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STYDYING ATMOSPHERE AND OCEANS FROM SPACE

Effects of the Wind and Ice Conditions on the Upwelling along the Western Kamchatka Coast (Sea of Okhotsk) Based on the Satellite Data

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Abstract—The variability of the upwelling along the western coast of the Kamchatka Peninsula (northeastern part of the Sea of Okhotsk) has been studied based on an analysis of the multisensor satellite data. The intensity of upwelling is estimated on the basis of wind-forced offshore Ekman transport (upwelling index). The wind data for studying the seasonal variation of upwelling were collected in 1999–2009 using a QuikSCAT/SeaWinds scatterometer. The upwelling events along the western Kamchatka coast were observed in December at the beginning of the winter monsoon period. During the period of strong winter monsoon northern winds from January to the middle of March, the drifting ice prevents the upwelling of the deep water at the western Kamchatka shelf edge under the mean conditions. The oceanographic data show that upwelling in the western coastal zone of Kamchatka was also observed during the transitional periods from winter to the summer monsoon (April). In summer, upwelling events are rarely observed in this region. The main cause of the summer upwelling is the propagation of the atmospheric cyclones over the Kamchatka Peninsula.

Keywords: upwelling, Ekman transport, seasonal and synoptic variability, wind and ice conditions, monsoon winds, multisensor satellite data, Sea of Okhotsk, western coast of the Kamchatka Peninsula

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INTRODUCTION

According to the Convention on Biological Diversity Protection adopted by the UN Environment Programme (UNEP), the Russian western Kamchatka shelf of the Sea of Okhotsk is an ecologically and biologically important region of the World Ocean. Wind upwelling is related to the main processes influencing the productivity of the oceanic coastal regions. The coastal upwelling is induced by the wind parallel to the shore so that in the Northern Hemisphere the shore is on the right of the wind direction. Upwelling and water ascent of deep water is accompanied by the transport of large amounts of nutrients to the euphotic layer, which provides a high level of the primary production, being a basis of the food chain in marine ecosystems.

The Sea of Okhotsk is located in the region of the influence of the Asian-Pacific mid-latitude monsoon circulation that determines the periodicity of the atmospheric processes. In summer, wind blows from sea to land (the southeastern and southern winds dominate). In the period of the summer monsoon, winds favorable for the development of stable coastal upwelling are observed at the eastern coast of Sakhalin Island located to the left relative to the direction of the dominating winds (Zhabin and Dmitrieva, 2016). The summer upwelling on the western coast of Kamchatka can be related only to the specific meteorological situations (when the atmospheric cyclones propagate to the basin of the Sea of Okhotsk and cause strong winds of northwestern directions). During the winter monsoon, the mean transport of air masses is directed from land to sea (strong winds of the northwestern and northern directions dominate, which are favorable for the development of upwelling in the absence of drifting ice).

In winter, ice cover is observed at the western coast of the Kamchatka Peninsula. The development of ice conditions depends on many factors, which varies from one year to another. According to (*Gidrometeorologiya*..., 1998), the mean probability of ice occurrence at the western coast of Kamchatka is 0–50% in December, but it increases in January to 50–100%; it reaches the maximum in February and the beginning of March (100%). Under mean ice conditions, ice decline begins in the second half of March. Fast ice is almost not formed on the western coast of Kamchatka. The southwestern coast of Kamchatka is a region of low ice cover. The ice drifts predominantly along the coastline of the western coast of Kamchatka (Fig. 1).

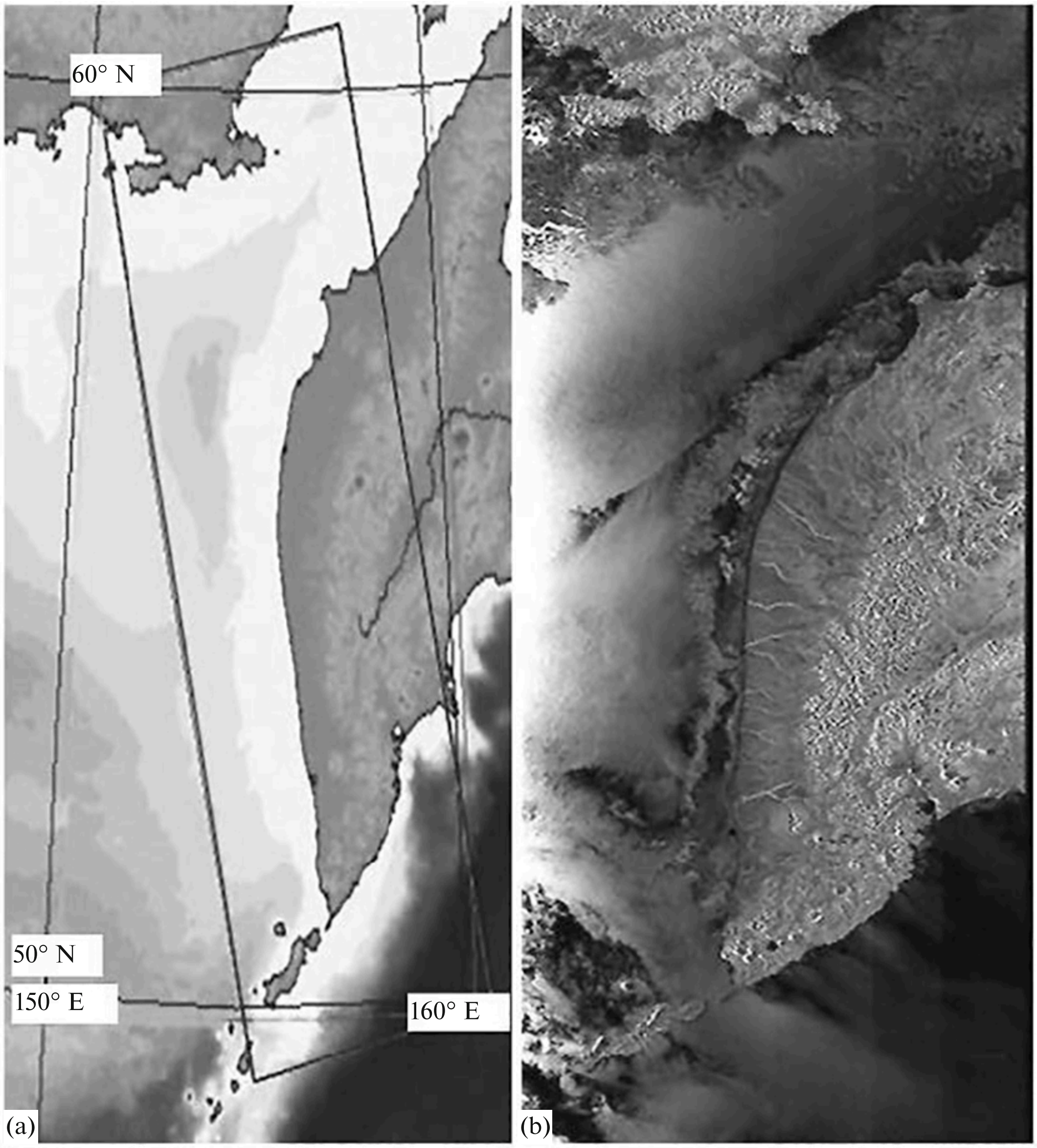

Fig. 1. Geographical location of the Envisat radar image (a) and an image showing the distribution of drifting ice on the western coast of Kamchatka on January 27, 2007 (b).

In the absence of ice, the dominating strong winter monsoon winds of northern and northwestern directions should form favorable conditions for the development of upwelling on the western coast of Kamchatka. However, direct measurements (Alexander and Niebauer, 1981; Buckley et al., 1979; Johannessen, 1983; Tang and Ikeda, 1989) and numerical modeling (Roed and O'Brien, 1983; Häkkinen, 1986) showed that the existence of drifting ice significantly changes upwelling and downwelling (descent of water) in the ice edge zone. Differential Ekman transport (higher wind stress over ice compared to the ice-free sea surface) causes weak downwelling when the stress vector is directed along the ice edge, so that the drifting ice is on the left and the ice-free part of the sea is on the right (winter situation at the western coast of Kamchatka). Upwelling is developed in the opposite situation: the ice is on the right and the ice-free sea is on the left of the wind direction blowing along the ice edge zone (winter conditions at the eastern coast of Sakhalin).

Satellite observations are currently among the main instruments of oceanic research. The multisensor approach (the application of the maximum satellite information about the object of research collected from various sensors installed on satellites) can be considered one of the most promising methods for investigating the structure and dynamics of waters in the coastal zones of the oceans and seas. Various active and passive satellite sensors operating in the optical, infrared (IR), and microwave ranges of the electromagnetic spectrum are used for measuring the parameters that characterize the state of the marine environment: color, temperature, sea level, and roughness. In particular, processing and analyzing the remote data sensing (RDS) of the sea surface allow us to gather information about the velocity and direction of the surface wind (QuickSCAT and MetOp satellites), the characteristics of the ice cover (Envisat and Aqua satellites), the thermal structure of water (satellites of the NOAA and Landsat series), and chlorophyll-*a* concentration (Suomi NPP satellite).

The main objective of this research has been formulated on the basis of new possibilities: to consider the hydrometeorological conditions under which upwelling is observed at the western coast of Kamchatka based on a joint analysis of satellite data and oceanographic observations.

DATA AND METHODS OF CALCULATION

A united dataset of satellite data gathered using various scatterometers is currently being developed; therefore, we used only the measurements performed using the SeaWinds scatterometer installed on the QuickSCAT satellite (NOAA Coast Watch Wind Data) to calculate the monthly mean wind velocities. The SeaWinds/QuickSCAT scatterometer has been operating on orbit in 1999–2009. The spatial resolution of the initial dataset is 0.25° × 0.25°. The range of measured wind velocities is from 3 to 20 m/s, the accuracy velocity is 2 m/s, and the direction accuracy is 20°. To study the seasonal variation of upwelling based on the monthly mean tangential wind stress over the entire period of observations using the SeaWinds/QuiKSCAT scatterometer, we calculated the upwelling indices in three regions of the western Kamchatka coast with different orientation of the coastline. The locations of the regions and points of calculation are shown in Fig. 2. The points of calculation were located at a distance of 25–50 km from the coast or from the ice edge in the winter period (the satellite scatterometers do not make it possible to obtain data in a coastal/ice edge zone that is 25 km wide). To study the influence of the synoptic variability of wind velocity on the coastal upwelling, we used 3-day average scatterometer data: SeaWinds/QuickSCAT (April 2007) and ASCAT/EUMETSAT MetOp-A (August 2015), which has been operating in orbit since 2007. The nominal resolution of the ASCAT data is 0.25° × 0.25°, the accuracy of wind speed measurements is 2 m/s in the range 4–24 m/s, and the accuracy of direction measurements is 20°.

In the first stage of calculating the upwelling index, we determined the zonal and meridional components of the Ekman transport

$$Q_x = \boldsymbol{\tau}_y/\rho f,\ Q_y = -\boldsymbol{\tau}_x/\rho f,$$

where $\boldsymbol{\tau}_y$ and $\boldsymbol{\tau}_x$ are monthly mean values of the zonal and meridional components of the tangential wind stress, ρ is the density of seawater (1025 kg/m^3), and f is the Coriolis parameter at midlatitude for each of the selected regions.

The Ekman transport directed normally to the coastline (upwelling index) was calculated from the following equation:

$$UI = Q_x \sin \mathrm{O} - Q_y \cos \mathrm{O},$$

where O for the western Kamchatka coast is the angle between the straight line approximating the coastline and the corresponding meridian. Thus, in the northern region O = 225°, in the central region O = 200°, and in the southern region O = 110°. In this case, the positive values of the upwelling index correspond to the offshore Ekman transport, which induces coastal upwelling.

To characterize the ice conditions, we generally used the data of the AMSR-E improved microwave scanning radiometer installed on the Aqua satellite (spatial resolution is 25 km) and the data from radar with synthetic aperture ASAR installed on the Envisat satellite (Miravi database; images of moderate resolution). The oceanographic observations were made during the oceanographic survey conducted by the TINRO Center (Vladivostok) in April 2007 from the R/V *Professor Kaganovskii*. We used the data of sea surface temperature as additional information (from satellites of the NOAA series, radiometer AVHRR, with a resolution of 1.1 km, and from the Landsat-7 ETM+ satellite, thermal range, spatial resolution of 80 m), and distribution of chlorophyll-*a* (satellite Suomi NPP, radiometer VIIRSN, spatial resolution 4 km). We analyzed surface weather charts issued by the Japan Meteorological Agency to investigate the influence of the synoptic wind conditions on the development of the summer upwelling.

ICE CONDITIONS ON THE WESTERN COAST OF KAMCHATKA BASED ON SATELLITE DATA

The western coast of Kamchatka was conventionally divided into three regions, depending on the form of the coastline: 56.5°–58° N (northern), 55.5°–56.5° N (central), and 52°–54.5° N (southern). Based on the data of the AMSR-E improved microwave scanning radiometer installed on the Aqua satellite and radar with synthetic aperture on the Envisat satellite (2002–2009), the ice appears in the northern region in the end of December as fast ice. In winter, the dominating part of the ice drifts from Shelikhov Bay. The ice usually completely disappears in the second half of March. In individual years (for example, in 2006), immobile ice in the bays of the northern region could be found at the end of April. The appearance of ice in the central region was recorded on the last days of December to mid-January. This ice can be connected with the coast as a narrow band (fast ice); in individual years, mobile nonstationary ice fields were observed here. Usually, the drifting ice appears here in the sec-

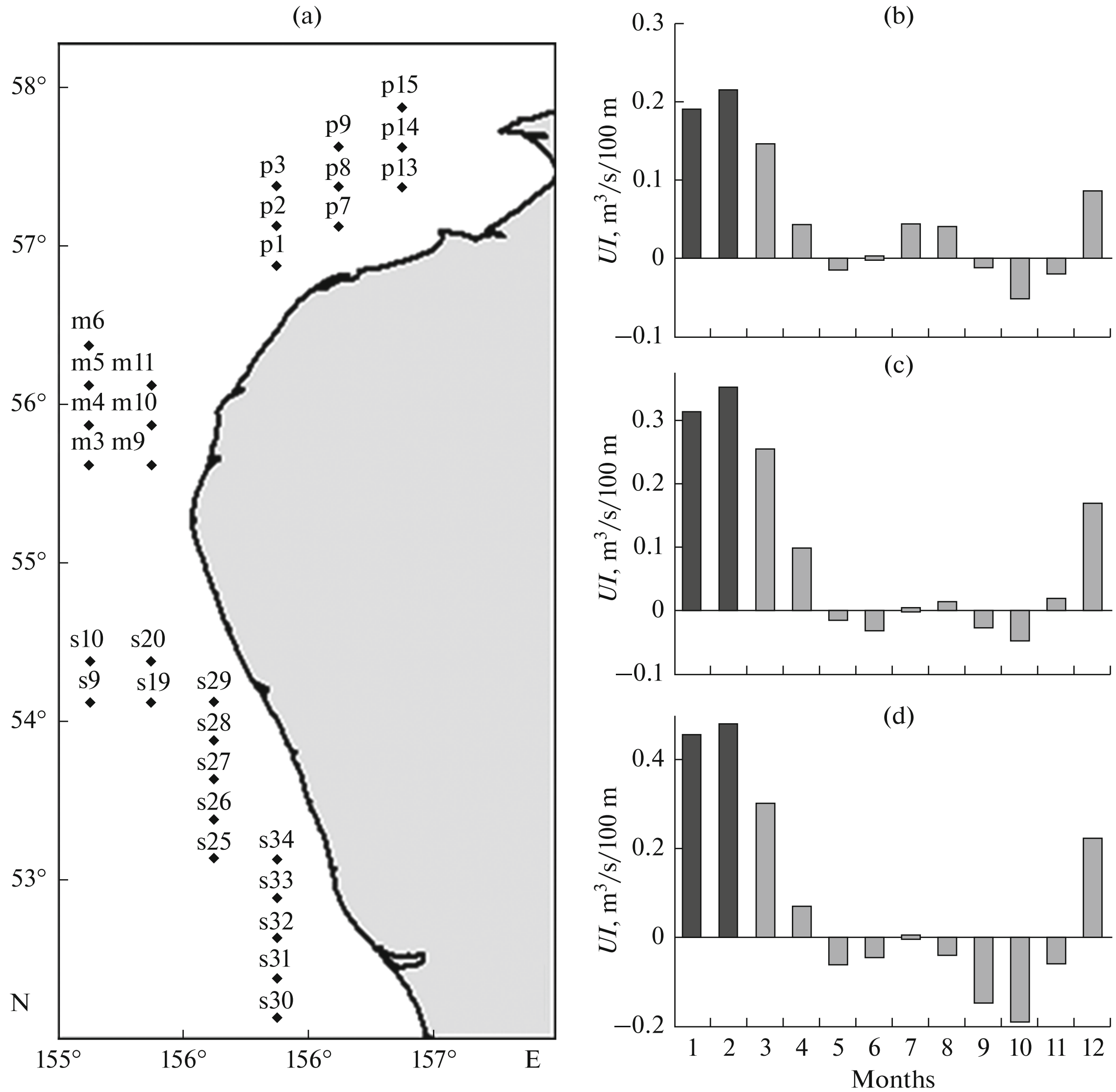

Fig. 2. Locations of region and calculated points (a) and results of a calculation of monthly mean values of upwelling indices in the northern (b), central (c), and southern (d) regions of the coastal zone. The black bars indicate the months (January–February) during which the drifting ice suppresses upwelling development at the coast. Notations: p is northern, m is central, and s is southern regions.

ond half of January. The complete disappearance of ice in the central region occurs in the first half of March. In the southern region, the drifting ice is observed at 53° N in the second half of January to the beginning of March. In individual years, ice can drift as far as 52° N. Ice begins breaking in the first half of March. Under conditions close to the mean ones, the entire coast becomes ice-free in the last decade of March. The southwestern coast of the peninsula is ice-free during the entire winter period. In February 2007, drifting ice was observed in the region from Shelikhov Bay to 52° N (Fig. 1). In the first decade of March, the ice cover began to break. In the second half of March, almost the whole coastal region became free of ice. The observations from the R/V *Professor Kaganovskii* were carried on April 3–23, 2007.

INFLUENCE OF THE WIND CONDITIONS ON THE UPWELLING ON THE WESTERN COAST OF KAMCHATKA

We excluded the period from January to February from the analysis of all regions, taking into account the mean ice conditions (drifting ice at the coast). The existing models and theories do not make obtaining quantitative estimates of the upwelling/downwelling intensity in the presence of drifting ice on the coast possible. March, as the month with favorable conditions for the development of upwelling, may be considered only if the winters are warm or moderate, when early ice breaking and melting occurs, which leads to the fast changes in the ice conditions up to the complete disappearance of ice in the central and southern parts of the region considered here. The results of calculating the upwelling index showed (Fig. 2a) that the intensity of this process and its seasonal variability along the western coast of Kamchatka change from one region to another. In the northern region, wind conditions favorable for upwelling are observed in December, March–April, and June–August. In the central region, upwelling can develop in December and March–April, while in the summer months it is poorly manifested.

On the southwestern coast of Kamchatka, wind can also induce upwelling in December and March–April, but in August the upwelling index is close to zero. According to the calculations of the upwelling index, upwelling in December is a general property of the shelf waters of western Kamchatka, which is related to the beginning of the period of strong winter monsoon winds. The spring wind upwelling (second half of March–April) is observed in the transition period from the winter to summer monsoon. During this time period, strong variations in the speed and direction of the wind are observed on the western Kamchatka coast. In general, the intensity of the winter (December) upwelling is higher in the central and southern regions of the western Kamchatka shelf. In general, one can get qualitative and quantitative characteristics of upwelling/downwelling in the ice period only by a joint analysis of satellite data on the surface wind and field data from ships.

The summer upwelling on the western coast of Kamchatka is not a permanent phenomenon (low values of the upwelling index). In the northern part of the region, it can be related to the local orographic winds. In the center and southern part of the Kamchatka shelf zone, upwelling is generated only under the influence of relatively rare synoptic situations related to the appearance of atmospheric cyclones, which cause strong and long winds in northern and northeastern directions.

THERMOHALINE WATER STRUCTURE IN THE PERIOD OF THE SPRING UPWELLING

Hydrological data measured on April 18–19, 2007, allow us to consider the peculiarities of the thermohaline and density water structure in the period of the spring upwelling (Fig. 3).

The section was occupied along 57° N. In the period from April 6 to 17, the synoptic meteorological conditions were characterized by strong northern winds of long duration and an absence of ice on the coast (the satellite data from the AMSR-E improved microwave scanning radiometer installed on the Aqua satellite); these conditions were favorable for the development of this process. Weak thermal contrasts at the sea surface (the temperature was approximately 0.4°C) do not make it possible to distinguish the upwelling zone on the satellite temperature charts of the sea surface. However, the salinity and density distributions clearly show that isohalines and isopycnals reach the surface, which is characteristic of zones of the coastal upwelling. The ascent of waters to the surface layers occurred approximately from depths of 100 m.

SUMMER UPWELLING ON THE WESTERN COAST OF KAMCHATKA

A period of active cyclogenesis over the Sea of Okhotsk begins in the second half of summer; therefore, the intensification of wind is usually related to the fact that atmospheric cyclones propagate to the Kamchatka territory and the adjacent part of the Sea of Okhotsk. In specific synoptic situations, this can cause upwelling in the coastal zone of Kamchatka (Figs. 4a, 4b).

In August 2015, strong winds of long duration in northern and northeastern directions with speeds of about 10 m/s, related to the propagation of a cyclone to the Kamchatka Peninsula (August 22–25), caused the development of upwelling in the coastal zone. The summer upwelling was accompanied by the development of submesoscale processes, which provide transfrontal exchange between the waters of the zone and the outer part of the shelf (Fig. 4c). The chlorophyll-*a* concentration at the surface strongly increased in the upwelling zone (Fig. 4d), which indicates an increase in biological productivity over the shelf of western Kamchatka. However, an analysis of the archived satellite IR images showed that summer wind upwelling has been rarely observed in the shelf zone of Kamchatka. Usually, the strong stratification of coastal waters related to radiation warming and freshening of the surface layer suppresses the development of wind upwelling.

CONCLUSIONS

Satellite data including the observations of the surface wind, ice conditions, sea surface temperature, currents, and distribution of chlorophyll-*a*, supplemented with land-based observations (hydrological and meteorological data), allowed us to get new information about the coastal upwelling on the western coast of the Kamchatka Peninsula (northeastern part of the Sea of Okhotsk). The influence of the upwelling on the spatiotemporal variability of the surface-layer structure was estimated within the traditional approach: the upwelling intensity was quantitatively characterized by the upwelling index calculated from the QuickSCAT scatterometer data. We took into account the variations in the response of the coastal

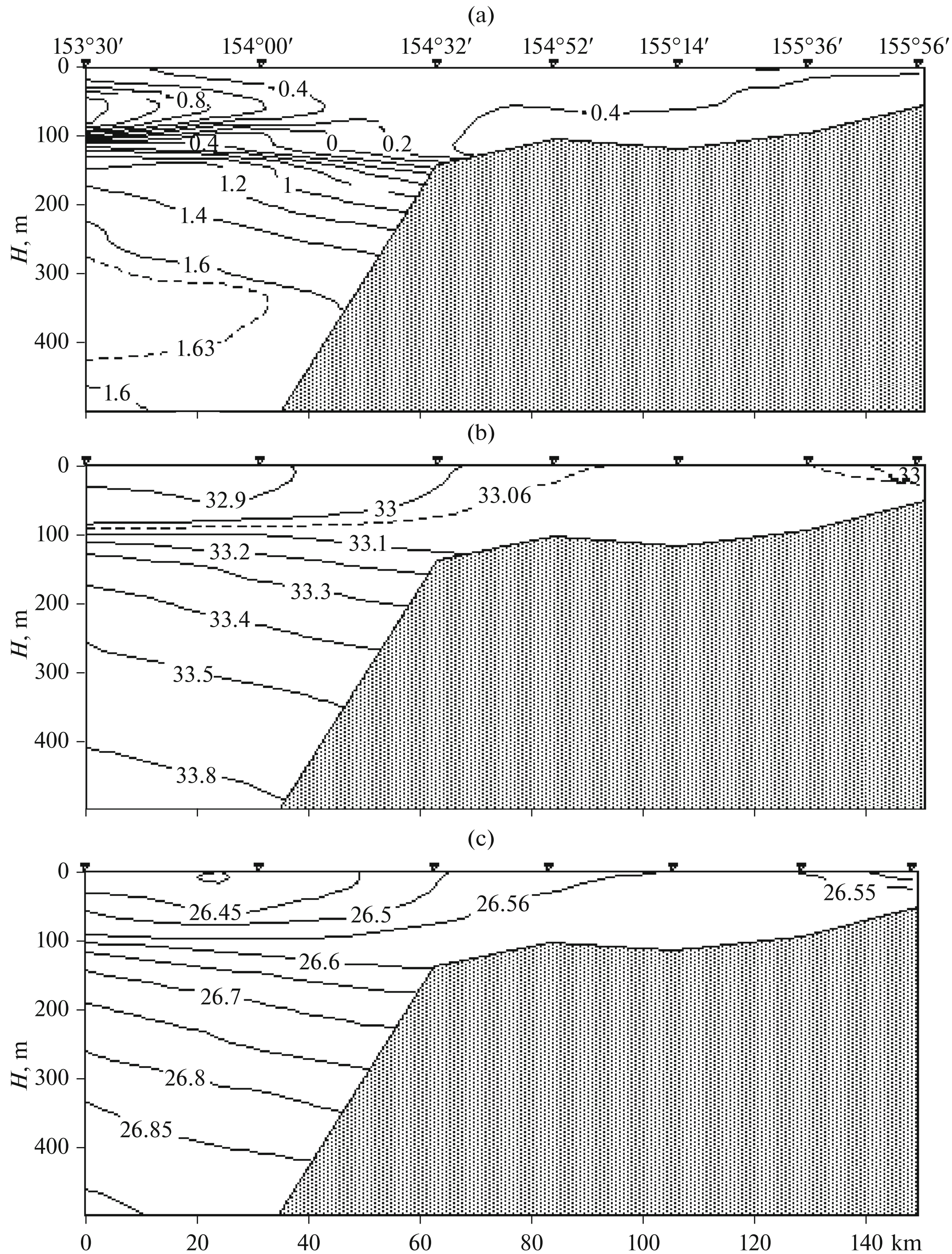

Fig. 3. Vertical distribution of temperature (a), salinity (b), and density (c) over the section along 57° N crossing the upwelling zone on the Kamchatka coast. The section was occupied on April 18–19, 2007.

waters to the alongshore wind forcing related to the presence of the drifting ice in the winter period.

The results of the calculation of the upwelling index showed that the winter (December) upwelling is a general feature of the shelf water zone at the western coast of Kamchatka. It is related to the beginning of the period of strong monsoon winds in northern and northwestern directions. The appearance of drifting ice at the coast (January to the beginning of March) causes a change in upwelling to weak downwelling at the ice edge zone. In the spring transition period from the winter to summer monsoon after the breaking of the ice cover on the Kamchatka coast (the second half

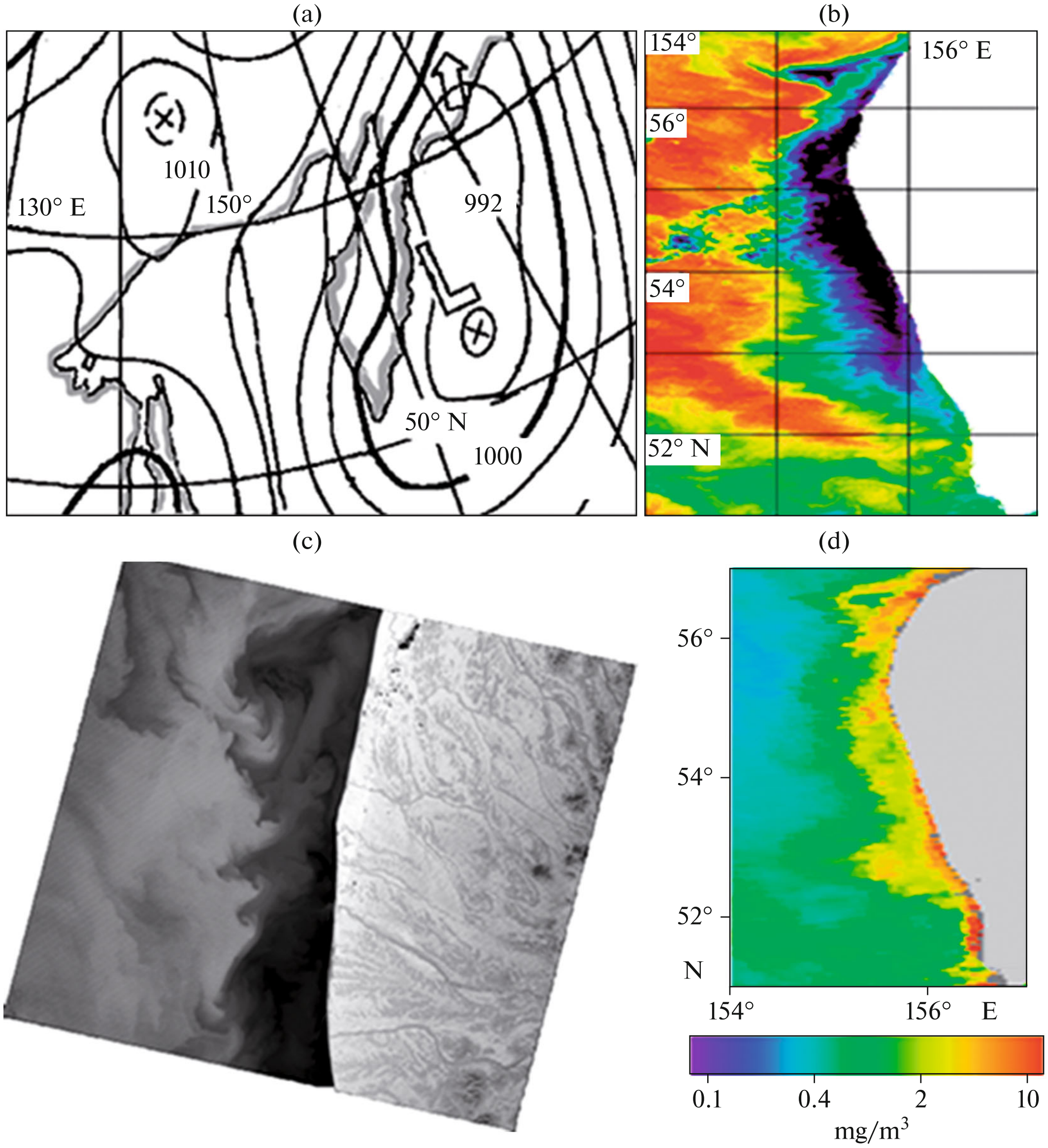

Fig. 4. Synoptic meteorological situation related to a deep cyclone that caused upwelling in summer on the western coast of Kamchatka on August 25, 2015, based on the data of a surface analysis of the Japan Meteorological Agency (a); IR image of the zone of coastal upwelling from the NOAA-19 AVHRR satellite on August 25, 2015 (b); image in the thermal band (Landsat-7 ETM+, August 27, 2015) showing submesoscale structures in the frontal zone of upwelling (d), and distribution of chlorophyll-*a* near western Kamchatka during the upwelling period on August 22–28, 2015 (Suomi VIRSN) (*c*). The dark blue areas in the satellite IR-image correspond to the cold waters on the Kamchatka coast.

of March–April), favorable conditions for the development of wind upwelling appear again.

Multisensor data collected in various wavelength ranges with different spatial and temporal resolution made it possible to get an idea about the summer winter upwelling on the western coast of Kamchatka. In the summer period, well-developed upwelling is rarely observed; this is related to the specific synoptic meteorological situations (propagation of the atmospheric cyclones to the territory of the Kamchatka Peninsula and the adjacent part of the Sea of Okhotsk). The zone of the coastal upwelling limited by the upwelling front is clearly distinguished in the satellite charts of the surface temperature. The image from the Landsat 7 satellite in the thermal spectral range showed that the high level of submesoscale activity is related to the front at the boundary of the upwelling. According to the data of the Suomi NPP satellite (optical range of the VIIRSN radiometer), the concentration of chlorophyll-*a* in the zone of coastal upwelling was significantly higher when compared to the adjacent regions of the deep sea. Thus, the summer upwelling increases the biological productivity of the western Kamchatka shelf in the Sea of Okhotsk.

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