-term satellite observational data on the SST distribution showed that two main regions are distinguished off the eastern coast of Sakhalin Island with stable and intense upwelling. One of the stable upwelling zones is formed near the northeastern coast of Sakhalin Island, and the second one is formed in the central part of the East Sakhalin shelf. Besides, upwelling is observed in the region of the Crillon Peninsula and near Cape Crillon. The width of the coastal upwelling zone with minimal surface temperatures ranges from 10 to 60 km. In some years, the effect of upwelling can be traced at a distance of 100–120 km from the Sakhalin Island coast.

An analysis of the seasonal variability of the upwelling index showed that favorable wind conditions for the development of upwelling near the eastern coast of Sakhalin Island are observed in July–August. Off the coast of the Cape Patience, upwelling lasts from August to September. The most favorable wind conditions for the development of upwelling are

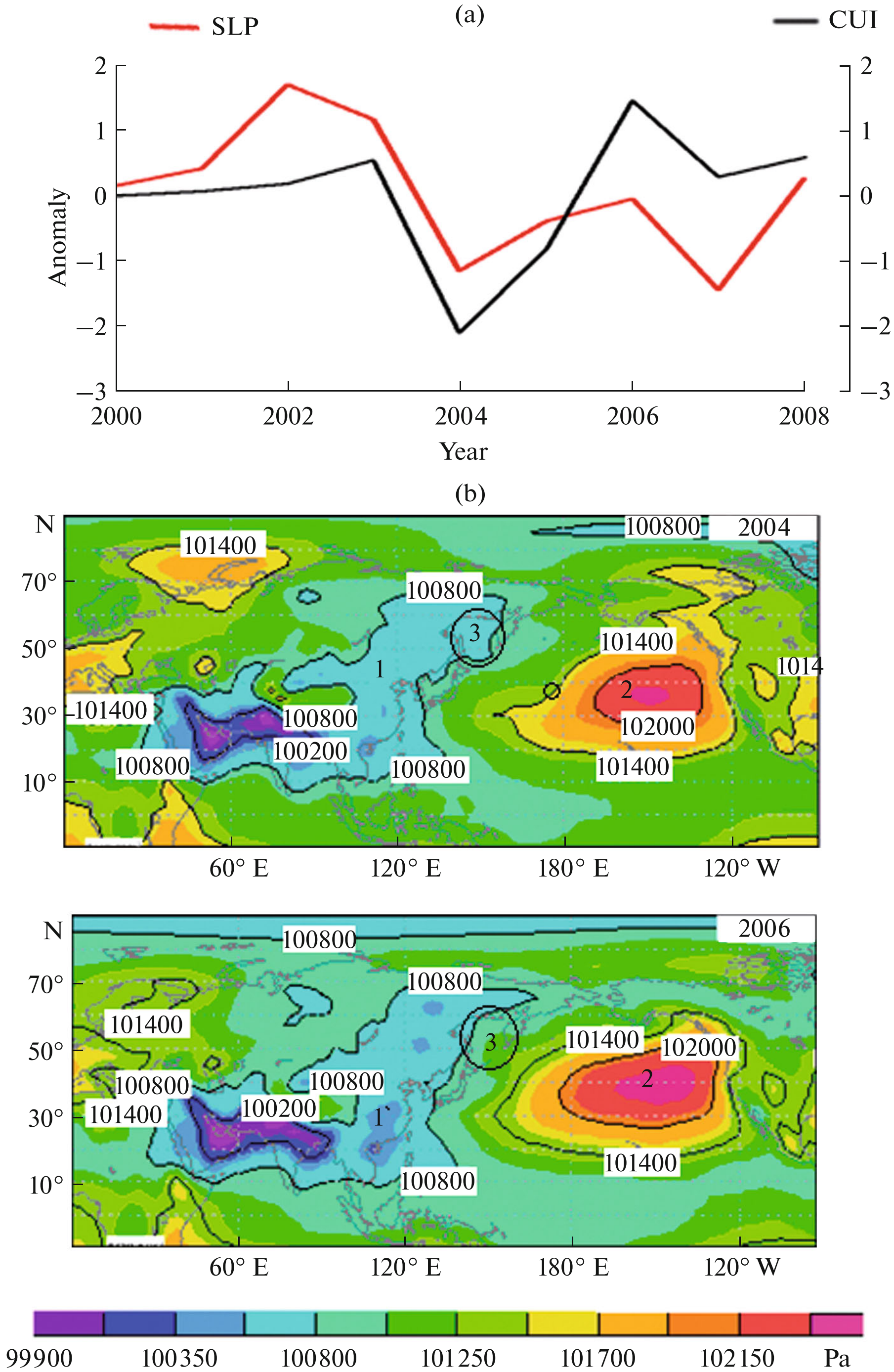

Fig. 5. (a) Interannual variability of the normalized anomalies of the accumulated upwelling index and the Okhotsk anticyclone index and average fields of surface atmospheric pressure in July–August (b) 2004 and (c) 2006. Legend: SLP is the normalized anomaly of the Okhotsk anticyclone index, CIU is the normalized anomaly of the accumulated upwelling index, (1) Asian depression, (2) North Pacific maximum of atmospheric pressure, and (3) Okhotsk anticyclone.

typical for the central part of the eastern coast of Sakhalin Island: in this part of the shelf, upwelling is well pronounced in July and August, and the magnitude of the Ekman transport causing upwelling is approximately two times greater than that in the northern part of the shelf. Differences in the duration of the upwelling season in different areas of the main upwelling zone are associated with the peculiarities of the wind mode in the Sea of Okhotsk. The results obtained from the analysis of satellite measurement data are in good agreement with the data of direct oceanographic observations.

Off the Sakhalin Island coast, upwelling develops both due to the Ekman transport and as a result of the action of the Ekman pumping associated with the positive vorticity of the wind stress field. In this case, the values of the vertical water transport associated with the divergence of wind currents can be comparable with the value of the Ekman transport directed away from the coast, which is the main cause of upwelling.

The interannual variability of upwelling is mainly determined by the state of the Okhotsk anticyclone as the main regional center of atmospheric impact, which determines the wind mode of the Sea of Okhotsk. In years with a well-developed Okhotsk anticyclone, there was a tendency to intensify upwelling off the eastern coast of Sakhalin Island, while its intensity noticeably decreases in years with a weakly expressed Okhotsk anticyclone.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

Alvarez, I., Gomes-Gesteria, M., de Castro, M., and Novoa, E.M., Ekman transport along the Galician Coast (NW Spain) calculated from QuikSCAT Winds, *J. Mar. Syst.*, 2008, vol. 72, pp. 101–115.

Bakun, A., Coastal upwelling indices, west coast of North America, NOAA Tech. Rep. NMF 671, 1973.

Castelao, R.M. and Barth, J.A., Upwelling around Cabo Frio, Brazil: The importance of wind stress curl, *Geophys. Res. Lett.*, 2006, vol. 33, no. 3, 03602. https://doi.org/10.1029/2005GL025182

Craig, M.R. and Dudley, B.C., A global climatology of surface wind and wind stress fields from eight years of QuikSCAT scatterometer data, *J. Phys. Oceanogr.*, 2008, vol. 38, pp. 2379–2413.

Freilich, M.N. and Dunbar, R.S., The accuracy of the NSCAT 1 vector winds: Comparisons with National Data Buoy Center buoys, *J. Geophys. Res.*, 1999, vol. 104, pp. 11231–11246.

Gidrometeorologiya i gidrokhimiya morei. Gidrometeorologicheskie usloviya. Okhotskoe more (Hydrometeorology and Hydrochemistry of the Seas. Hydrometeorological Conditions. The Okhotsk Sea), Leningrad: Gidrometeoizdat, 1988, vol. 9.

Gruzevich, A.K., Arzhanova, N.V., and Sapozhnikov, V.V., Hydrochemical processes within a system of conjugated mesoscale eddies over the Sakhalin shelf, *Oceanology (Engl. Transl.)*, 1996, vol. 36, no. 5, pp. 677–684.

Krasavtsev, V.B., Puzankov, K.L., and Shevchenko, G.V., Wind-induced formation of upwelling on the northeastern shelf of the Sakhalin Island, *Gidrometeorol. Ekol. Usloviya Dal'nevost. Morei: Otsenka Vozdeistv. Mor. Sredu DVNIGMI*, 2000, no. 3, pp. 106–120.

Ogi, M., Tachibana, Y., and Yamazaki, K., The connectivity of the winter North Atlantic Oscillation (NAO) and the summer Okhotsk High, *J. Meteorol. Soc. Jpn.*, 2004, vol. 82, no. 3, pp. 905–913.

Nakamura, H. and Fukamachi, T., Evolution and dynamics of summertime blocking over the Far East and the associated surface Okhotsk High, *Q. J. R. Meteorol. Soc.*, 2004, vol. 130, pp. 1213–1233.

Pickett, M.H. and Paduan, J.D., Ekman transport and pumping in the California Current based on the NAVY's high resolution atmospheric model (COAMPS), *J. Geophys. Res.*, 2003, vol. 108, no. 10. https://doi.org/10.1029/2003JC001902

Popudribko, K.K., Putov, V.F., and Shevchenko, G.V., Assessment of the characteristics of sea currents in the Pil'tun-Astokh hydrocarbon deposit field (the northeastern shelf of the Sakhalin Island), *Meteorol. Gidrol.*, 1998, no. 4, pp. 82–95.

Rutenko, A.N., Khrapchenko, F.F., and Sosnin, V.A., Near-shore upwelling on the Sakhalin shelf, *Russ. Meteorol. Hydrol.*, 2009, vol. 34, no. 2, pp. 93–99.

Send, U., Beardsley, R.C., and Winant, C.D., Relaxation from upwelling in the Coastal Ocean Dynamic Experiment, *J. Geophys. Res.*, 1987, vol. 92, no. C2, pp. 1683–1698.

Translated by A. Ivanov