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Wind Effects on the Upwelling Variability in the Coastal Zone of Primorye (the Northwest of the Sea of Japan)

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Abstract—The variability of upwelling events in the coastal zone of Primorye in the northwestern part of the Sea of Japan is studied using the SeaWinds/QuikSCAT scatterometer wind data for the period of 1999–2009. The intensity of upwelling is defined by the wind-induced offshore Ekman transport (the upwelling index). It was found that along the southern coast of Primorye upwelling events occur from September to March (April). The winter monsoon period is the most favorable for the upwelling development. In the eastern part of the coastal zone of Primorye upwelling is observed in transitional seasons between winter and summer monsoon (February–April and September–October). On the northeastern coast of Primorye, the upwelling season is from August to October (November). The common feature of the coastal zone of Primorye is a wind-driven upwelling in autumn (September–October). The interannual variability of winter upwelling along the southern coast of Primorye is related to the East Asia high pressure center (the Siberian High). The upwelling intensifies in the years with positive air pressure anomalies in the Siberian High and weakens in the years with negative anomalies.

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1. INTRODUCTION

Upwelling is water motion from subsurface levels towards the ocean surface. In the Ekman model for the infinitely deep ocean, upwelling is induced by the wind directed along the coast so that the coast (in the Northern Hemisphere) is situated on the left. In this case the offshore Ekman transport carries surface water away from the coast that causes the compensatory lift of colder deep water. Despite the limitations related to the ocean depth, the value of Ekman transport in the zones of coastal upwelling is considered as a parameter of favorable conditions for this process. Upwelling is affected by the seasonal and synoptic variability of wind, by the density stratification and shelf morphology. Wind-driven upwelling is one of the processes defining the biological productivity of coastal areas.

Wind-driven upwelling in the Sea of Japan is observed along the southern coast of Primorye in autumn (September–October) [3, 4, 7]. Upwelling affects the regional climate in this area. Long-period negative trends in water temperature were registered in the upwelling zone which do not correlate with air temperature and differ from the general trend towards the increase in sea surface temperature (SST) [1]. It was found that the upwelling-related water advection across the shelf is of key importance for the variations in production characteristics in the southern coastal zone of Primorye in autumn [5]; in this season upwelling exerts appreciable influence on the distribution of phytoplankton [6].

The map of average long-term distribution of sea surface temperature of the Sea of Japan (September–October) and the satellite data reveal (Fig. 1) that autumn upwelling is clearly pronounced in the SST field not only along the southern coast but also along the eastern coast of Primorye. In autumn the zones of cold deep water reaching the sea surface along the Primorye coast (low values of SST) are clearly observed

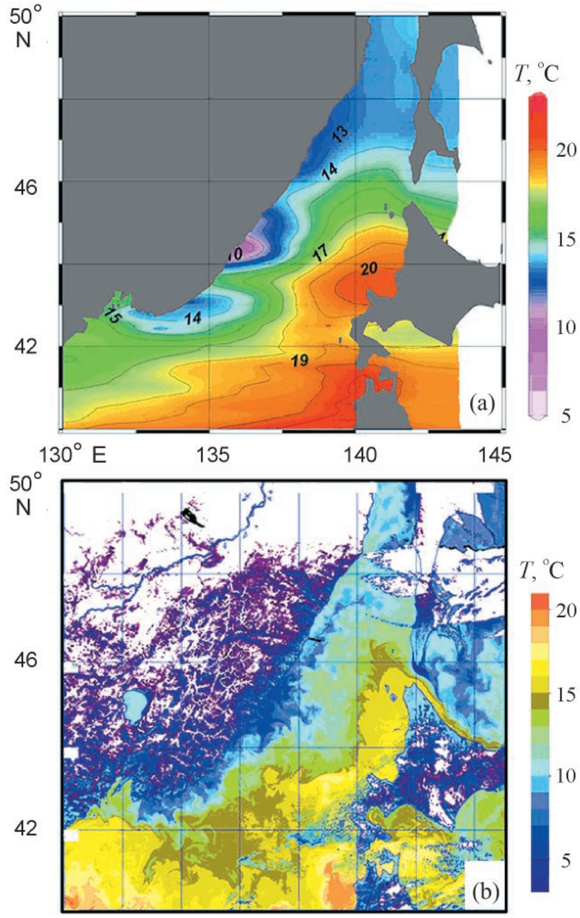

Fig. 1. (a) Average long-term distribution of sea surface temperature in the northern part of the Sea of Japan and (b) the satellite infrared image of the zone of coastal upwelling along the Primorye coast on October 12, 2008.

against a background of the well-heated surface layer in the open sea. In November the autumn-winter cooling results in the smoothing of temperature contrasts between the zone of coastal upwelling and the adjoining part of the Sea of Japan. The wind data obtained from satellite scatterometers (microwave radars) can be used for upwelling investigation. In this case, the intensity of upwelling is estimated by the value of wind-induced offshore Ekman transport (the upwelling index [9]). Recently this approach has been widely used for studying coastal upwelling in different parts of the World Ocean [8, 10].

The main objective of the present paper is to investigate the seasonal variability of upwelling along the Primorye coast based on the analysis of satellite data on surface wind. Besides, the effects are considered of large-scale atmospheric processes on interannual variations in the intensity of winter upwelling observed along the southern coast of Primorye.

2. DATA AND METHODS

The data on the speed and direction of surface wind were obtained with the SeaWinds scatterometer installed on the QuikSCAT satellite (NOAA CoastWatch Wind Data) during the period of its on-orbit operation from 1999 to 2009. The spatial resolution of the initial dataset is 0.25 0.25 , the range of wind speed measurement is 3 to 20 m/s at the accuracy of 2 m/s, and the accuracy of wind direction measurement is 20 [11]. To investigate the seasonal variability of upwelling, monthly mean values of wind stress for the whole period of observations were used for computing the Ekman transport for five areas located in the coastal zone of Primorye with different orientations of the coastline. The location of the area and computation points is presented in Fig. 2a. Computation points were situated at the distance of 25–50 km from the coast (the peculiarities of satellite scatterometers do not allow obtaining the data in the coastal zone with the width of 25 km). The width of the shelf zone of Primorye to the isobath of 200 m is 20–30 km (in some

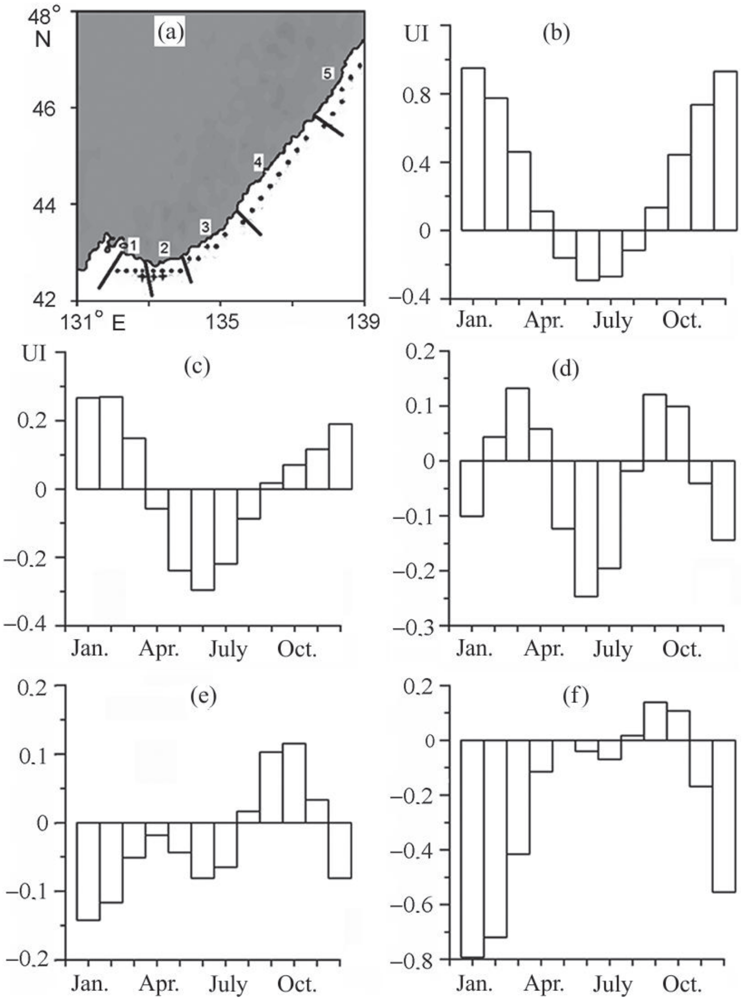

Fig. 2. (a) The location of the areas 1–5 and points of the computational grid and monthly mean values of the upwelling index UI (m^3/s per 1 m of the coastline) along the (b, c) southern, (d, e) eastern, and (f) northeastern coast of Primorye. The crosses are the points the cumulative upwelling index was computed for.

areas, 5–15 km). Therefore, the data used do not include the shallow coastal zone and cover the external part of the shelf (the depth is more than 100 m) and the continental slope. At the first stage of calculations, the value of zonal and meridional components of the Ekman transport was determined:

$$Q_y \quad {}_y / \; f, \; Q_x \quad {}_x / \; f$$

where ${}_y$ and ${}_x$ are monthly mean values of zonal and meridional components of wind stress; is the density of sea water (1025 kg/m^3); f is the Coriolis parameter at the middle latitude of each selected area.

The Ekman transport directed perpendicular to the shoreline (the upwelling index) is computed from the equation

$$\mathrm{UI} \quad Q_x \sin \quad Q_y \cos \;, \quad\quad /2$$

where for the Primorye coast is an angle between the straight line approximating the coastline and the respective circle of latitude. In this case, the positive values of the upwelling index correspond to the offshore Ekman transport which causes coastal upwelling. Monthly mean values of the upwelling index at the computation points were averaged within each selected area.

The authors of the present paper also used the data of the U.S. National Center for Environmental Information (World Ocean Database 2013) and monthly mean fields of sea-level air pressure (NCEP/DOE Reanalysis-II).

3. WIND EFFECTS ON SEASONAL VARIABILITY OF UPWELLING ALONG THE PRIMORYE COAST

The results of the upwelling index computation revealed (Fig. 2) that the intensity and seasonality of this process significantly vary along the Primorye coast. Along the southern coast of Primorye (area 1 located between Vladivostok and Nakhodka, Fig. 2b), the upwelling season is from September to April. The more intense upwelling in this period in November–February is associated with the winter monsoon characterized by strong northwestern and western wind. The most favorable wind conditions for the winter upwelling are observed in January. In transition seasons (September–October and March–April) the intensity of upwelling is considerably reduced. In area 2 situated along the southern coast of Primorye (Fig. 2c), the upwelling season duration changes insignificantly (September–March), the intensity of upwelling decreases by about twice. The change in the coastline orientation relative to the direction of prevailing winter monsoon leads to less favorable conditions for the development of upwelling in this area. The summer monsoon (May–August) characterized by light southeastern and southern winds results in downwelling (water sinking) along the southern coast of Primorye (areas 1 and 2).

In area 3 located along the eastern coast of Primorye, the variations in the wind regime in the coastal zone (the winter monsoon is mainly directed off the shore) lead to the fact that favorable conditions for upwelling exist in transitional seasons only (February–April and September–October). When one type of monsoon circulation changes the other (spring and autumn), the winds of different directions may be observed along the eastern coast of Primorye. The upwelling intensity near the eastern coast of Primorye is lower as compared to the southern coastal zone of Primorye.

In areas 4 and 5 situated along the northeastern coast of Primorye, favorable conditions for the development of upwelling are observed from August to November (to October in area 5). Relatively high values of the upwelling index fall on September and October that corresponds to the period of transition from the summer monsoon to the winter one; this period is characterized by the significant variability of wind speed and wind direction. The average long-term data and satellite data demonstrate (Fig. 1) that in autumn the upwelling zone along the northeastern coast of Primorye is clearly observed in the SST field. One of the factors affecting upwelling in this area is the long duration of the season with favorable wind conditions for upwelling. The upwelling season along the northeastern coast of Primorye begins in August but not in September (the southern and eastern coast of Primorye). In the northern part of the considered area (area 5) the strongly pronounced downwelling is observed in the period of the winter monsoon that is not typical of the other coastal zones of Primorye. Downwelling is related to specific features of the wind regime over the Sea of Japan. The transition of prevailing northwestern winds to northern and northeastern winds which form conditions for the upwelling development along the mainland coast takes place in the area of the Strait of Tartary in the winter monsoon period.

The results of calculation of the upwelling index demonstrated that the common feature of water in the Primorye shelf zone is wind-driven upwelling in autumn (September–October). Wind-driven upwelling in autumn is observed during the transition period from the summer monsoon to the winter one. At that time the significant variability of wind speed and wind direction is registered along the Primorye coast. The period of active cyclogenesis starts over the Sea of Japan in autumn; therefore, the wind strengthening is usually associated with atmospheric cyclones coming to the territory of Primorye and adjoining water area of the Sea of Japan. In general, wind conditions in autumn are favorable for the development of upwelling in the coastal zone of Primorye. Besides, the clearly pronounced winter wind-driven upwelling is observed along the southern coast of Primorye from November to March. The winter wind-driven upwelling is connected with the period of winter monsoon characterized by the prevalence of strong stable northwestern and western winds [2].

4. VARIABILITY OF WATER THERMOHALINE STRUCTURE IN THE UPWELLING ZONE

The thermohaline structure of water along the southern coast of Primorye related to wind-driven upwelling may be studied from hydrological data obtained in the autumn of 2000 (Fig. 3). The cloudless infrared image of this area was obtained on October 27, 2000 (Fig. 3a). Very cold (due to upwelling) water was observed along the Primorye coast. The main center of intense upwelling (SST minimum values) was situated near Cape Povorotnyi. The measurements with the SeaWinds/QuikSCAT scatterometer conducted on October 25–28, 2000 demonstrated that the speed of western wind inducing upwelling along the southern coast of Primorye was about 20 m/s.

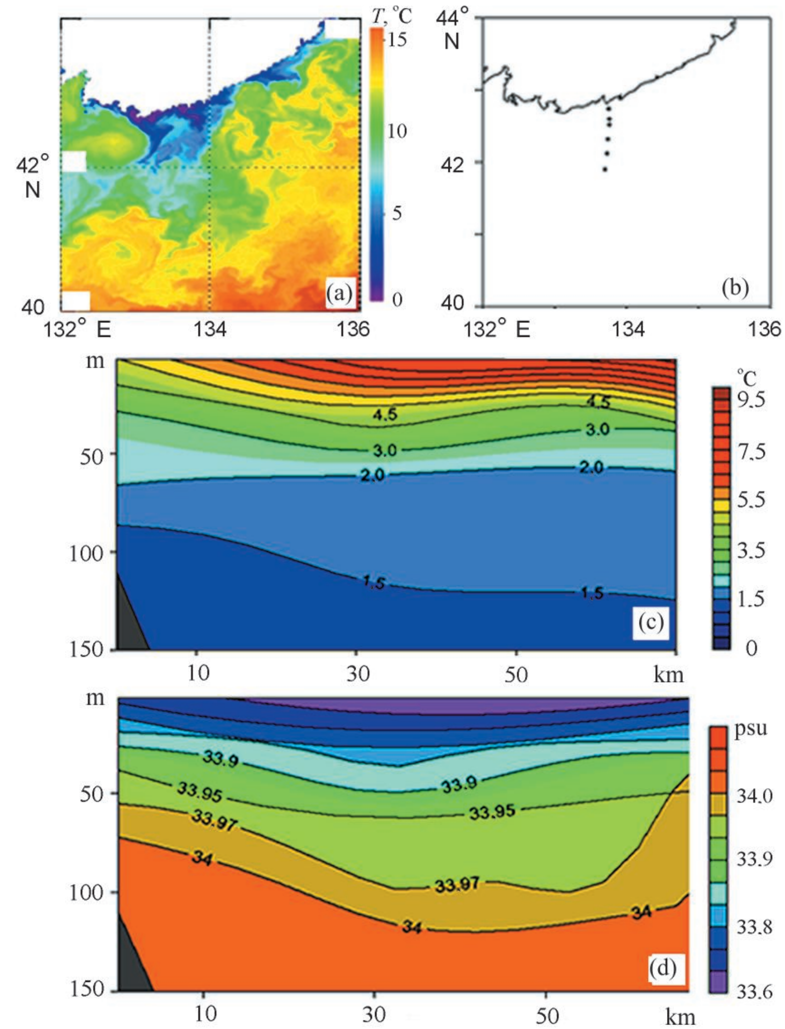

Fig. 3. (a) The upwelling zone along the southern coast of Primorye in the satellite infrared image on October 27, 2000; (b) the location of gaging stations, and the vertical distribution of (c) temperature and (d) salinity at the cross-section from October 31, 2000.

The distribution of hydrological parameters at the cross-section near the southern coast of Primorye on October 31, 2000 (Figs. 3b, 3c, and 3d) allows considering the thermohaline structure of water after the intense upwelling. In that period the thermocline was completely destructed in the process of the surface layer cooling in autumn; therefore, the displays of upwelling (the lift of isolines as approaching the coast) were observed in the shelf zone. According to the results of measurements, close to the shelf edge salinity significantly exceeded its values obtained for the subsurface layer in the areas of the continental slope and deep water. The most probable reason for water salinity increase in the external part of the shelf is wind-driven upwelling. Intermediate waters which were transported to the surface in the area of the shelf edge had temperature below 1.2 C and salinity above 34.07 psu. The appearance of cold and salt water in the bottom layer near the shelf edge cannot be related to the usual seasonal water cycle. The comparative analysis of the vertical profiles of potential temperature and salinity revealed that the water lift occurred from the depth of 275–400 m. Upwelling essentially modified stratification in the continental slope zone: the weakly stratified layer with relatively high salinity was situated directly under the seasonal layer of discontinuity. At such type of stratification favorable conditions for the development of winter convection and ventilation of intermediate waters of the Sea of Japan are formed along the southern coast of Primorye.

5. WIND EFFECTS ON THE INTERANNUAL VARIABILITY OF WINTER UPWELLING ALONG THE SOUTHERN COAST OF PRIMORYE

Winter upwelling along the southern coast of Primorye may affect the formation and ventilation of water in the northwestern part of the Sea of Japan. The lift and transport of saltier water from the intermediate layer to the surface and its subsequent cooling increase the density of shelf water that may lead to slope convection (cascading). On the one hand, this process defines the recharge and ventilation of bottom water of the Sea of Japan [13]. On the other hand, autumn-winter upwelling leads to the salinity increase in the water of the Primorye Current that forms conditions for the development of deep convection in the open part of the Sea of Japan involved in deep water formation [14].

The main pressure centers defining atmospheric circulation and the type of air mass transport over the Sea of Japan in winter are the Siberian High and Aleutian Low. The Siberian High situated over East Asia exerts direct influence on the air pressure field over the Sea of Japan. The Aleutian Low intensifies in the northern part of the Pacific Ocean in winter. This atmospheric center of action exerts much smaller influence on wind over the Sea of Japan. The zone of the highest air pressure gradients is formed between the cold continent and relatively warm Pacific Ocean in winter. This leads to the formation of stable (in strength and direction) airflows directed from the land to the sea (the East Asia winter monsoon). Strong northwestern and western winds with the speed of 10–15 m/s prevail over the Sea of Japan in the winter monsoon period [2, 12].

The winter monsoon forms favorable conditions for the development of upwelling along the southern coast of Primorye (Figs. 2b and 2c). The interannual variability of upwelling may depend on the Azores High state and on the air pressure gradient between the eastern part of the continent and the Pacific Ocean. To verify this hypothesis, the conjoint analysis of parameters characterizing the Siberian High was carried out, namely, of the air pressure gradient over the Sea of Japan and upwelling intensity along the southern coast of Primorye. The Siberian High index was computed as the average value (November–March) of sea-level air pressure in the area of 40 –65 N, 80 –120 E [12]. The North Pacific index characterizing the pressure field in the northern part of the Pacific Ocean and the activity of the Aleutian Low was computed as the average value (November–March) of sea-level air pressure in the area of 30 –65 N, 160 E–140 W [15]. The analog of air pressure gradient on the land–ocean interface was computed as the difference of the values of the Siberian High index and North Pacific index. The cumulative upwelling index was used for characterizing upwelling intensity. This index was determined from monthly mean values of wind stress for every winter in 1999–2009. Monthly mean values of the upwelling index averaged for three points were consecutively summed for November–March for computing the cumulative upwelling index. The location of computation points along the southern coast of Primorye is presented in Fig. 2a.

To analyze the data on interannual variability, the anomalies were considered of the cumulative upwelling index, Siberian High index, and difference between the Siberian High index and the North Pacific index normalized using the root-mean-square deviation (Fig. 4a). It is clear from the figure that the intensity of winter upwelling correlates qualitatively well both with the Siberian High index and with the difference in air pressure between two main regional atmospheric centers of action. The Siberian High is characterized by significant interannual variability. The well developed Siberian High was observed in 1999–2000, 2004–2005, and 2005–2006; the years when this atmospheric center of action demonstrated low activity, are 2001–2002 and 2006–2007. Thus, winter upwelling intensified along the southern coast of Primorye in the years with the well developed Siberian High and weakened in the years with the poorly pronounced Siberian High.

The distribution of sea-level air pressure in November–March in 2005–2006 (intense upwelling) and 2006–2007 (weak upwelling) may be judged by the data presented in Figs. 4b and 4c. The maps demonstrate that the Siberian High was well developed in the cold season of 2005–2006 (high values of cumulative upwelling index). The effects of the Aleutian Low were observed in the northern part of the Sea of Japan. This situation corresponds to the strengthening of winter monsoon over the Sea of Japan which increased the upwelling intensity along the southern coast of Primorye. In 2006–2007 (the minimum values of the cumulative upwelling index) the considerable weakening of the Siberian High was observed and the Aleutian Low was poorly developed. This led to the decrease in air pressure gradients between the continent and the Northwest Pacific. In such case wind conditions over the Sea of Japan were least favorable for the upwelling development along the southern coast of Primorye over the whole period of observations.

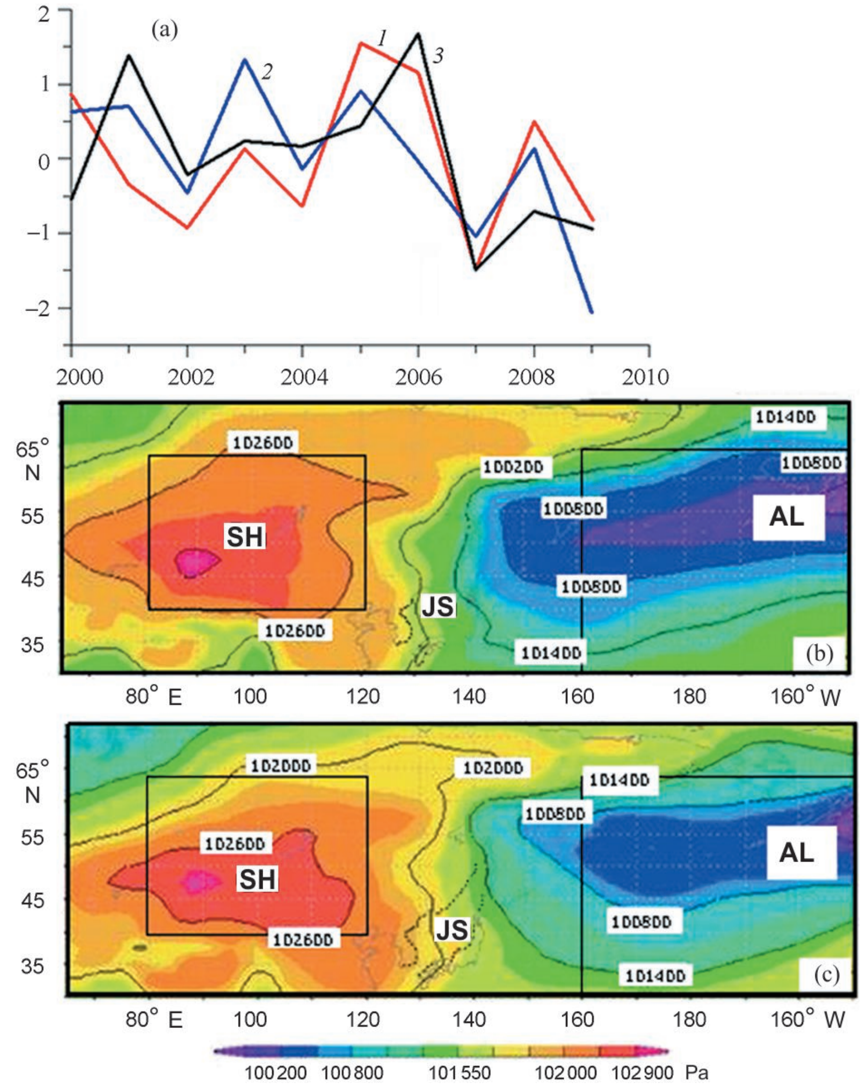

Fig. 4. (a) Interannual variability of normalized anomalies of (*1*) the Siberian High index, (*2*) difference between the Siberian High index and North Pacific index, and (*3*) cumulative upwelling index; the mean fields of sea-level air pressure in November–March in (b) 2005–2006 and (c) 2006–2007. SH is the Siberian High; AL is the Aleutian Low; JS is the Sea of Japan. The rectangles are the areas the Siberian High index and North Pacific index were computed for.

6. CONCLUSIONS

The seasonal variability of upwelling in the coastal zone of Primorye was studied from the long-term satellite data on surface wind. The intensity of upwelling is defined by the wind-induced offshore Ekman transport (the upwelling index). The upwelling season along the southern coast of Primorye is from September to March–April. The most intense upwelling (November–February) is associated with the winter monsoon period characterized by strong stable northwestern and western winds. On the eastern coast of Primorye favorable wind conditions for upwelling are observed in transition seasons only (February–April and September–October). The upwelling season along the northeastern coast of Primorye is from August to October–November; the relatively high intensity of upwelling is observed in September and October that corresponds to the period of transition from the summer monsoon to the winter one. In general, the common feature of water in the shelf zone of Primorye is wind-driven upwelling in autumn (September–October). The winter wind-driven upwelling is clearly pronounced along the southern coast of Primorye. The interannual variability of winter upwelling is basically defined by air pressure variations in the Siberian High being the main atmospheric center of action in East Asia. The intensity of upwelling is also affected by the value of the air pressure gradient between the eastern part of the continent and the northern part of the Pacific Ocean. Upwelling intensifies along the southern coast of Primorye in the years with the well developed Siberian High and weakens in the years with the weak Siberian High.

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