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Original article

Features of the Oceanological Conditions as a Prerequisite for Formation of a Food Base for Gray Whales in the Marine Feeding Area (Northeastern Shelf of the Sakhalin Island)

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Abstract
Purpose. The paper is purposed at proving (based on the data of a special field experiment) the importance of vertical tidal mixing which is conditioned by the diurnal shelf waves, on the one hand, and determines the specific conditions for forming food supply for gray whales in the Marine feeding area near the Sakhalin northeastern coast, on the other hand.
Methods and Results. The materials for the research were formed of the data resulted from the instrumental measurements of current velocities, water temperature and salinity (and their variations) in the bottom layer carried out at three diurnal oceanological stations in the Marine feeding area in autumn 2019 as well as the satellite data on the chlorophyll *a* concentration (2003–2017).
Conclusions. The results of the diurnal station measurements showed that in the Marine feeding area of gray whales (on the Sakhalin northeastern shelf), there was a constantly working mechanism which intensified and weakened together with the diurnal tides (cycle was a half a month). It is manifested in the diurnal seawater temperature and salinity variations near the bottom, as well as in the vertical distributions of oceanological parameters. Due to the diurnal shelf waves providing local tidal mixing, the conditions contributing to the sustainable formation of food supply for gray whales arise in this area.

Keywords: Sea of Okhotsk, tidal mixing, diurnal shelf waves, satellite data, water temperature, salinity, current velocity, chlorophyll *a* concentration

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Introduction

The behavior of gray whales (*Eschrichtius robustus*) is unique among baleen whales: they live in coastal waters, are characterized by extremely long migrations, and feed by intermittent suction, eating benthos. Gray whales, which live in the North Pacific Ocean, have historically been divided into two populations. The first is the Eastern North Pacific (ENP) (also called the Chukchi-Californian one), estimated at about 20,000 animals [1], living in the Eastern North Pacific and adjacent open ocean between North America and Asia. The second population is from the Western North Pacific (WNP) (formerly called Asian or Okhotsk-Korean one), lives in the waters of the Western North Pacific, estimated at less than 250 animals, and is endangered [1] [2]. Currently, based on new data, the International Union for Conservation of Nature (IUCN) considers gray whales feeding in the coastal waters of the Sea of Okhotsk to be the western subpopulation. In the latest edition of the Red Data Book of the Russian Federation, these whales are classified as part of the Sea of Okhotsk population [2].

Although Western gray whales of the Pacific Ocean once used to feed on the entire northern coast of the Sea of Okhotsk, the core population now feeds from June to November primarily off the northeastern coast of Sakhalin Island.

In the shelf waters of northeastern Sakhalin, gray whales in recent years have concentrated during the feeding period in two nearby areas of the sea, conventionally called the Piltunsky and Marine feeding areas (Fig. 1). In the area of northeastern Sakhalin, the distribution of gray whales has a clearly defined seasonality, and at the same time is subject to the same temporal patterns from year to year [3], in which the approach period (June – July) and the feeding period (from the end of July to October) are distinguished. At the same time, some gray whales remain in this area until November, sometimes until early December. By mid-December, almost all whales leave the waters of northeastern Sakhalin.

The oceanological conditions for the formation of the food supply of gray whales are better studied in the coastal Piltunsky feeding area; in the Marine area, the situation is less clear. A number of questions still remain unresolved as to why specific benthos species actively consumed by gray whales are grouped in these areas. The main question is: how do these areas differ in hydrodynamic and hydrological conditions from other water areas of the Sakhalin northeastern shelf located in similar physical and geographical conditions?

Despite the large volume of performed research, a clear idea on this issue has not been formed. For example, in [3] it was suggested that the main development of benthos species consumed by animals occurs in winter, although this is difficult to imagine given the negative values of sea water temperature in the study area during the cold season sharply reducing the production rate of benthic crustaceans.

These areas are also distinguished by the nature of the soil conditions: in contrast to the rest of the northeastern shelf area, where coarse and medium sand predominate, here in most samples of bottom soil, fine-grained sand with an admixture of silts is found [4]. This difference has also not yet been explained.

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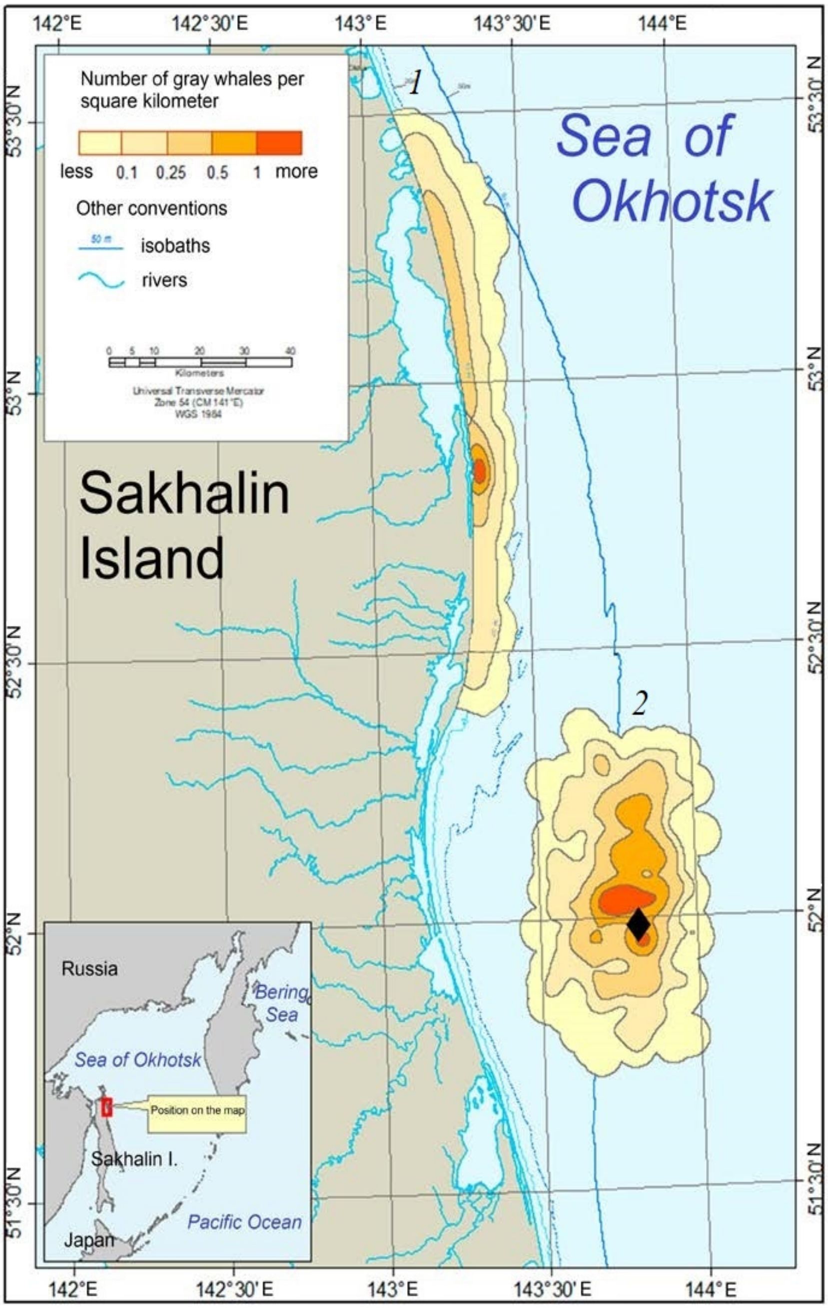
[1] Swartz, S.L. and Jones, M.L., 2018. Gray Whale Eschrichtius Robustus. In: B. Würsig, J. G. M. Thewissen and K. M. Kovacs, eds., 2018. *Encyclopedia of Marine Mammals*. Third Edition. London: Academic Press, pp. 422-428. doi:10.1111/mms.12499

[2] Pavlov, D.S., ed., 2021. *Red Data Book of the Russian Federation*. Vol. “Animals”. 2nd Edition. Moscow: FSBI "VNII Ecology", 1128 p. (in Russian).

[3] Vladimirov, A.V., 2007. [*Spatio-Temporal Characteristics of the Distribution of Gray Whales (Eschrichtius Robustus) of the Okhotsk-Korean Population off the Coast of Northeastern Sakhalin*]. Abstract of Thesis Cand. Biol. Sci. Moscow, 22 p. (in Russian).



F i g. 1. Average distribution of the gray whales density in the Piltunsky (*1*) and Marine (*2*) feeding areas based on the data for 2002–2021. Black diamond marks the location of autonomous buoy station [4] installed in the Marine area in autumn 2019. The inset shows the position of the area under study (red rectangle)

[4] Sakhalin Energy, 2022. *Report on Gray Whale Monitoring Programs off Northeast Sakhalin Island in 2021*. Yuzhno-Sakhalinsk: Sakhalin Energy Publ., 70 p. (in Russian).

Another question is related to the clearly defined thermocline, which lies at a depth of 10–15 m and is characteristic of the study area in summer. The transition layer prevents the entry of phytoplankton products required for the development of the benthos population into the bottom layer, and active blooming requires the rise of nutrients into the surface layer from deeper ones. Many experts associate these processes with the seasonal phenomena of upwelling and downwelling [5, 6], however, these phenomena cover the entire area of the northeastern shelf and manifest themselves over several months, and therefore cannot explain the local features inherent in the Piltunsky and Marine areas.

The purpose of this work is a detailed consideration of the peculiarities of oceanological conditions issue that contribute to the formation of the food supply of gray whales in the Marine feeding area. The work focuses on a special experiment carried out in September – October 2019, aimed at testing the hypothesis based on the analysis of available information about the important role of tidal mixing in the formation of special hydrological conditions in the area under consideration [7]. Such a hypothesis looks very unusual for the waters of a flat, extended shelf, remote from straits, capes, and seamounts, which are usually associated with vertical sea water movements caused by tides, so the results of this experiment are of significant interest. The special nature of conditions in feeding areas is also confirmed by the results of an analysis of the spatio-temporal variability of chlorophyll *a* concentration based on satellite data.

Observation materials and research methods

To test the hypothesis about the important role of tidal mixing caused by the specific features of shelf tidal waves, a special experiment was carried out in the Marine feeding area of gray whales under an agreement with Gazpromneft-Sakhalin LLC from September 16 to October 19, 2019. It included the deployment of an autonomous buoy station (ABS), which included ADP SonTek acoustic Doppler current profiler and SBE-37 logger to measure seawater temperature and salinity, as well as variations in bottom hydrostatic pressure (sea level). The instruments were mounted on a stainless-steel instrument frame, which was installed on the seabed. The ABS was deployed from *Siem Sapphire* vessel at coordinates 52°01.9′N and 143°39.33′E, the sea depth at the installation point is about 48 m. The station was lifted aboard *Siem Garnet* vessel on October 19, 2019.

Measurements of currents were carried out hourly in 23 layers, each 2 m thick (layers were numbered from the instrument located near the bottom), the length of the resulting series was 791 hourly counts. Measurements of seawater temperature and salinity and bottom hydrostatic pressure were also carried out hourly, the length of the resulting series was 792 hourly counts. When processing the obtained materials, standard methods of statistical analysis were used.

During the work, daily oceanological stations were carried out three times (September 16–17 and 27–28, October 19–20), vertical profilings of the water column with the SBE-19plus V2 CTD probe were carried out at one point every three hours. The instrument had sensors for temperature, salinity, hydrostatic pressure, and chlorophyll *a* concentration. Soundings were carried out near the place where ABS was installed, at a point with coordinates 52°02′N and 143°39.29′E. The obtained materials were grouped with a depth step of 1 m, the vertical distributions of oceanological parameters were constructed using the *OceanDataView* specialized data processing complex.

The material for this study also included daily data on level 2 chlorophyll *a* concentration from the MODIS color scanner of the *Aqua* artificial Earth satellite provided by the *Ocean Color Processing Group* (https://oceancolor.gsfc.nasa.gov) for the period from 2003 to 2017. The information was considered in the area limited by coordinates 143°–144.5°N and 51°–54.5°E, with a spatial resolution of about 2 km. Projection of data onto a coordinate grid was carried out using the SeaDAS program (https://seadas.gsfc.nasa.gov). A comparison of satellite and ship data on the concentration of chlorophyll *a* showed that remote measurements are in good agreement with the results of expeditionary studies off the northeastern coast of Sakhalin, which makes it possible to trust the obtained estimates of the seasonal and interannual dynamics of the substance content in the surface layer [5].

To describe the spatio-temporal variability of pigment concentration quantitatively, the method of empirical orthogonal functions (EOF), which is effectively used in the analysis of variations in hydrometeorological and oceanological fields, was applied [8]. In the EOF method, a given field is represented as a product of two functions, one of which depends on the coordinates, and the second one – on time. These time functions are the same for all points of the study area, and the spatial distribution of the mode characterizes the difference in the intensity of variations, for example, the seasonal variation of the parameter under study. The spatial distribution of the mode can have regions with different signs, indicating changes in antiphase in different regions, and a nodal line between them, at which there are no variations. One of the advantages of the EOF method is that the main contribution to the total expansion, as a rule, comes from several terms with the largest weight, and these terms best describe the nature of the process being studied.

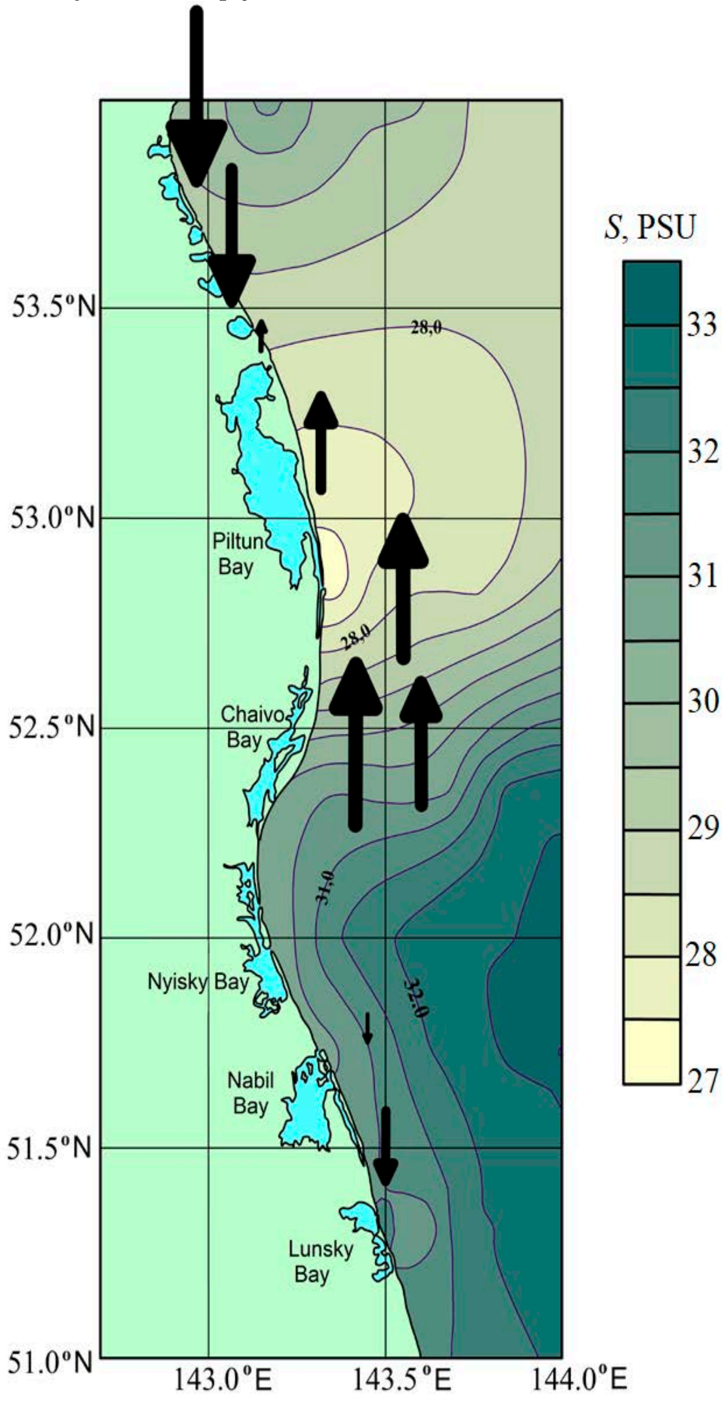
For the numerical implementation of the EOF method, the software of the TeraScan satellite system installed at SakhNIRO (https://www.seaspace.com/) was applied. When analyzing the factors influencing the distribution of chlorophyll *a* concentration, we used the data on water surface temperature and ice concentration obtained by the TeraScan SakhNIRO station from the NOAA series satellites.

Results and discussions

Basic information about diurnal shelf waves. Diurnal shelf waves at the Sakhalin northeastern shelf were first discovered when analyzing materials from instrumental measurements of currents in offshore oil and gas fields [9] due to the anomalously high velocities of diurnal currents. Their most detailed description is given in [5, 10] based on the analysis of data from a large number of ABSs installed on an extended shelf area, as well as measurements of ice drift velocity by three coastal radar stations. It was demonstrated that tidal shelf waves

[5] Tskhai, Zh.R., 2017. [*Spatiotemporal Variability of Chlorophyll-a Concentration in the Surface Layer of the Sea of Okhotsk and Adjacent Waters according to Satellite Data*]. Thesis Cand. Geogr. Sci. Yuzhno-Sakhalinsk: SakhNIRO, 125 p. (in Russian).

were generated in the study area at K_1 and O_1 frequencies as a result of diffraction of large-scale Kelvin waves at the northernmost point of Sakhalin – Cape Elizabeth, which juts out sharply into the sea.



F i g. 2. Salinity distribution resulted from the oceanological survey carried out on the Sakhalin northeastern shelf at low tide in August 1990. Cross-sections were performed at one phase of a tide ([5])

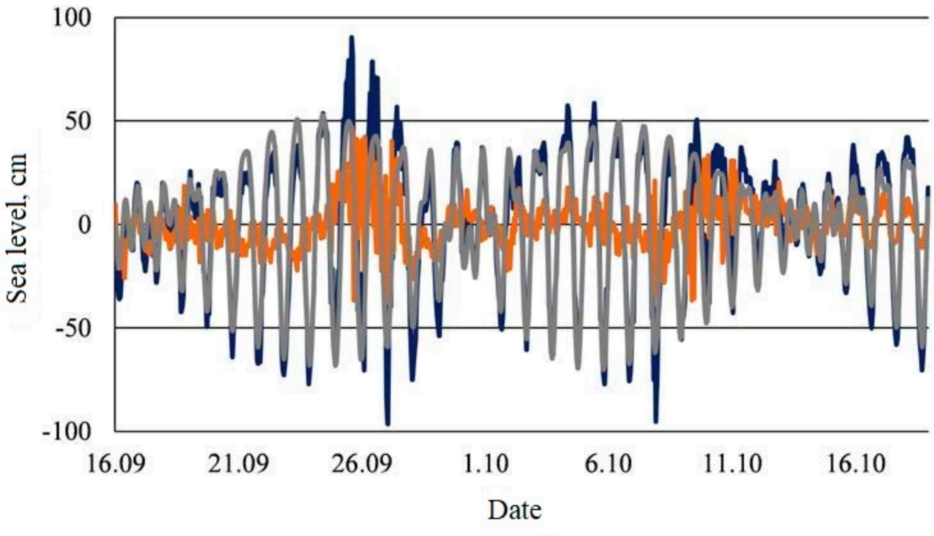
The impact of these waves ends in the area of Lunskoy Bay located about 340 km southwards of the indicated cape for wave K_1 and 380 km for wave O_1. Unusually short wavelengths for tidal components lead to the fact that at a distance of about 170 km, tidal currents are oriented in opposite directions (this also applies to ice drift, which leads to the formation of local zones of ice cover compression and rarefaction). Shelf waves do not move anywhere, which is due to their group velocity being close to zero. They are a pair of stationary eddies of different signs, changing every 12 hours. In Fig. 2, the results of an oceanological survey carried out by the Far Eastern Marine Geological Exploration Expedition in the summer of 1990 are presented. Oceanological sections were carried out at one tide phase (one per day), which made it possible to obtain a very clear picture of the shelf waves effect on the spatial distribution of salinity [5].

In the northern part of the northeastern shelf, directly in the offshore Piltunsky feeding area, a convergence zone and deepening of low-salinity water are observed; in the southern section (in the Marine area), a divergence zone and rise of cold salty water took place. Actually, it was this picture that made it possible to put forward a hypothesis about the important role of vertical movements caused by the effect of diurnal shelf waves in feeding areas. Testing this hypothesis was the subject of this work.

Special experiment in the Marine area in the autumn of 2019. Let's consider the materials of instrumental measurements obtained during the special experiment. It was aimed at determining the role of tidal mixing in the formation of specific conditions favorable for the development of the food supply of gray whales in the Marine feeding area (the work was carried out by order of Gazpromneft-Sakhalin LLC). As noted above, this experiment included the ABS installation containing the meters of seawater temperature and salinity, hydrostatic pressure (sea level fluctuations), and the velocity of sea currents, on the seabed, as well as the implementation of three diurnal hydrological stations.

Sea level fluctuations. The nature of sea level fluctuations was important from the point of view of the studied mechanism of vertical tidal mixing in the Marine feeding area. Graphs of the measured hourly values, as well as tidal and residual components, measured from the zero average level, are given in Fig. 3.

The main role in the total sea level fluctuations in the study area is played by tides, accounting for 87.7% of the total variance (energy) of variations. During the measurement period, level fluctuations were significant, the maximum range was only a little less than 2 m (extreme deviations from the zero mean were 90.3 cm and −96.5 cm). Residual fluctuations are usually small, but two cases of their sharp intensification took place on September 25–28 and October 10–11. In the first case, the variations were the most significant – the positive surge reached 47.4 cm, and the negative one reached -37.5 cm. The latter circumstance is very surprising, since noticeable surges are usually observed directly near the coast and much less often in relatively deep-water areas of the shelf. However, during the observation period, surges of 35 cm or more were observed four times.



F i g. 3. Variations in the total level (blue line), as well as its residual (orange line) and tidal (gray line) components in the Marine feeding area from September 16 to October 19, 2019

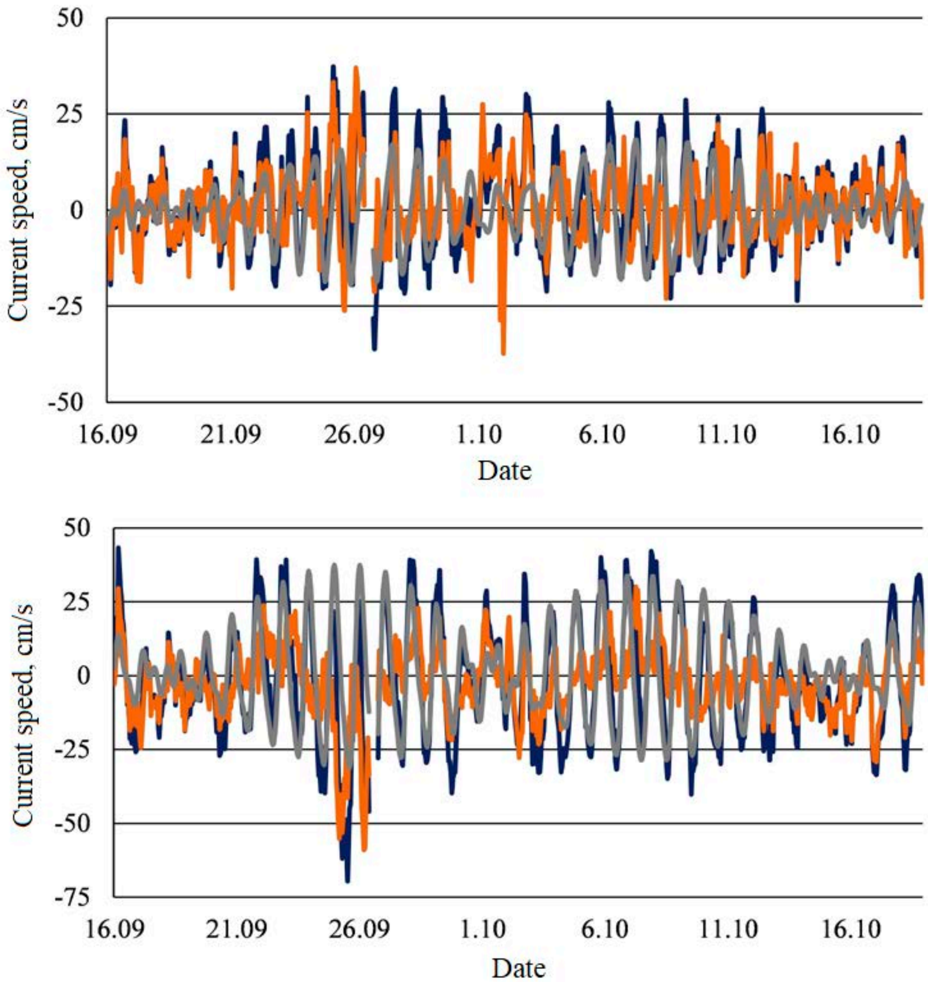
Tidal fluctuations were characterized by pronounced fortnightly modulations, typical of areas with the predominance of diurnal tides. The least squares method of tides harmonic analysis made it possible to obtain estimates of the amplitude and phase harmonic constants of the main tidal waves (four diurnal and four semidiurnal ranges). Ratio of the sum of amplitudes H of the main diurnal (O_1 and K_1) and semidiurnal (M_2 and S_2) waves, which determines the tidal regime:

$$R = \frac{HO_1+HK_1}{HM_2+HS_2},$$

was 4.5. That is, the tide in the study area is a regular diurnal one.

It is important to note that intense surge variations were observed on September 27–28, during the period of the second diurnal station. This time was also characterized by significant tidal fluctuations, in contrast to the first station, which was carried out both in calm weather conditions and during the period of weakening diurnal waves (equatorial tide). Semidiurnal tides prevailed on September 16 and 17, with two cases of high and low tide per day. When the diurnal station was carried out for the third time, on October 19–20, residual fluctuations were small, but tidal ones were of significant magnitude, and diurnal waves predominated. Below, when analyzing materials from diurnal stations, the nature of sea level fluctuations during their operation is considered in more detail.

Velocity and direction of currents. The projections of velocity vectors of the total currents, as well as the precalculated tidal and residual components (the latter obtained by subtracting the precalculated tide from the initial values) for the surface, intermediate, and bottom layers were analyzed. Layer 21 (horizon of about 6 m) was chosen as the surface layer, since when an acoustic Doppler profiler is deployed on the bottom, the observational data in one or two upper layers are distorted due to the violation of conditions for the acoustic signal passage in the near-surface layers (cell counting from the apparatus located near bottom). The first layer was chosen as the bottom horizon, and the 11th one – as the intermediate. In Fig. 4, corresponding graphs for the bottom layer are demonstrated.



F i g. 4. Projections of the measured current velocity vectors (blue line) in the bottom layer, as well as the tidal (gray line) and residual (orange line) components onto the parallel (*top*) and the meridian (*bottom*) based on the observations at ABS from September 16 to October 19, 2019

It is clear from the figure that diurnal tidal currents (as for sea level fluctuations, the nature of currents in the study area is regular diurnal) do not play a decisive role in the formation of total currents, which is usually observed in this area [5]. This especially applies to the surface layer, where the share of the tidal component is only 21% in the total variance of oscillations for projection onto the meridian. This may be stipulated by significant velocities of the residual component, which are noted throughout the water layer.

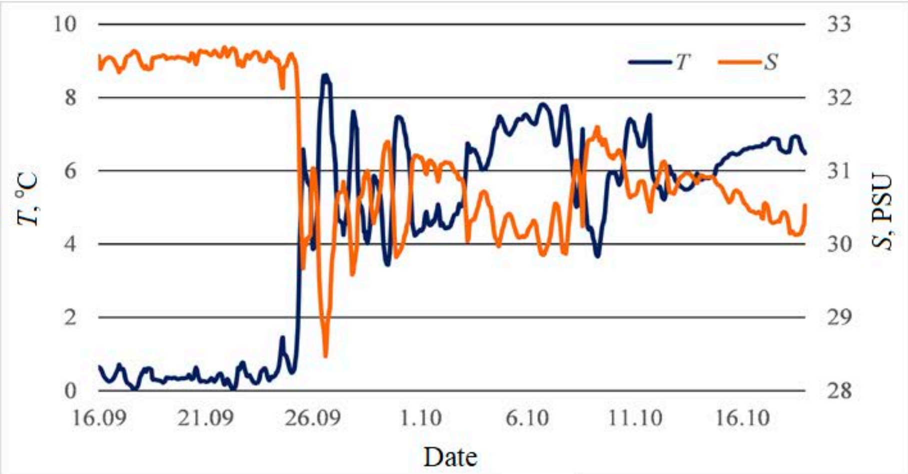
The sharp intensification of currents that began in the evening of September 25 (Sakhalin time) and continued on September 26, is of particular interest. The maximum value at the boundary of the day was 142 cm/s, the value of the residual component was 114 cm/s (for the meridional component, orientation to the south). This is a typical situation: as a rule, when a cyclone passes on the northeastern shelf of Sakhalin, first of all, the southern component of the current intensifies [5]. In this case, the intensification of the East Sakhalin Current flow was due to the peculiarities of the surface atmospheric pressure field – with the position of the deep cyclone center (973 hPa) in the northern part of the Sea of Okhotsk above the study area, the isobars are oriented to the south-southeast.

In the intermediate layer, the role of tidal currents is more significant, and they are stronger than near the surface, which is also somewhat unusual. When deepening, the extreme velocities of projection onto the meridian decrease slightly for both total currents (133 cm/s) and residual currents (106 cm/s), and they are observed 4 hours earlier than on the surface. For the parallel projection, the extreme values are slightly lower than in the surface layer (48 cm/s compared to 55 cm/s).

In the bottom layer, both tidal and residual currents are weaker than in the intermediate layer. This is true at least for the southern component, where the intensification during the passage of the cyclone on September 25–26 was most significant. The maximum velocity of the total current was 70 cm/s and was observed 5 hours later than in the overlying layers (the residual component reached 55 cm/s). The extreme value of the eastern component of the total current (38 cm/s) also shifted to the end of the day on September 25, the maximum value of the residual component (37 cm/s) was recorded almost a day later. By the time of CTD profilings, residual currents had weakened to normal levels (10–20 cm/s).

Temperature and salinity variations in the bottom layer. Fig. 5 shows the graphs of seawater temperature and salinity variations at the point where the ABS was installed in the bottom layer (the SBE-37 logger was located on the instrument frame at the bottom). During the first ten days of measurements, cold water with low salinity (average values of 0.4 °C and 32.5 PSU), typical for the study area during the warm period of the year, was observed. In the first 2.5 days, significant fluctuations in the oceanological parameters of diurnal periodicity were detected with an amplitude of about 0.25 °C and 0.1 PSU, which were then absent for about 3 days, after which they resumed with a smoothly increasing amplitude. The maximum temperature (and minimum salinity) were observed 2–3 hours after the highest tidal level. A sharp increase in temperature and a decrease in the salinity of seawater occurred on September 25 in the bottom layer, to average values of 6 °C and 30.6 PSU.

This is a typical picture for the northeastern shelf of Sakhalin [5], associated with the beginning of deepening of the Amur River runoff modified water as a result of the restructuring from the summer monsoon to the winter one. As a rule, this is preceded by the passage of a deep cyclone, which, as mentioned above, was observed precisely at this time.



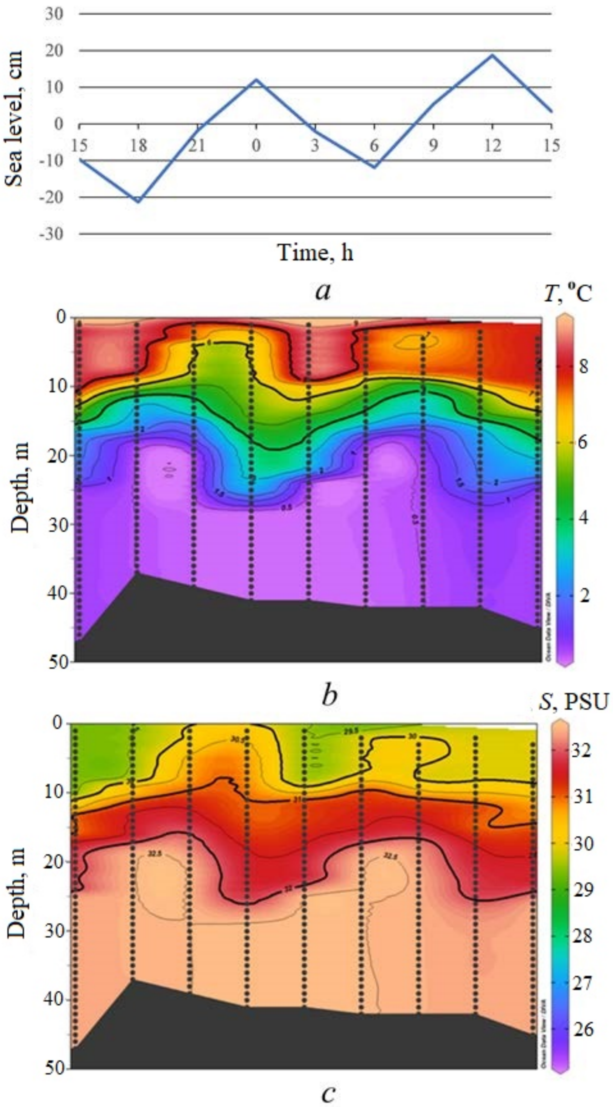
F i g. 5. Variations in seawater temperature (blue line) and salinity (orange) from September 16 to October 19, 2019 based on the *SBE*37 measurements in the Marine feeding area bottom layer

After this, particularly strong daily variations in temperature and salinity, the range of which on September 27 reached maximum values of 4.5 °C and 2.5 PSU, were recorded. Probably, such significant fluctuations are due to the fact that the process of wind downwelling, which occurs on the northeastern shelf of Sakhalin during the restructuring of the wind field to the north-northwesterly winds characteristic of the cold period of the year, was only in the initial stage, and the vertical structure of temperature and salinity was not settled yet.

Note also that when the tides observed with a two-week cycle (equatorial tides) weaken, daily fluctuations in temperature and salinity in the near-bottom layer become almost imperceptible. This does not happen immediately, but with some time shift (about two days). Thus, when performing the first diurnal station on September 16–17, although the diurnal waves were weak and a relatively small semi-diurnal variation in the level was observed, variations in temperature and salinity were noted. They were absent on September 19–21, when the tide amplitude began to increase. A similar picture was observed on October 1–3 and 15–17. The physical cause for this delay is of great interest and has not yet been identified.

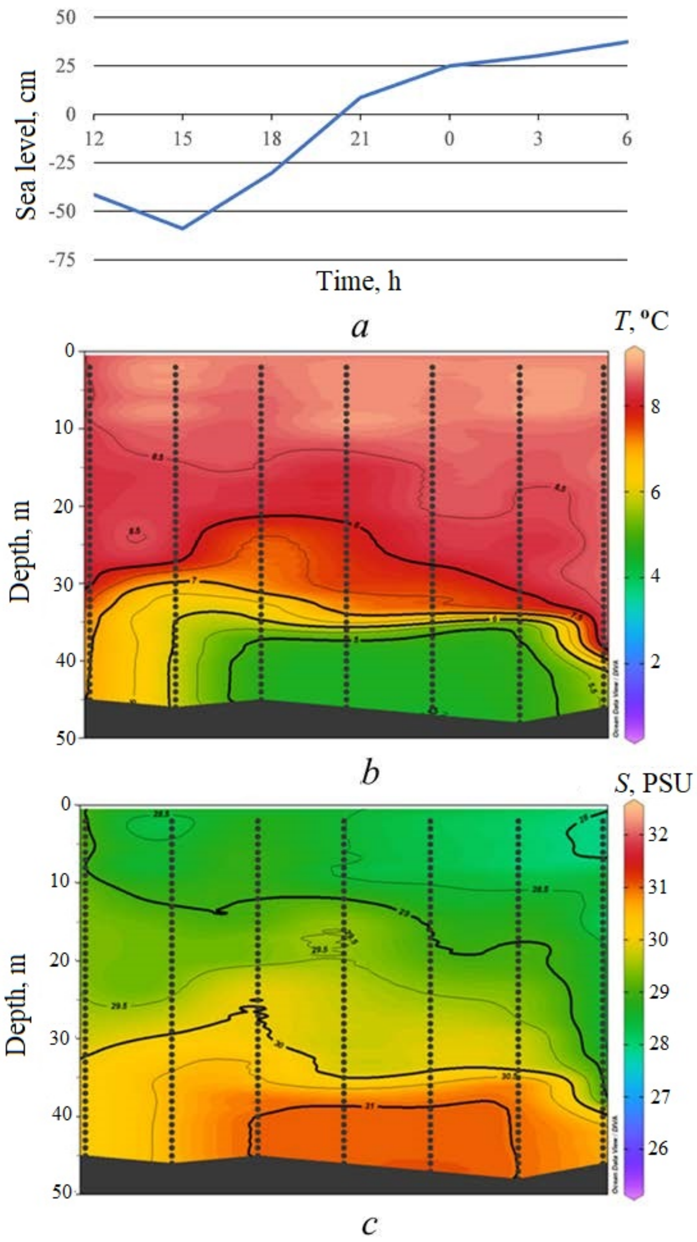
Diurnal oceanographic stations. We are to consider the results of water column vertical profilings in the area where the ABS was installed, carried out at intervals of 3 hours from 15:00 on September 16 to 15:00 on September 17. In Fig. 6, *a*, a graph of the tidal level and vertical distributions of seawater temperature and salinity, constructed from nine consecutive profilings (values with

1 m step were selected from the obtained materials marked with black dots), is given. When performing measurements, it was not possible to control the immersion depth of the probe, so it did not sink to the bottom in all cases. During the operation of the station, two profilings were carried out at low tides (at 18:00 and 06:00), and two – at high tides (at 00:00 and 12:00).

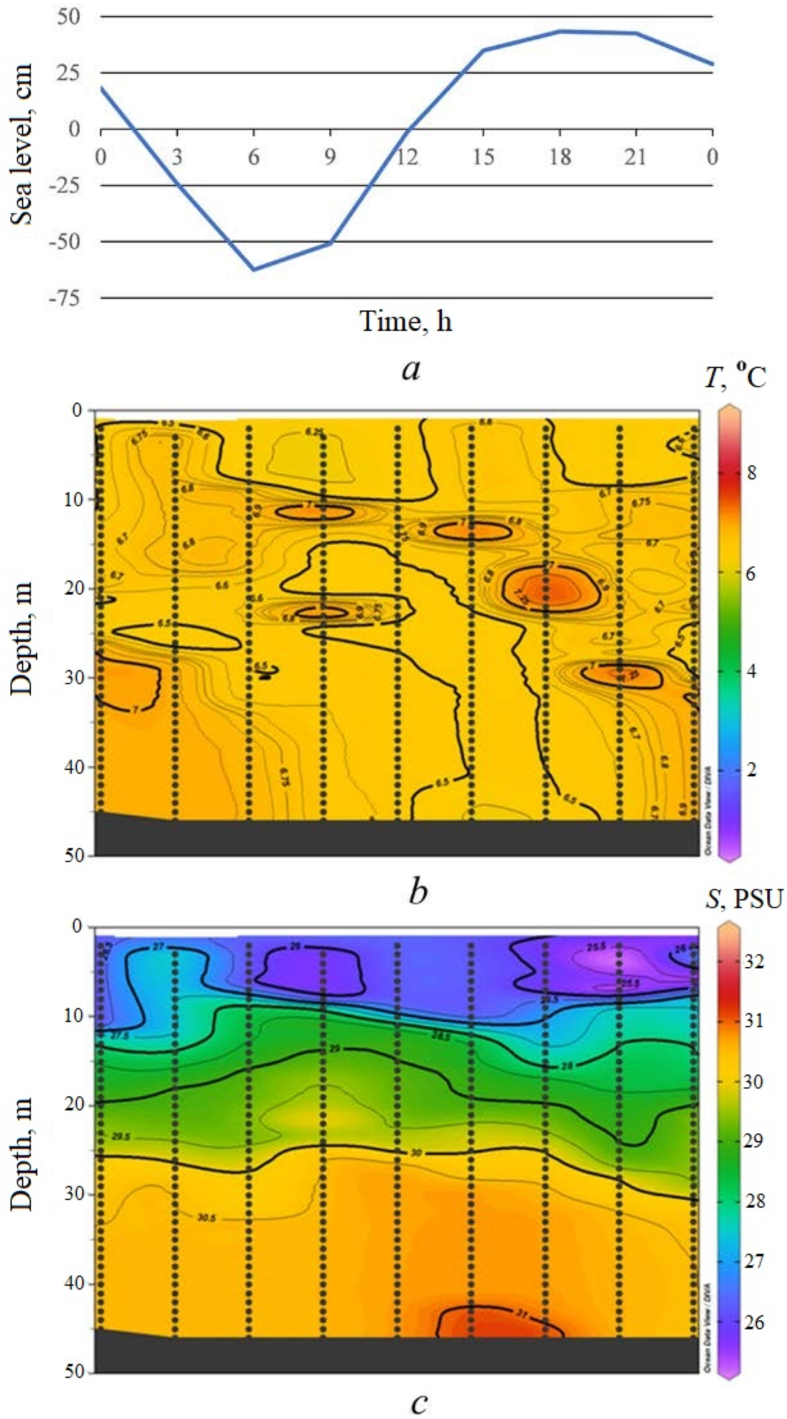


F i g. 6. Variations of the tidal level during the diurnal oceanological station on September 16–17, 2019 (*a*), as well as the seawater temperature (*b*) and salinity (*c*)

Despite the relatively small sea level fluctuations, significant temperature and salinity variations, clearly associated with them, attract attention. As the level decreased, a rise of colder water from deep layers was observed (with some time shift near the surface), and as the level increased, a deepening of surface warmer water with lower salinity was noted. Variations in the depth of isotherms and isohalines were 10–15 m, which indicates a significant scale of vertical tidal mixing in the Marine feeding area. The materials from this particular survey turned out to be the most successful ones from the point of view of the phenomenon being studied, since under oceanological conditions characteristic of the summer season with a well-defined thermocline, the process under study is most obvious, despite relatively small tidal variations.



F i g. 7. Variations of the tidal level during the diurnal oceanological station on September 27–28, 2019 (*a*), as well as the seawater temperature (*b*) and salinity (*c*)



F i g. 8. Variations of the tidal level during the diurnal oceanological station on October 19–20, 2019 (*a*), as well as the seawater temperature (*b*) and salinity (*c*)

The second diurnal station (Fig. 7) was not performed in full due to the vessel being busy with other work: seven CTD profilings from 12:00 on September 27 to 06:00 on September 28. The level was minimum at 15:00 and then rose until the end of the measurements, increasing significantly (about 1 m). The work was carried out, as noted above, when wind downwelling had begun, which complicated the interpretation of the data obtained significantly. Nevertheless, based on the position of the 8 °C isotherm and 29 PSU isohaline, one can judge the gradual deepening of surface water. A more complex picture was observed in the lower layers from 15:00 on September 27 to 3:00 on September 28. It indicates an influx of colder and more saline water.

The third diurnal oceanological station was carried out at the time when the water temperature had almost leveled out throughout the entire water layer as a result of wind-induced deepening of the Amur River runoff modified water. The process of deepening with increasing tidal level can be most clearly observed using the example of a warm water lens (more than 7 °C), which was recorded in several measurements and smoothly sank from a depth of about 11 m at 09:00 on October 19 to 28 m 12 hours later (Fig. 8).

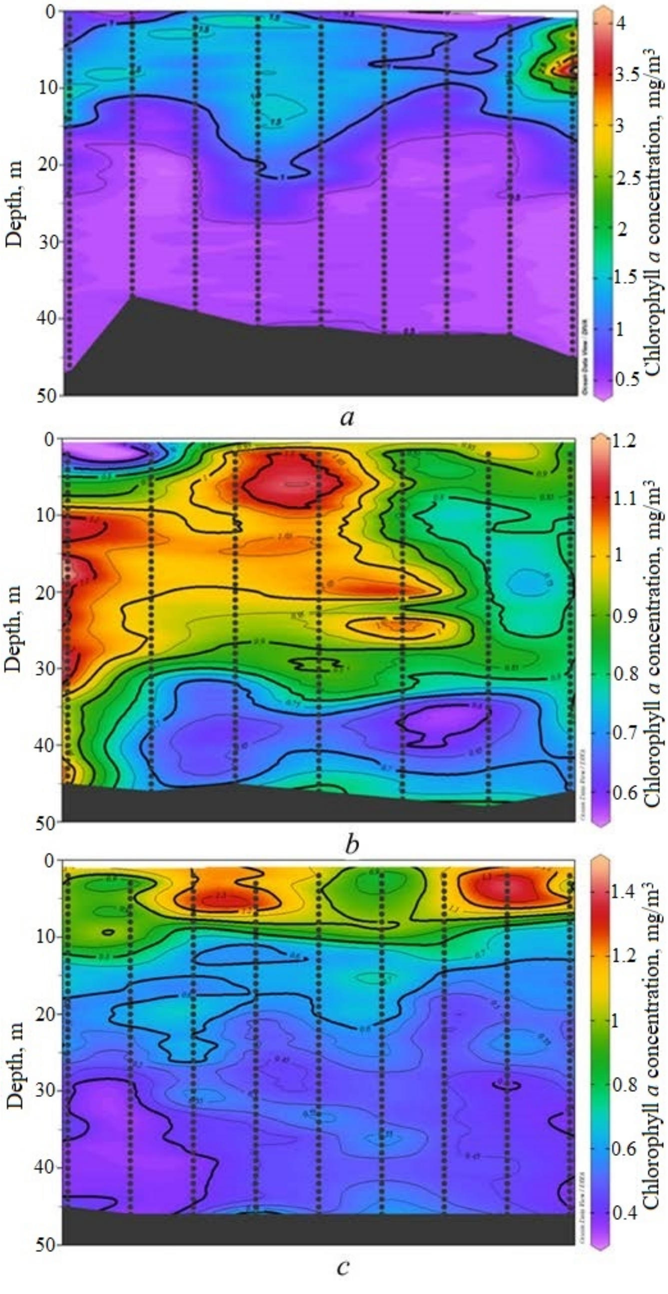
A more clearly studied process of tidal mixing can be traced in the salinity distribution, especially in the position 28 and 29 PSU of isohalines. The most significant rise was noted at 18:00, when the low tide had passed, and its rise was just beginning. The greatest deepening occurs at the moment of the maximum level at 21:00, or at the beginning of its decrease at 00:00 on October 20.

The vertical distributions of chlorophyll *a* concentration (Fig. 9) in seawater revealed a clear deepening of surface water, characterized by a higher content of phytopigment, at moments when the tidal level increased during the first survey.

In distributions constructed according to the materials from later measurements, the chlorophyll *a* concentration throughout the entire water layer was characterized by lower values than in the first case. However, the processes of vertical mixing could be traced quite clearly. Thus, during the survey on September 27–28, the first probing, which occurred with a decrease in the tidal level, showed the increased chlorophyll *a* concentrations in almost the entire water column (from 10 m horizon to the bottom), with the exception of the upper 5-meter layer. Then the phytopigment content decreased, especially in the lower layers, but with an increase in the tidal level, the deepening of water with an increased concentration of chlorophyll *a* to a depth of 30–35 m was observed again.

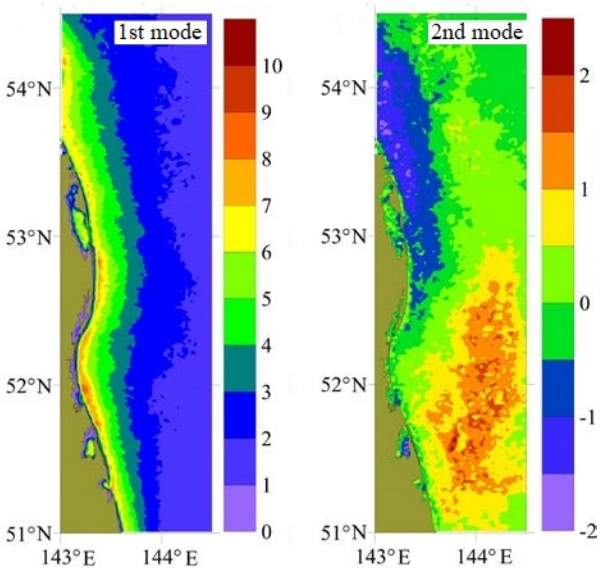
During the next survey on October 19–20, two lenses with higher concentrations (up to 1.3 mg/m^3) at lower temperatures and salinity were noted in the surface 8-meter layer. These lenses were not associated with processes of vertical movements, but rather with the passage of small portions of water with different oceanological characteristics near the surface. However, the deepening of water with a relatively high phytopigment content against the background of rising tidal levels can be seen quite clearly.

This circumstance contributes to the formation in the Marine feeding area of local highly productive accumulations of benthos species, which are the food supply for gray whales (amphipods, cumaceans). In neighboring areas of the Sakhalin northeastern shelf, macrobenthos communities, which are not used by gray whales as food sources (this issue is discussed in more detail in [7]), are predominant.



F i g. 9. Vertical distributions of the chlorophyll *a* concentration resulted from the diurnal oceanological stations on September 16–17 (*a*), September 27–28 (*b*), and October 19–20, 2019 (*c*)

Spatio-temporal variations in chlorophyll *a* concentration. The obtained estimates of variations in chlorophyll concentration during diurnal stations stimulated a more detailed study of the spatio-temporal variability of this parameter using satellite data. The intensity of phytoplankton development, the duration of the blooming active phase, the nature of variability in time and space depend on oceanological, hydrochemical, and a number of other conditions [6] [11]. The northeastern shelf of Sakhalin is a dynamically active area with abundant nutrients coming from several sources. In this regard, the spatio-temporal variability of chlorophyll *a* concentration in this area has its own characteristic features. The results of decomposition of the initial field of this parameter using the EOF method showed that the first 10 modes describe 80% of the total variance, where the first mode accounts for more than 67%, which indicates a stable structure of seasonal photosynthesis processes in this area. Fig. 10 shows the spatial distributions of the first two (key) modes of decomposition of the chlorophyll *a* concentration field in EOF (assumed to be dimensionless), and Fig. 11 shows the corresponding time functions.

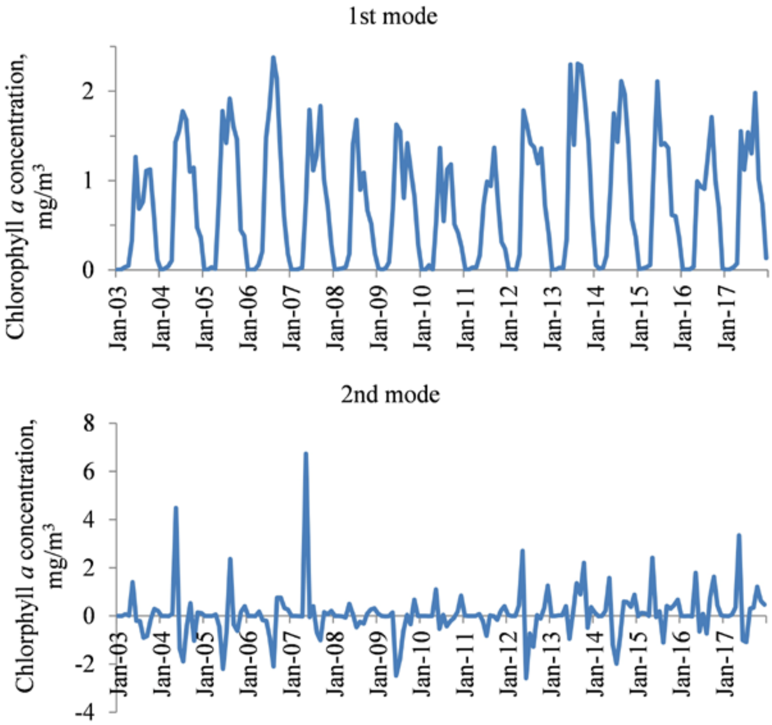


F i g. 10. Spatial distribution of the vectors of the first and the second EOF modes near the Sakhalin northeastern coast for 2003–2017

The graph of time function of the first mode reveals the main patterns of variability in the chlorophyll *a* concentration, which were of a stable seasonal nature. From January to April, most of the area is covered with ice, and the ice-free surface is characterized by weak photosynthetic activity due to a number of causes, including unfavorably low water temperature [5], so the time function values are close to zero. Active photosynthetic processes occur in this area throughout the ice-free period. In the first mode amplitude, two seasonal peaks of phytoplankton bloom are distinguished: spring, usually in June, and autumn one – in September, which is characteristic of subarctic seas [12]. In some years, the spring maximum shifted to May, less often to July, and the autumn maximum – to October.

[6] Matveev, V.I., 2006. [*Hydrochemical Conditions of Biological Productivity of the Sea of Okhotsk*]. Thesis Cand. Geogr. Sci. Vladivostok: TINRO, 141 p. (in Russian).

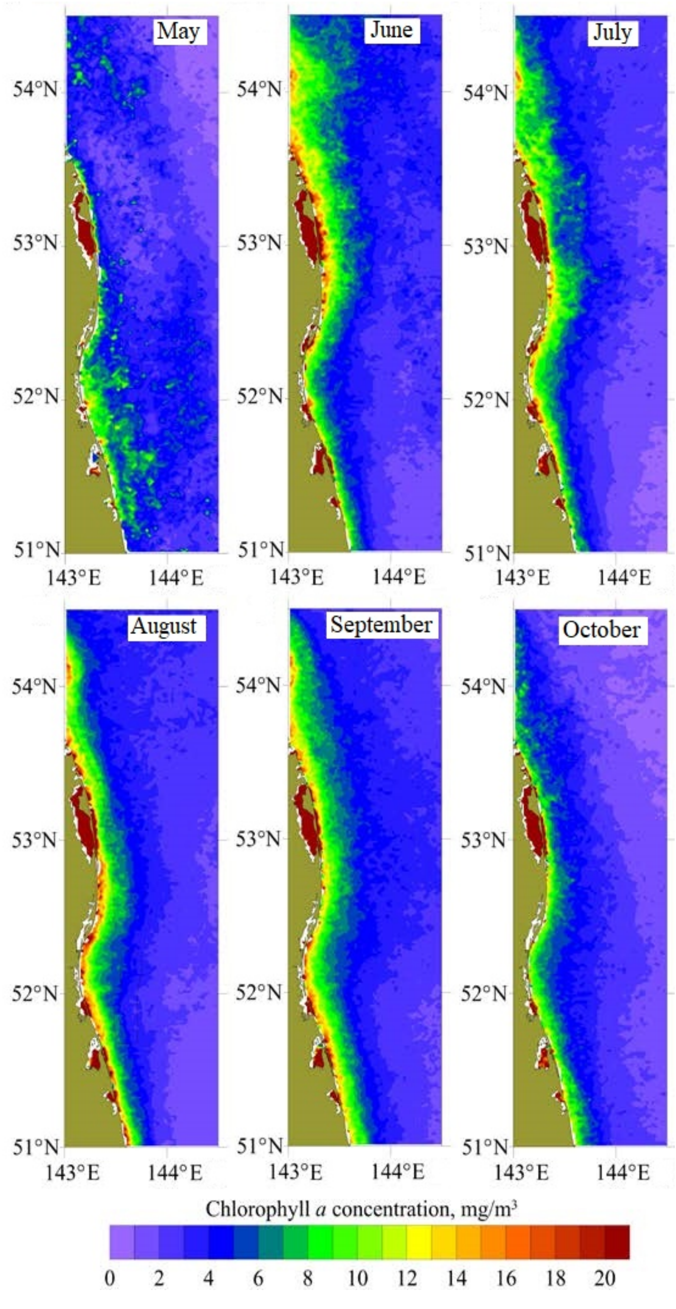
The intensity of the bloom had significant interannual variations and depended primarily on the interaction of several key factors: the dynamics of ice melt, water surface temperature, and nutrient availability caused mainly by river runoff [13].



F i g. 11. Time functions of the first and the second EOF modes near the Sakhalin northeastern coast for 2003–2017

The spring phase of microalgae development is determined largely by the melting rate of the ice cover formed in winter. In 2006 and 2011, due to the low-ice winter, spring blooming was weak [5]. The main part of the nutrients entered this area with the Amur River runoff. Therefore, the activity of photosynthesis processes depended primarily on the volume of the Amur River runoff. The influence of this factor is associated with a decrease in phytoplankton production during the summer low-water period and the abundant development of phytoplankton during the period of autumn runoff increase due to the intensification of cyclonic activity over the Amur region. Therefore, unlike other areas of the Sea of Okhotsk, where spring blooms of phytoplankton dominate, the intensity of autumn blooms in the area under study is often higher.

Based on the spatial distribution of the first EOF mode, the zones of increased phytoplankton production were identified (Fig. 12). The chlorophyll *a* concentration increased from the seaward part to the coast. In the coastal zone, the pigment content increased significantly (up to 10 mg/m^3 and higher). A significant number of nutrients near the coast arrived not only with the modified Amur water, but also with the runoff from numerous lagoons, which, in turn, were estuary zones of rivers.



F i g. 12. Average long-term distributions of the chlorophyll *a* concentration near the Sakhalin northeastern coast for 2003–2017

According to the EOF decomposition method, the second and subsequent modes reveal local variability features of the parameter under study. In our case, the second EOF mode (3% of the total variance) identified two areas (Fig. 10), in which the peak of phytoplankton bloom is reached at different times, and, therefore, active photosynthetic processes occur in antiphase in them.

The first area of high chlorophyll *a* concentrations (Table) corresponds entirely to the Piltunsky feeding area during the period from June to July (in some years to August). At this time, the bulk of the modified Amur waters rich in nutrients are grouped there [5, 14, 15].

Average long-term chlorophyll *a* concentrations (mg/m^3) near the Sakhalin northeastern coast based on satellite data

Feeding area	May	June	July	August	September	October
Piltunsky	6.1	13.5	11.8	12.6	11.8	8.9
Marine	5.7	4.2	4.1	4.6	5.2	4.3

The second section, located southwards of 53° N at the isobaths from 20 to 200 m, includes the Marine feeding area. The area experiences two periods of high chlorophyll *a* concentration. The first one, as a rule, is in May, during the phytoplankton bloom on the edge of the melting ice. The second period is from August to October, when a zone of increased phytoplankton production forms in this area. The cause for this phenomenon is unclear. One of the possible explanations is the above-mentioned hypothesis about possible tidal mixing, which ensures the necessary supply of nutrients from deep layers. The most intense blooming in this area was observed in August 2005 and 2013, October 2013 and 2016.

Thus, as a result of the satellite data analysis using the EOF method, the most significant patterns and features of the spatio-temporal variability of chlorophyll *a* concentration in the surface layer of the Sakhalin northeastern shelf were determined. They include the spatial structure of the second mode, in which the Piltunsky and Marine feeding areas of gray whales are distinguished as zones of increased chlorophyll *a* concentration.

Conclusion

The analysis of the materials from the field experiment showed clearly that in the Marine feeding area of gray whales on the Sakhalin northeastern shelf, there is a constantly working mechanism (increasing and weakening along with the diurnal tides with a semi-monthly cycle), ensuring the existence of local zones with vertical water movement. Moreover, the zones coincide with the feeding areas of gray whales.

Significant diurnal variations of the seawater temperature and salinity in the bottom layer, which increased sharply at the initial stage of the Amur River runoff water deepening on September 25–28 (maximum range 4.5 °C and 2.5 PSU), were identified. The maximum temperature and minimum salinity occurred 2–3 hours after the maximum tide. With a sharp decrease in tides within the framework of fortnightly modulations (equatorial tide), diurnal fluctuations in temperature and salinity become almost imperceptible, but not immediately, however, with a shift of about 2 days.

The role of tidal mixing is revealed more clearly by the results of diurnal oceanographic stations. Even at relatively low tides on September 16–17, the depth of isotherms and isohalines reached 10–15 m; at high tides, the surface layer water is deepening down to the bottom. This mechanism promotes the entry of phytoplankton into the depths from the surface, which provides the necessary nutrition for the benthos and affects the nature of the bottom soil, increasing the proportion of fine sand and silt fractions. The water rich in nutrients rises to the surface. This result is consistent with the features of the second mode spatial structure obtained by analyzing the variability of satellite data on the chlorophyll *a* concentration by the EOF method. Maximum concentrations for this mode were observed in the Piltunsky and Marine areas, although at different time intervals (in the first – in June – August, in the second – in May and September – October). Most likely, the formation of the food base of specific benthic communities, in which seston-feeders predominate, is precisely due to these features of the hydrological regime.

It is due to diurnal shelf waves at the Sakhalin northeastern shelf, which provide local tidal mixing (very rarely observed far from straits, seamounts, and other features of the bottom topography), that conditions contributing to the sustainable formation of the food supply of gray whales occur in the Marine feeding area.

REFERENCES

1. Laake, J.L. and Punt, A.E., 2012. Gray Whale Southbound Migration Surveys 1967–2006: An Integrated Re-Analysis. The *Journal of Cetacean Research and Management*, 12(3), pp. 287-306. doi:10.47536/jcrm.v12i3.559
2. Bogoslovskaya, L.S., 1996. The Gray Whale. *Priroda*, (12), pp. 46-60 (in Russian).
3. Durkina, V.B., Chapman, J.W. and Demchenko, N.L., 2018. Ampelisca Eschrichtii Krøyer, 1842 (Ampeliscidae) of the Sakhalin Shelf in the Okhotsk Sea Starve in Summer and Feast in Winter. *Peer J Preprints*, (6), e3496v2. doi:10.7287/peerj.preprints.3496v2
4. Fadeev, V.I., 2007. [Study of Benthos and Food Supply in the Summer Feeding Areas of the Korean-Okhotsk Gray Whale Population (Eschrichtius Robustus) in 2001–2003]. In: A.V. Adrianov, ed., 2007. *Response of Marine Biota to Environmental and Climatic Changes. Materials of the Complex Regional Project of the Far Eastern Branch of RAS according to the Program of the Presidium of RAS*. Vladivostok: Dalnauka, pp. 213-232 (in Russian).
5. Vlasova, G.A., Vasilev, A.S. and Shevchenko, G.V., 2008. *Spatial and Temporal Variability of the Water Structure and Dynamics of the Sea of Okhotsk*. Moscow: Nauka, 359 p. (in Russian).
6. Rutenko, A.N., Khrapchenkov, F.F. and Sosnin, V.A., 2009. Near-Shore Upwelling on the Sakhalin Shelf. *Russian Meteorology and Hydrology*, 34(2), pp. 93-99. doi:10.3103/S1068373909020058
7. Labay, V.S., Kim, S.T., Smirnov, A.V., Chastikov, V.N., Schevchenko, G.V. and Tzkhay, Zh.R., 2019. Assessment of Carrying Capacity of the Gray Whales (Eschrichtius Robustus) Habitat in Their Feeding Areas off the Northeastern Sakhalin Island. In: MMC, 2019. *Marine Mammals of the Holarctic*. *Collection of Scientific Papers*. Arkhangelsk, Russia: RPO "Marine Mammal Council". Vol. 1, pp. 174-185. doi:10.35267/978-5-9904294-0-6-2019-1-174-185
8. Bagrov, N.A., 1959. [Analytical Representation of Meteorological Field Series by Natural Orthogonal Components]. In: CIF, 1959. *Trudy TsIP* [Transactions of the Central Institute of Forecasts]. Leningrad: Gidrometeoizdat, (74), pp. 3-24 (in Russian).
9. Rabinovich, A.B. and Zhukov, A.E., 1984. Tidal Fluctuations on the Shelf of Sakhalin Island. *Oceanology*, 24(2), pp. 238-244 (in Russian).
10. Shevchenko, G.V., Rabinovich, A.B. and Thomson, R.E., 2004. Sea-Ice Drift on the Northeastern Shelf of Sakhalin Island. *Journal of Physical Oceanography*, 34(11), pp. 2470-2491. doi:10.1175/JPO2632.1

11. Mordasova, N.V. and Metreveli, M.P., 1997. [Phytopigments in the Sea of Okhotsk]. In: V.V. Sapozhnikov, ed., 1997. *Complex Studies of Ecosystem of the Sea of Okhotsk*. Moscow: VNIRO, pp. 199-205 (in Russian).
12. Ventzel, M.V., Krylov, V.V. and Levashova, S.S., 2000. [Patterns of Phytoplankton Distribution in the Waters of the North-West Pacific]. In: VNORO, 2000. *Marine Hydrobiological Researches*. Moscow: VNIRO, pp. 11-21 (in Russian).
13. Tzkhay, Zh.R., 2007. Description of Seasonal Variability of Chlorophyll *a* Concentration by an Empirical Orthogonal Function Method in the Okhotsk Sea from SeaWiFS Satellite Data. *Issledovanie Zemli iz Kosmosa*, (6), pp. 37-45 (in Russian).
14. Rutenko, A.N. and Sosnin, V.A., 2014. Hydrodynamic Processes on the Sakhalin Shelf in the Coastal Piltun Area of the Grey Whale Feeding and Their Correlation with Atmospheric Circulation. *Russian Meteorology and Hydrology*, 39(5), pp. 335-349. doi:10.3103/S1068373914050070
15. Shevchenko, G.V. and Chastikov, V.N., 2019. Seasonal Variability of Oceanological Conditions on the Northeastern Sakhalin Shelf Based on the Surveys on Standard Sections. *Journal of Oceanological Research*, 47(3), pp. 246-263. doi:10.29006/1564-2291.JOR-2019.47(3).19 (in Russian).

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Valeriy N. Chastikov – participation in field experiment, processing and complex data analysis, construction of graphs and distributions, discussion of the work results

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The authors declare that they have no conflict of interest.