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SEASONAL AND INTERANNUAL VARIATIONS IN OCEAN SURFACE TEMPERATURE IN THE AREA OF THE NORTHERN KURIL ISLANDS ACCORDING TO SATELLITE DATA

© 2025 G. V. Shevchenko[a, b, *], Zh. R. Tshay[a], and D. M. Lozhkin[a]

[a]Sakhalin Branch of "VNIRO" ("SakhNIRO"), Yuzhno-Sakhalinsk, Russia

[b]Institute of Marine Geology and Geophysics Far Eastern Branch Russian Academy of Sciences, Yuzhno-Sakhalinsk, Russia

*e-mail: shevchenko_zhora@mail.ru

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Abstract. The average monthly values of ocean surface temperature in the area of the North Kuril Islands for 1998–2022 are analyzed. On the basis of a 25-year series of observations, the norms are calculated for each month — the average long-term distributions. It is shown that in the coastal area from the Simushir Island to the Fourth Kuril Strait, a cold spot area with very low temperatures (about 6 °C) and small annual cycle amplitudes (about 3 °C) is formed in summer. Seasonal fluctuations are characterized by an annual cycle with maximum values in August–September and minimum values in February–March. In general, they are well described in the region by a combination of annual and semi-annual harmonics with amplitudes of 4.9 and 1.1 °C, respectively. The interannual variability is reflected in variations of summer maxima with a period of about six years. In the summer and autumn period, outside the cold spot area, there is a steady trend towards an increase in temperature, the most significant in the northwestern Pacific Ocean (about 1 °C in 25 years). In the winter-spring season in the Sea of Okhotsk, the reverse situation is observed with a tendency to decrease of thermal parameters. When calculating deviations of average monthly temperatures from normal values, it was revealed that large-scale zones with significant temperature anomalies, mainly negative ones, can be formed in the area of the North Kuril Islands, which can pose a serious danger to aquatic organisms.

Keywords: *thermal regime, temperature anomalies, linear trend, harmonic analysis, method of natural orthogonal functions, Kamchatka Peninsula, Sea of Okhotsk, Northwestern Pacific Ocean*

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INTRODUCTION

The waters adjacent to the North Kuril Islands and southeastern Kamchatka are of major commercial importance. A significant number of commercial fish species and invertebrates — Pacific salmon, pollock, cod, herring, saffron cod, saffron cod, flounder, crabs (Kamchatka crab, blue crab, Bairdi strigun), etc. are caught here. For this reason, the study of hydrological regime peculiarities of this area, seasonal and interannual variability of oceanological conditions is of considerable interest.

Comparatively few studies are based primarily on the results of ship-based oceanological surveys (Kono, Kawasaki, 1997; Kantakov, 2000; Samko, Novikov, 2004). Significantly more works are devoted to the wider Northwest Pacific Ocean (NWPO), where a wide range of data, including meteorological information, is analyzed (Joyce, Dunworth-Baker, 2003; Hen et al., 2004; Rogachev, Shlyk, 2005; Glebova et al., 2009; Byshev et al., 2016; Rostov et al., 2020, 2021; Tskhai et al., 2022). A number of papers are devoted to climatic changes in the Sea of Okhotsk (Hydrometeorology..., 1998; Hen et al., 2008, 2022; Rostov et al., 2017; Zuenko et al., 2019; Lozhkin and Shevchenko, 2019, 2022). In their article, V.I. Byshev et al. (2016) stated a very complex character of thermal variations in the NWPO.

A similar conclusion can be made with respect to the Sea of Okhotsk, where, according to oceanological soundings, an increase in heat content in various layers, a decrease in the depth of winter convection and the intensity of geostrophic flows were detected (Zuenko et al., 2019). This conclusion applied predominantly to the eastern part of the basin, where TINRO *in situ* studies are the most detailed. At the same time, according to satellite observations, a steady decrease in the surface layer temperature in winter and spring was observed in the western part of the Sea of Okhotsk (Lozhkin and Shevchenko, 2019), which was attributed by the authors to an increase in the depth of winter convection due to a decrease in ice cover. These features determine the interest in studying the thermal regime of the area adjacent to the North Kuril Islands.

Due to the great remoteness of this area, oceanological data collection was carried out by SakhNIRO only three times — in spring 2013, 2015 and 2016, in the mode of accompanying ichthyoplankton surveys, which did not allow us to consider the peculiarities of the thermal regime on the basis of expeditionary soundings.

Unlike traditional ship-based surveys, satellite observations of ocean surface temperature (OST) are characterized by full coverage of the area and regularity of data availability. Therefore, they are the most suitable material for characterizing the spatial and temporal variations of SST in modern conditions, when the number of marine expeditions is decreasing.

MATERIALS AND METHODOLOGY

SakhNIRO has accumulated a significant amount of satellite observations of the surface temperature of the Sea of Okhotsk and adjacent waters thanks to the TeraScan® satellite receiving station (https://www.seaspace.com) installed in 1997. Since 1998, regular reception of incoming data and formation of a database, based on daily SST distributions with a spatial resolution of about 2 km, have been organized.

This study used monthly average SST data for 1998–2022 (25 years) in the region bounded by coordinates 47–52°N and 152–160°E. (Fig. 1). The initial matrix consisted of 300 temporal layers of dimension 285×284 points. For each month and spatial cell, long-term averages, which were considered as norms characterizing typical thermal regime parameters, and standard deviations σ were calculated. Anomalies as the difference between the current monthly averages and the norm were considered significant if the absolute value exceeded twice the σ value (Tskhai and Shevchenko, 2013).

The decomposition of the initial matrix by natural orthogonal functions (Bagrov, 1959) was used to determine the nature of interannual variations of SST. The amplitudes and phases of the annual and semiannual harmonics were obtained by the least squares method when analyzing seasonal temperature variations. A similar calculation was performed for the values averaged over the entire area. Also, linear trend coefficients (LTC), characterizing unidirectional trends in the interannual changes in SST, were calculated at all points of space (Lozhkin and Shevchenko, 2019). When assessing the contribution of cyclic components, the amplitude and phase of the harmonic with a given period were calculated

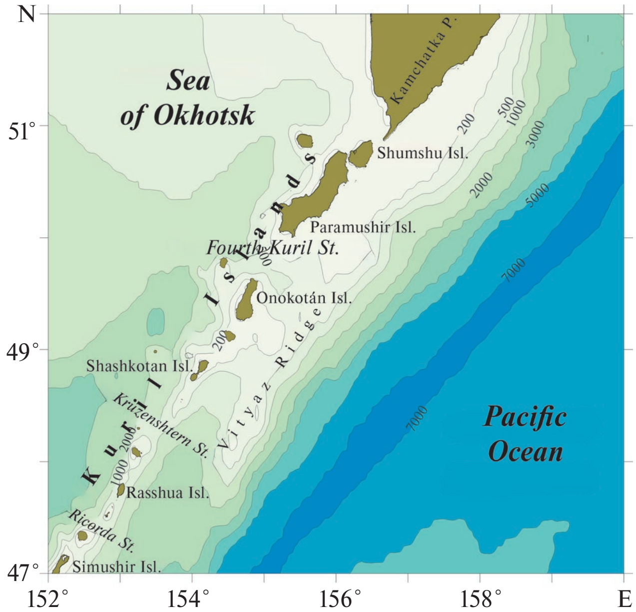

Fig. 1. Map of the study area.

from samples for August (envelope by maxima). Then this component was subtracted from the initial series; the significance of the harmonic contribution was determined by the ratio of the variance of the residual series to the variance of the initial series summed over the entire area. Periods of cyclic components were set from three to 12 years with a step of three months (Lozhkin and Shevchenko, 2020).

RESULTS AND DISCUSSION

Mean monthly SST distributions. Fig. 2 presents the mean multiyear distributions of ocean surface temperature in the area of the North Kuril Islands. In January-March, the coldest conditions are observed, characterizing, as in other Far East seas and the adjacent part of the Pacific Ocean, the winter thermal regime (Hydrology and Meteorology..., 1998). During this period over most of the area the values of SST fluctuate from 0 to +2 °C. On the shelf of the Shumshu and Paramushir Islands and also off the southeastern coast of Kamchatka they fall below zero. In general, the temperature in the Okhotsk Sea water is lower than in the Pacific Ocean.

In April, the spring processes of surface layer warming are hardly noticeable, the zone of negative temperatures over the mainland slope of southeastern Kamchatka and the northernmost Kuril Islands disappears. In May, in the waters off the Kuril Islands, SST values increase to +2 °C, and in the rest of the water area — to +3 °C. The increase in thermal indices becomes noticeable only in June, most of the area warms up to

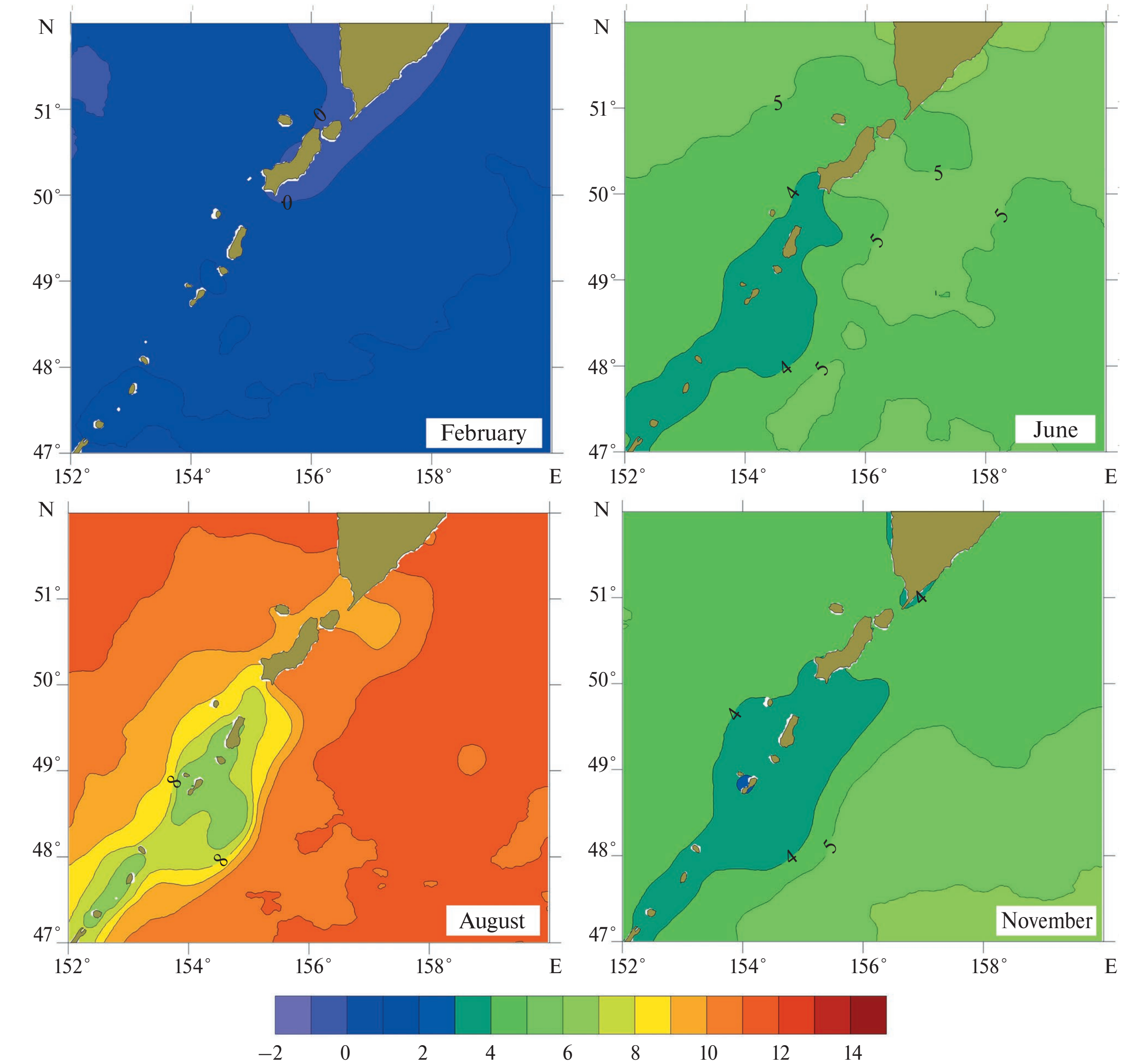

Fig. 2. Mean multiyear distribution of SST (in °C) in the area of the North Kuril Islands in winter (February), spring (June), summer (August) and fall (November).

+5–6 °C, but at the same time near the Kuril Islands to the south of Paramushir Island, the formation of the area of the Kuril Islands begins. An area of lower temperatures from +3 to +4 °C begins to form near the Kuril Islands south of Paramushir Island.

During the summer months, the spatial distribution of SST generally has the same features as in June: the coldest water is observed in the pre-Kurilian waters south of 50°N, with temperature values increasing with distance from the islands both into the open ocean and the Sea of Okhotsk. The widest area of cold water is observed in the vicinity of Shiashkotan Island. The widest area of cold water is observed near Shiashkotan Island, where a second spot appears near the sharply defined northern spur of the Vityaz Ridge. This peculiarity emphasizes the determinant role of the bottom relief in the appearance of the cold zone in this part of the Kuril Ridge covering the area from Simushir Island to the Fourth Kuril Islands. Simushir Island to the Fourth Kuril Strait.

In July, as in June, the warmest water (+9–10 °C) is mainly located to the north of the 51st parallel,

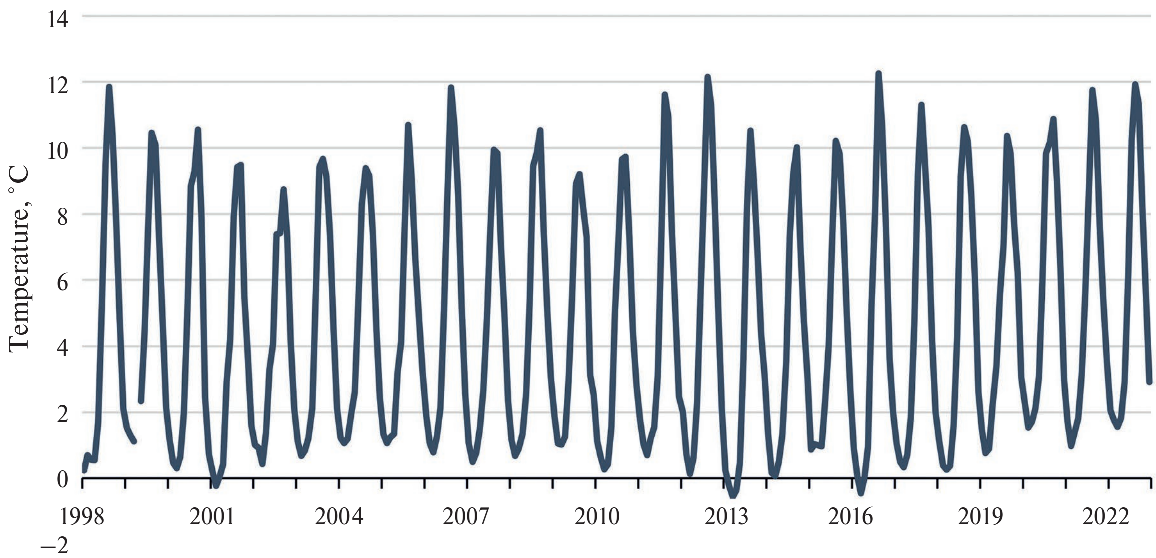

Fig. 3. Graph of SST variations (in °C) averaged over the water area off the North Kuril Islands.

and near the western boundary of the study area it extends southward to 50°N. In the main part of the area SST values vary within fairly narrow limits — +8–9 °C. As one approaches the Kuril Islands, the temperature gradient increases, and colder water (below 6 °C) is occurred in coastal areas. In August-September near the coast the values remain the same, while in the rest of the area they increase to 10–12 °C.

In October-November, the temperature distribution is similar to summer. In October, in the areas with the warmest water in the north-west and south-east of the area, the water temperature decreases most rapidly — to 8–9 °C. The area near the islands cools down to the least extent, where the minimum values drop to 4 °C. In November, the temperature does not exceed 4–6 °C in most of the area. The spatial distribution of SST is significantly transformed in December, when as a result of surface layer cooling it becomes more homogeneous and the area near the islands is no longer distinguished. Thermal indices in the coastal areas decrease to 1–2 °C, in the moribund areas — to 3 °C.

The dynamics of average monthly values of SST is presented in Fig. 3. These fluctuations are dominated by the annual variations and interannual variations are clearly visible, which are expressed primarily in the envelope of both maxima and minima (although significant changes of the latter are less typical for sea water temperature). There is also a unidirectional tendency for the SST increase, and in recent years it is clearly increasing. While the linear trend coefficient for the whole series is about 0.04 °C/year, which means an increase of 1 °C for 25 years, it is almost an order of magnitude higher (about 0.3 °C/year) when calculated for the last seven to eight years.

The graph shows well-defined variations of thermal conditions in the summer period (envelope along the maxima). In 1998, 2006, 2012, 2016 and 2022, the areas adjacent to the North Kuril Islands experienced significantly warmer conditions than in “normal” years, when water temperatures are close to long-term averages. Cold conditions in 2002, 2009, 2014 and 2019, differences in mean SST values by area reached 3.5 °C.

Quasi-rhythmic components can be traced in the variations of the SST maxima. The smallest share of the residual variance was obtained for the harmonic with a period of six years. The amplitude value of this component was close to 1 °C, the highest values were recorded in the southern part of the study area (up to 1.7 °C), the lowest — on the southeastern shelf of Kamchatka and on the ocean shelf of the North Kuril Islands.

Seasonal variations of SST. Table 1 shows statistical characteristics of seasonal variations: multiyear average values of SST for each month, the value of standard deviation σ, maximum and minimum values for the entire observation period. The maximum heating is observed in August (10.4 °C) and September (10.0 °C), the minimum — in February-March (0.7 °C).

The fluctuations are well described by a combination of the annual and semiannual harmonics. The annual variation is relatively weakly expressed, the amplitude of the annual component was 4.9 °C and its phase was 224°, which corresponds to the maximum in the middle

Table 1. Multiyear averages, standard deviation σ and extreme values of SST by months (°C)

Month	Average	Sigma	Minimum	Maximum
January	1.3	0.6	0.2	2.3
February	0.7	0.5	−0.2	1.8
March	0.7	0.6	−0.6	1.7
April	1.1	0.7	−0.4	2.2
May	2.3	0.8	0.5	3.4
June	4.8	0.8	3.1	6.0
July	8.4	0.9	7.1	10.2
August	10.4	1.2	7.4	12.3
September	10.0	0.8	8.2	11.3
October	7.5	0.7	5.5	9.0
November	4.7	0.9	2.5	6.3
December	2.5	0.6	0.7	3.5

of August. The amplitude of the semiannual harmonic is four times smaller (1.1 °C), and its phase corresponds to the maxima in early February and August. The amplitude of the annual harmonic differed significantly in different years — the lowest value was recorded in cold 2002 (4.0 °C), the highest — in warm 2016 (5.8 °C).

Let us consider the spatial distributions of amplitude and phase of annual and semiannual harmonics for the period from 1998 to 2022 (Fig. 4). It follows from the figures that the intensity of seasonal variations of SST varies not only in time, but also in space. Over most of the area both in the NWPO and in the Sea of Okhotsk, the amplitude of the annual harmonic varies from 5 to 6 °C. As it approaches the Kuril Islands, its values decrease and reach their minimum values (from 2.3 to 2.6 °C) in the areas from Onekotan Island to Shiraya Island. Onekotan Island to Shiashkotan Island and from Rasshua Island to Simu Island. Rasshua Island to Simushir Island. The phase of the annual harmonic varies within small limits — from 214 to 234°. Its minimum values, indicating a slightly earlier onset of the summer temperature maximum, are observed near the Kuril Islands and on the shelf of the Kamchatka Peninsula, while its maximum values are observed in the southeast of the study area.

Variations in the amplitude of the semiannual component are small, its values increasing from 0.7 °C in the coastal zone of the Kuril Islands to 1.4 °C in other areas. The phase of this component is also minimal in the coastal zone of the archipelago and on the southeastern shelf of Kamchatka (about 42°), and increases to 95° as one moves out to the Pacific Ocean.

Interannual variability of thermal conditions. In modern conditions, when global warming plays the main role in climate changes on the Earth, when studying variations of thermal conditions in marine areas, the question of unidirectional trends (trends) in them most often arises. Fig. 5 presents the results of calculations for different seasons of the year, where the linear trend coefficients are summarized to the values for 10 years.

The character of the spatial distribution of SST in winter (January-March) is rather complex and mosaic, but in general, a decreasing trend in SST prevails in the Sea of Okhotsk, while in the NWPO, on the contrary, an increasing trend prevails. The most significant negative trends are observed along the western boundary of the area (up to 0.5 °C/10 years or 1 °C over 20 years). The rate of increase in the Pacific Ocean adjacent to the Kuril Islands is about half as large.

In spring, the area with negative values of LTC expands at the expense of a significant part of the NWPO; positive trends are observed only in the northeastern section adjacent to the southeastern coast of Kamchatka. At the same time, the SST decrease rate decreases as compared to the winter period, while the increase rate increases up to 0.4 °C/10 years.

In summer, a warming trend prevails over most of the water area, with very high growth rates in the open ocean — up to 1.1 °C/10 years. The exception is the above-mentioned cold spot off the coast of the Kuril Islands, where a decrease in SST is observed with rather high rates (from 0.2 to 0.4 °C/10 years). In the fall, the tendency to increase the temperature of the surface water layer prevails, and the rate of increase varies from 0.3 to 0.7 °C/10 years, which can also be considered significant.

Significant SST anomalies. In fact, the warm and cold years shown above are visual estimates. At the same time, the identification of SST anomalies (deviations

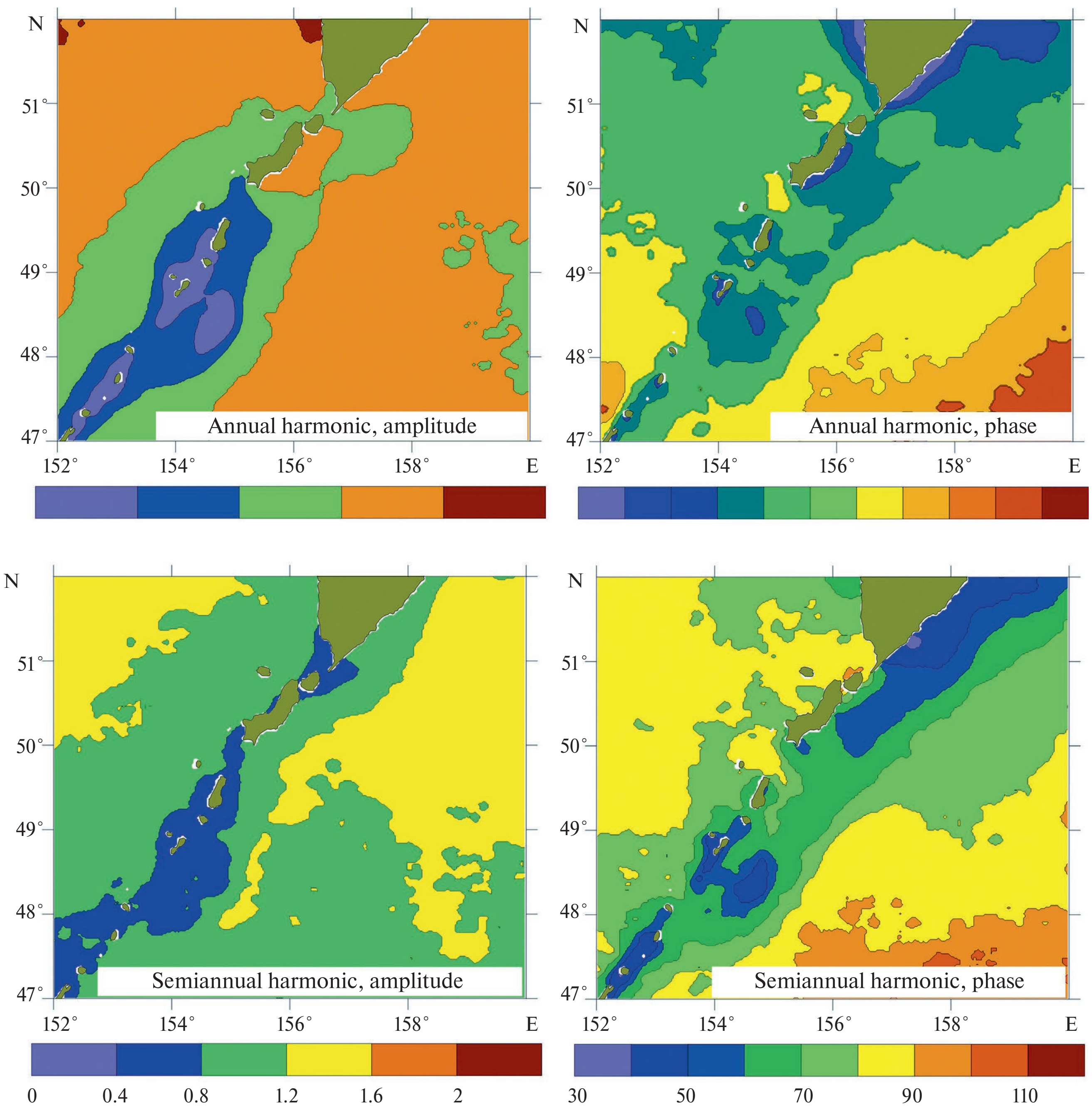

Fig. 4. Spatial distribution of the amplitude (in °C) and phase (in °C) of the annual and semiannual harmonics of SST in the area of the North Kuril Islands.

from multiyear averages, called "norms") that are large-scale in both magnitude and area is of considerable interest. Usually, deviations from the norms obey a normal distribution, for which the 2σ value corresponds to the boundary within which 95% of values lie, and going beyond it indicates extraordinary thermal conditions (some experts even use the term "thermic catastrophe") of the environment (Ustinova, 2021). If such anomalies spread over a large part of the water area, the situation becomes really dangerous for the life of hydrobionts, especially at the early stage of their development, and deserves careful study. Figure 6 presents a graph showing the proportion of the area of significant anomalies in relation to the entire study area.

Of greatest interest were the situations when such anomalies occupied a significant part of the study basin. In most cases, they appeared in small areas of 2–5% of the study area and relatively rarely exceeded

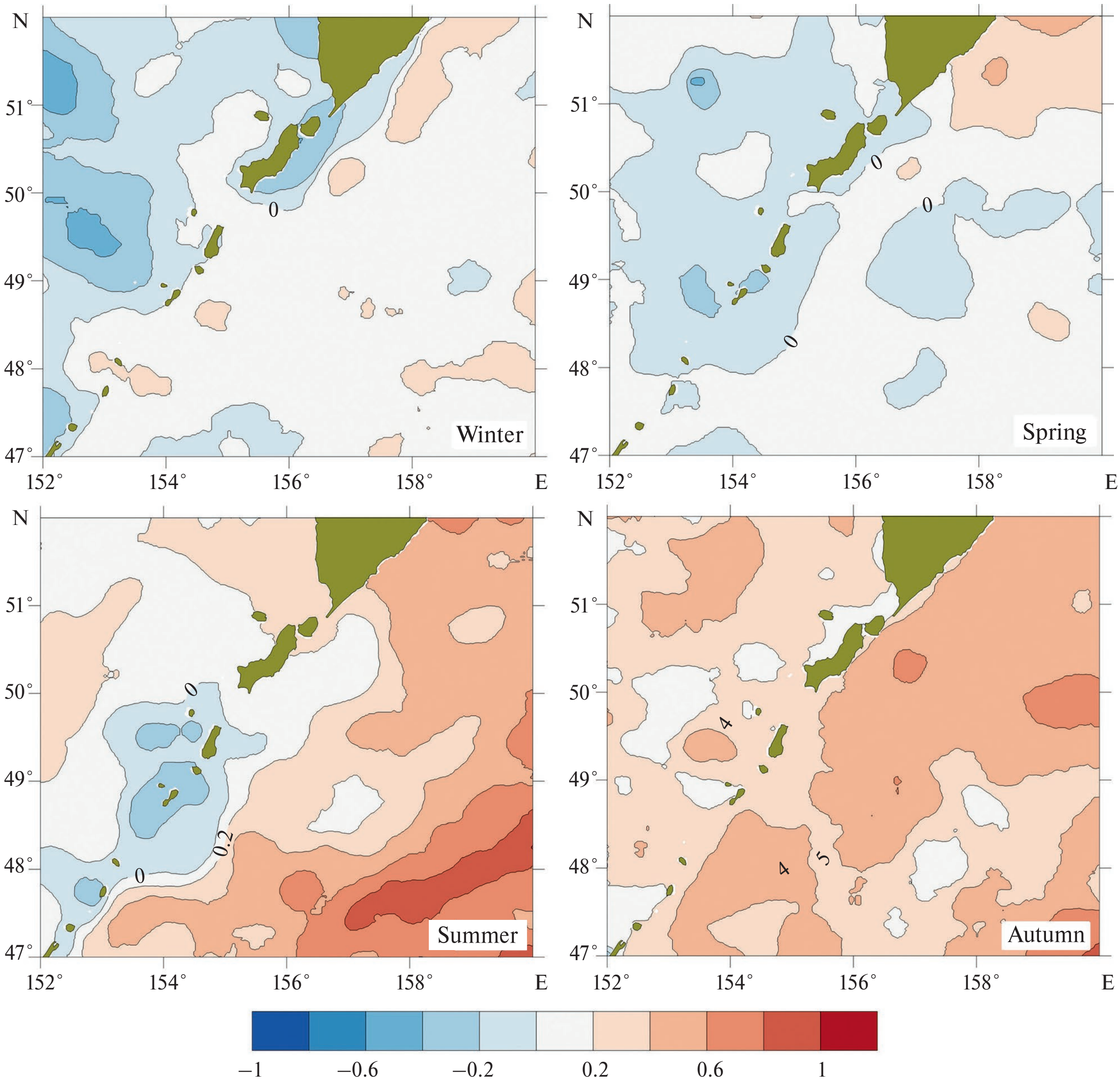

Fig. 5. Spatial distribution of linear trend coefficients in SST variations (in °C/10 years) in different seasons of the year in the area of the North Kuril Islands.

the 10% mark. Interestingly, this was not observed once during a number of years (from 2003 to 2009), and in some years repeatedly (e.g., in 2013 for six months). Note that a linear trend was not subtracted from the data when calculating the anomalies, which could have led to an increase in the number of positive anomalies in recent years. However, as can be seen from Fig. 6, this did not happen; apparently, the effects associated with the presence of a tendency to an increase in SST did not significantly affect the phenomenon under consideration.

For a more thorough analysis, situations where the area of significant anomalies was higher than 20% were selected (Table 2). There were ten of them, in nine of them negative and only in one case positive anomalies were observed. In four of them the areas of extreme temperatures occupied more than 40% and in eight cases more than a quarter of the total area. This indicates that deviations of the thermal regime from the "norm" in the North Kuril Islands can be large-scale. At the same time, cases of extremely cold conditions

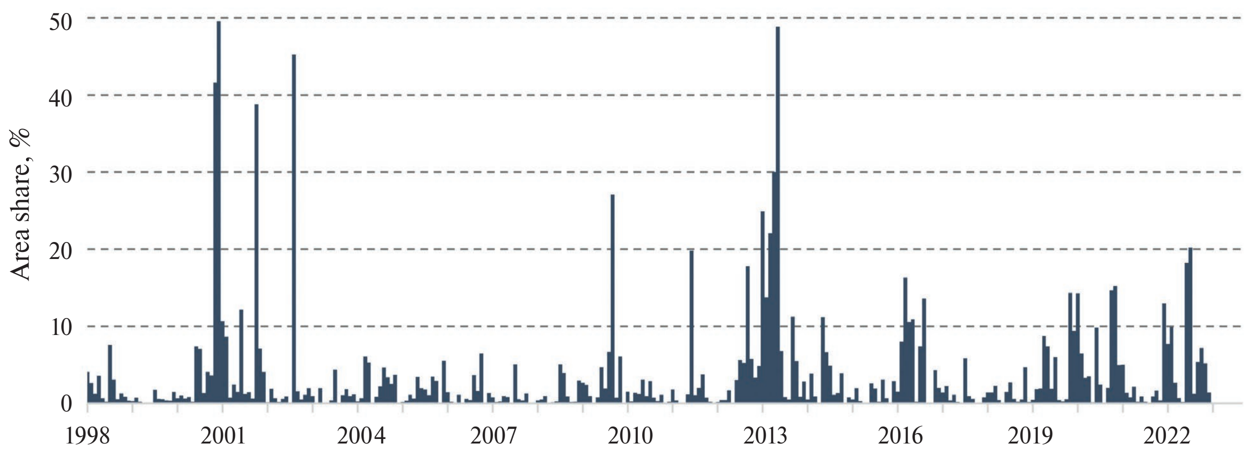

Fig. 6. Fractions of the area of extreme SST anomalies exceeding 2σ in the area of the North Kuril Islands.

clearly predominate. This disproportion is highly unusual, its physical causes are unclear and require further study.

Fig. 7 presents the spatial distributions with the most significant SST anomalies. In December 2000, the temperature in most of the area was 2 °C and in some areas 2.5 °C below the mean multiyear average. Usually, such indicators are considered as regular events, but in December, the SST variability is relatively low with the value of standard deviation of 0.6 °C (see Table 2).

In August 2002, the negative anomalies covered practically the entire area, and at the areas remote from the coast both in the Sea of Okhotsk and in the Pacific Ocean, they had a significant value from –4 to –6 °C. Near the coast of Kamchatka and the Kuril Islands, they were much smaller and did not exceed 1–2 °C.

In the spring of the "anomalous" 2013, the area of deviations exceeding 2σ in magnitude comprised more than 20% of the area during the three following months — from March to May (see Table 2). In May, almost half of the study area (49%) was in the zone of significant negative anomalies (up to 3 °C).

In August 2022, the only case when significant positive SST anomalies were recorded over a sufficiently large area was recorded. In some areas, the water temperature was 4 °C above the multiyear average. In the coastal areas of southeastern Kamchatka and Kuril Islands, the thermal indices generally corresponded to the mean multiyear average.

Decomposition of the SST field by EOF. Important features of seasonal and interannual variability can be determined using decomposition of hydrometeorological fields by natural orthogonal functions (Novinenko and Shevchenko, 2007).

Table 2. Information on the most significant SST anomalies in the area of the North Kuril Islands

Period	Share of area, %	Anomaly sign
November 2000	41.64	Negative
December 2000	49.61	Negative
October 2001	38.81	Negative
August 2002	45.25	Negative
September 2009	27.09	Negative
January 2013	24.91	Negative
March 2013	22.07	Negative
April 2013	30.03	Negative
May 2013	48.86	Negative
July 2022	20.22	Positive

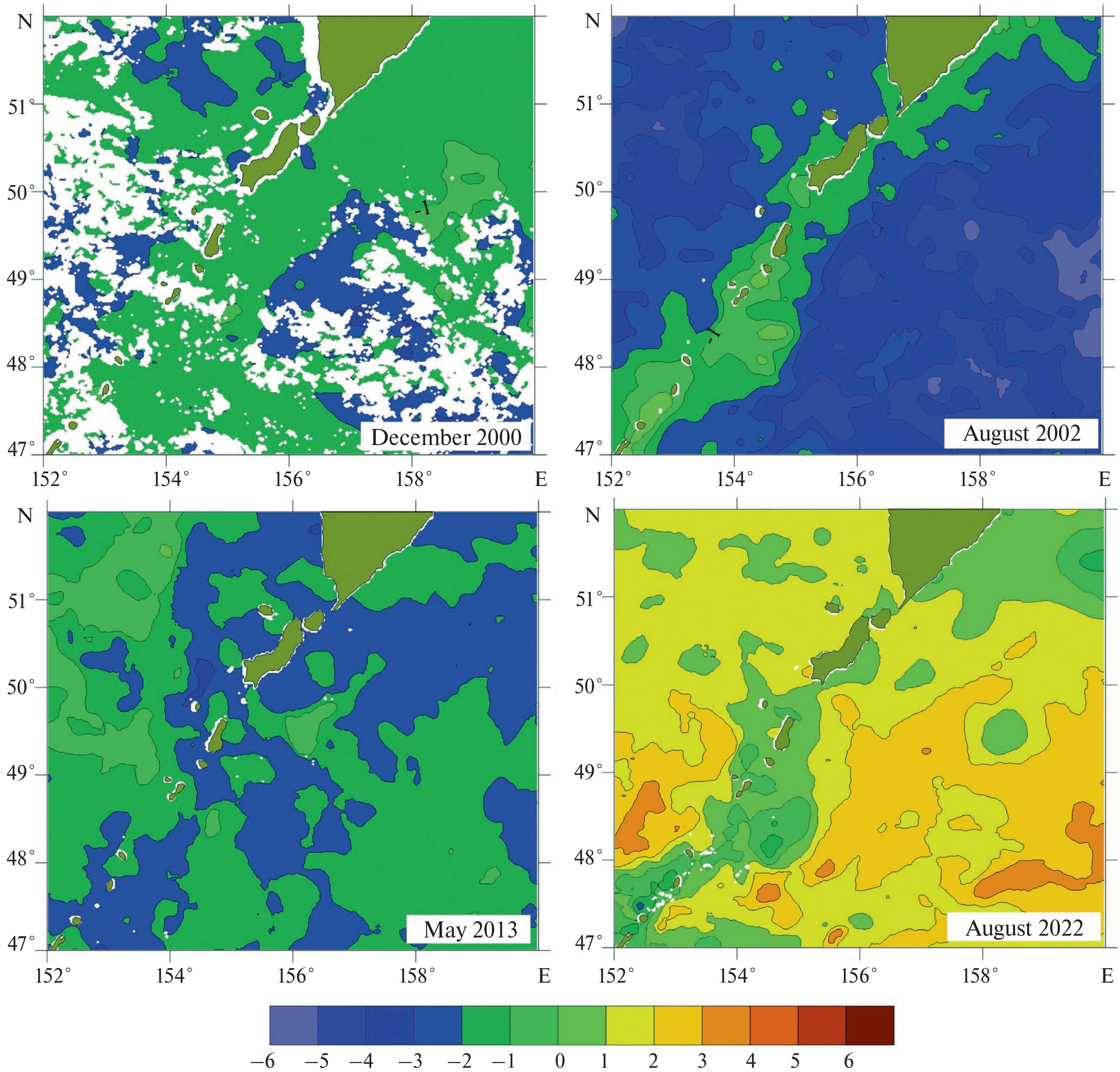

Fig. 7. Spatial distribution of the most significant SST anomalies (in °C) in the area of the North Kuril Islands.

The calculation results in the form of spatial distributions of the first three main modes (they account for 96.65; 0.51 and 0.25% of the total variance) and their corresponding time functions are presented in Fig. 8.

When the EOF method decomposes hydrometeorological fields with a pronounced seasonal course (variations in sea water or atmospheric air temperature are among the most striking examples of this kind), the first mode gives an overwhelming contribution to the total parameter dispersion, which, however, does not devalue the role of higher components.

The spatial structure of the first mode is practically identical to the averaged distribution of SST in summer (low values near the coast of the Kuril Islands and high values in the open ocean and in the remote part of the Sea of Okhotsk), and its temporal function has a very high correlation ($r = 0.996$) with the mean monthly temperature values. For this reason, there is no point in considering the main component

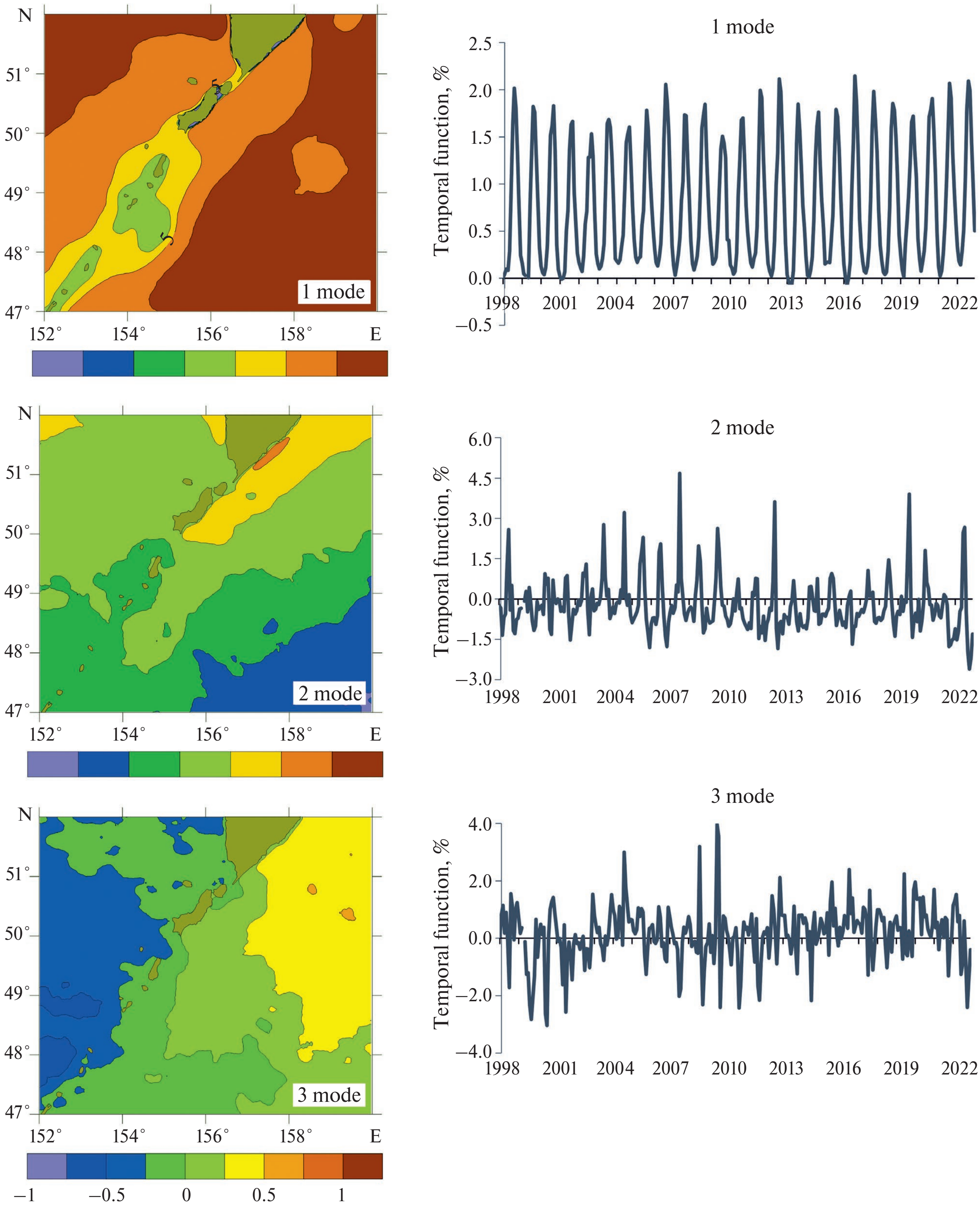

Fig. 8. Spatial distribution (dimensionless) and plots of time functions (in °C) of the first three modes of the SST field decomposition by EOF in the area of the North Kuril Islands.

of the EOF in detail. Let us only note that the time function is well approximated by a combination of annual and semiannual harmonics with amplitudes of 0.9 and 0.2 °C, reaches maximum values in August-September and minimum in February-March. The first mode describes the parameter oscillations, which occur in-phase in the entire region, although with different intensity in the areas characterized by the spatial function.

The second mode reflects the variations of SST which do not fit into the idea of an identical course of the parameter. Therefore, the spatial distribution shows zones with different signs separated by a nodal line near which the contribution of this mode is insignificant. This line passes in the vicinity of the 49th parallel, to the north of which the mode values are positive (up to 1.2 near the southeastern coast of Kamchatka), and to the south — negative (up to –1.1 at the southeastern site).

The averaged curve of the time function has positive values from June to August with a pronounced maximum in July. In other months, the values are negative, with minima in October-November. This means that in summer the second mode gives a correction to the main component, positive in the northern part of the area and negative in the southern areas. In the cold period of the year, the situation is opposite — its contribution is negative in the north and positive in the southern areas.

Significant interannual variations are noticeable in the temporal function of this mode; the 11–year cycle is significantly emphasized, and to a lesser extent — the 6–year cycle, while its annual course is generally preserved. The highest positive values and, consequently, the maximum contribution of the mode to the total SST field, are observed in July 2007, 2012, and 2019. In some years (e.g., 1999 and 2016), the summer maximum is weakened, with values of the time function an order of magnitude smaller than in cases of a pronounced maximum. Negative values are more stable, with extreme minima identified in the fall of 2022 (below –2 °C).

While the second mode gives a zonal correction to the main component, the third mode introduces a meridional correction. Its spatial function took negative values practically over the entire Okhotsk Sea section of the study area. In the NWPO, the nodal line was approximately along the 155th meridian with positive values in the eastern part of the water area and negative values in the western partThe variation of values was from –0.6 to +0.5 °C.

Unlike the first two modes, the time function of the third mode did not have a stable recurring seasonal character. Its averaged values for 1998–2022 for different months of the year were positive in January-June, August and December. In case of positive values of the time function, the positive correction took place in the eastern part of the study area, and the negative correction — in the western part. In case of negative values, the correction acquired the opposite character. The greatest total change in SST due to the contribution of the third mode was observed in July 2009, which amounted to about +2 °C in the eastern part of the basin and –2.5 °C in the western part of the basin.

CONCLUSION

Calculation of averaged SST distributions by seasons has established the main feature of the thermal regime in the area of the North Kuril Islands, expressed in the presence of a permanently existing area with low water temperature values. It covers the coastal water area of the archipelago from Simushir Island to the Fourth Kuril Islands. It covers the coastal water area of the archipelago from Simushir Island to the Fourth Kuril Strait and does not include waters near Shumshu and Paramushir Islands. Thermal indices increase as one moves away from it into both the open ocean and the Sea of Okhotsk. The cold water zone becomes most extensive near Shiashkotan Island, where the temperature in the vicinity of the Shumshu and Paramushir Islands increases. Shiashkotan Island, where second spot is formed near the northern spur of the Vityaz Ridge. This feature emphasizes the key role of the bottom relief in the formation of the cold zone.

Seasonal SST fluctuations are characterized by a distinct annual variations with maximum values in August-September and minimum values in February-March. They are well described by a combination of annual and semiannual harmonics with amplitudes of 4.9 and 1.1 °C, the fluctuations of which decrease in the zone of cold waters and increase as one moves away from the islands to the moribund regions. The interannual variability of the thermal regime is revealed mainly in the modulation of the annual variations with a period of about six years.

In the time functions of the two main modes of the decomposition of the SST field by the EOF in the envelope by summer maxima, cycles with periods of about 11 and six years are manifested. In the spatial structure of the first mode, the area of low values near the Kuril Islands is distinguished. The second mode indicates differences in thermal conditions in the northern and southern parts of the study area, and the third mode — in the waters of the Sea of Okhotsk and the NWPO.

Calculation of linear trend coefficients determined the direction of temperature increase in the whole area at a rate of about 1 °C over 25 years. The warming trend is most noticeable in the adjacent part of the NWPO in summer and to a somewhat lesser extent in the fall.

In the cold spot area, the opposite trend is predominantly observed in winter and spring.

The analysis of the SST fields for 25 years of observations showed that at times significant temperature anomalies exceeding twice the value of the standard deviation can be formed in the area of the North Kuril Islads. In ten cases out of 300, the proportion of the area over which such anomalies were observed was more than 20%, and in four of them — more than 40%. This indicates that deviations of the thermal regime can be large-scale, occur over a significant part of the area and pose a serious threat to the hydrobionts living there. At the same time, cases of anomalously cold conditions clearly prevailed. Such disproportion is very unusual, its physical causes are unclear and require further study.

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