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Seasonal and interannual variations in sea surface temperature in the Tatar Strait according to satellite data*

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Abstract. The aim of the work was to conduct a systematic statistical analysis of the spatial and temporal variability of sea surface temperature (SST) in the waters of the Tatar Strait based on satellite data accumulated in the Sakhalin branch of VNIRO using the TeraScan receiving station for 1998–2021. It was revealed that in different seasons of the year the SST structure is similar and characterized by the highest values in the southeast and the lowest in the northwest of the strait. The most significant differences are observed in autumn due to the formation of a strip of cold water along the western coast of Sakhalin (tapering in the southern part of the island), due to the formation of coastal upwelling under the influence of northerly winds typical of the cold season. The calculation of the linear trend coefficients revealed a trend towards a decrease in the temperature of the surface layer in the Tatar Strait, which is most pronounced in winter (in the northern part of the area) and in spring (from −0.5 to −1 °C / 10 years). An important new result was obtained by expanding of the SST field in terms of the EOF, which is associated with a sharp change in the nature of the time function of the third mode, which occurred in 2013–2014. Such changes can be considered as a climatic shift in the studied area most pronounced in the northwestern part of the strait and near the southwestern coast of Sakhalin Island, where the change was about 1 °C. This circumstance can have a noticeable effect on the state of populations of several species of shrimp and commercial fish.

Keywords: sea surface temperature, Tatar Strait, seasonal variations, trend, empirical orthogonal functions, climatic shift

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Introduction

The waters of the Tatar Strait are of great commercial importance. Herring and capelin harvest increases off the west coast of Sakhalin, also a significant amount of shrimp of various species is also caught here. However, negative trends were noticed in the state of their stock a few years ago, which was one of the springs of action for studying the spatio-temporal variability of thermal conditions in the area. Changes in the thermal regime under changing climate could also affect the significant growth in herring numbers observed in recent years, which was the most important target species in the basin from the mid-1940s to the mid-1970s, as well as the state of Pacific salmon populations.

Many works are devoted to the variations of thermal regime in the Tatar Strait. Most of them are based on the data of oceanographic surveys [1–9] and there is an increase in studies based on the satellite data [10–13] in recent years, less frequently on the measurements conducted at coastal

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hydrometeorological stations [14–17]. Interannual variations in sea temperature in the northern part of the strait were also considered in the study of the variability of ice conditions [18–19].

However, most of these studies were based on the data from shipboard measurements, which were, moreover, conducted prior to the arrival of the era of global warming. Other papers have studied certain aspects of the thermal regime (for example, the presence of unidirectional trends in surface water temperature variations) or have analysed the situations characterized by significant deviations from the normal regime. At the same time, there was no systematic statistical spatio-temporal analysis of these conditions.

The satellite sea surface temperature (SST) observations have full coverage and regular receipt of the data in contrast to traditional shipboard oceanographic surveys. They are, therefore, the most suitable material for studying the spatio-temporal variations of the thermal regime under changing climate using different methods of statistical analysis and significantly complement traditional shipboard studies (as well as oceanological soundings allow assessing the response of the entire water column to changes in the surface layer of the sea).

This work focuses on the interannual variability (as well as seasonal variations) of thermal conditions based on the satellite sea surface temperature observations for 1998–2021. The method of empirical orthogonal functions (EOF) is used to solve the problem.

Research materials and methods

The Sakhalin branch of VNIRO has accumulated a significant amount of the data from satellite observations of sea surface temperature due to the TeraScan satellite ground station installed in 1997. Since 1998, there has been a regular reception of incoming observation materials and the building of a database based on the daily distribution of a parameter with a spatial resolution of about 2 km.

In addition, there are bases with spatial resolution of a quarter degree and averaging time with periods of 10 days and 1 month for various calculations (determination of long-term averages – norms, temperature anomalies, linear trends, parameters of seasonal harmonics, etc.). Some satellite images have also been preserved over the past five years. The analysis of all these materials is performed below in order to determine the nature of seasonal and interannual variations of SST. Their most complete form is reflected in the expansion of hydrometeorological parameters in empirical orthogonal functions – EOF [20]. In addition to expansion of the SST field in EOF, this paper considers the average spatial distributions of this parameter in different seasons of the year, amplitudes and phases of annual and semi-annual harmonics and linear trend coefficients, as well as the most significant SST deviations from long-term averages, are calculated.

Results and discussions

Averaged SST distributions by seasons

Figure 1 shows the average long-term distributions of sea surface temperature in the Tatar Strait in different seasons. In winter (January–March), the water temperature is negative in the northern part of this area, north of the 49° N parallel. Ice is usually formed in this area, and the highest level of glaciation is observed in the second half of January. The lowest values, about –1 °C, are marked between the 50° and 51° parallels. Water with negative values, fluctuating smoothly from –0.6 to –0.1°C, occupies a band along the continental coast, the width of which is also gradually decreasing. The marks slightly below 0°C are observed near the west coast of Sakhalin Island, in the Chekhov-Ilyinskoye shallow water. In the southern part of the strait, the water is warmer, with positive SST values, that is due to the aftereffect of the warm Tsushima Current. The maximum temperatures (about 3.5 °C) are found at the southern boundary of the studied basin between the 140° and 141° meridians.

In spring, the structure of the spatial distribution of the sea surface temperature in the Tatar Strait is similar: the warmest water (7.5–7.8 °C) comes from the south with the Tsushima Current and moves towards the small Island of Moneron, leaving a narrow band of colder water near the coast of Sakhalin Island. A large spot of the coldest water (3.5–3.8 °C) is formed in the northern part of the studied basin, at some distance from the coasts, with the exception of the continental coast between 48.5° and 50° N.

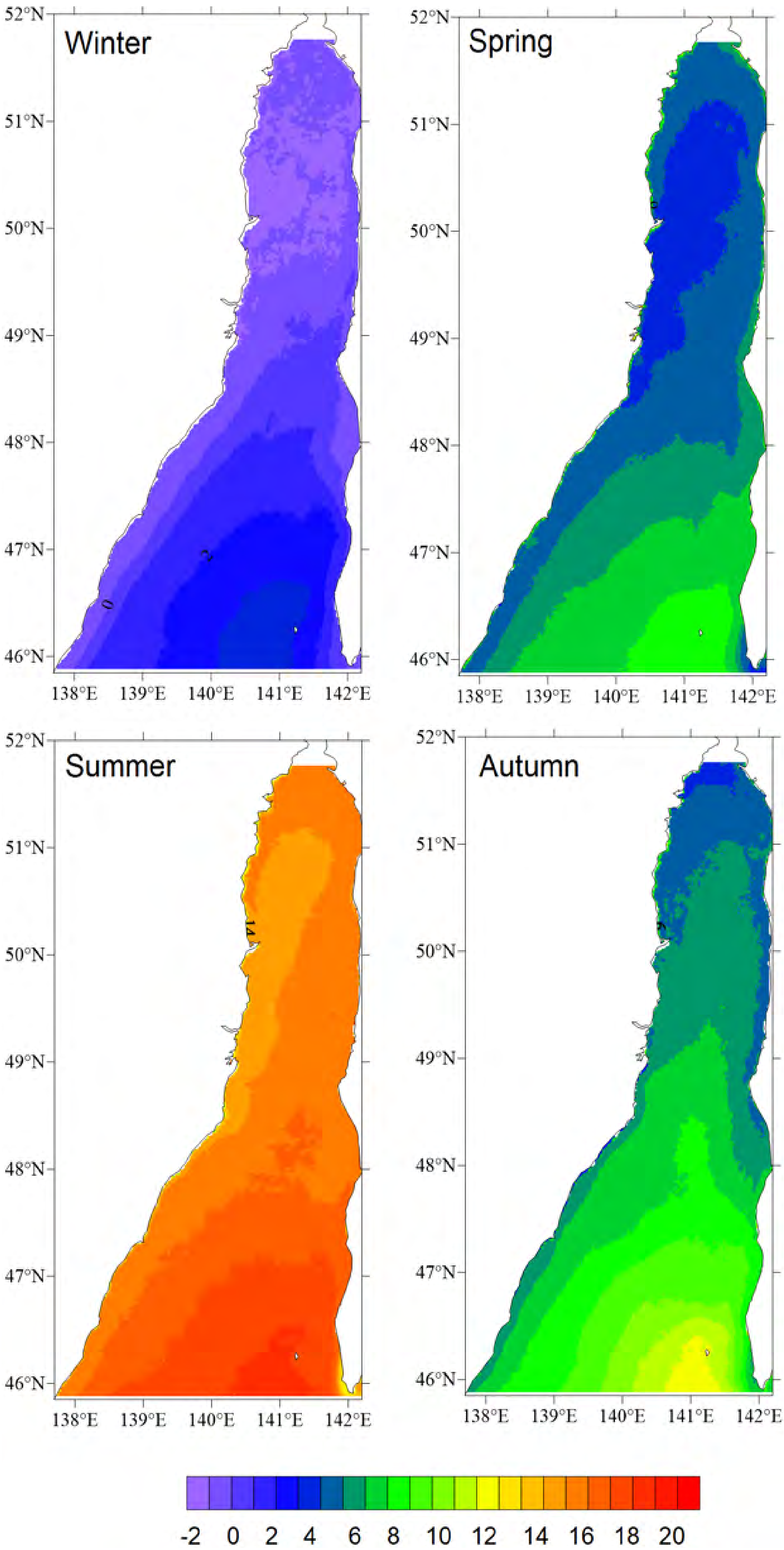

Fig. 1. Average long-term distribution of SST (in °C) in the Tatar Strait in winter, spring, summer and autumn.

In summer, the distribution structure is the same, with only SST values increasing significantly throughout the strait. Thus, in its southeastern part, in the zone of the Tsushima Current, the maximum values of 18.4 °C are marked, and the minimum values of 14.5 °C are marked in the northwest one.

In autumn, there are certain changes in the SST distribution due to the restructuring of the wind field to a winter monsoon characterized by strong and stable northwest and north winds. As a result of their offshore action, the coldest water with a temperature of about 3.5 °C is observed in the northern part of the water area adjacent to the Nevelsky Strait. Less dense, although relatively cold water moves south along the mainland coast due to the flow of discharged desalinated water of the Amur River from the Amur Liman. There is also cold water along the west coast of Sakhalin, but it is caused by wind, namely the formation of wind upwelling when the air flow leaves the shore on the left [3, 9]. A high density coastal stream of water directed to the south is formed due to the lower temperature. As follows from Fig. 1, it reaches the Chekhov-Ilyinskoye shallow water, where this water pushes the warm water of the Tsushima Current into the central part of the Tatar Strait. On the southwest coast of the island upwelling is less pronounced.

To study the SST variations in time, the water area

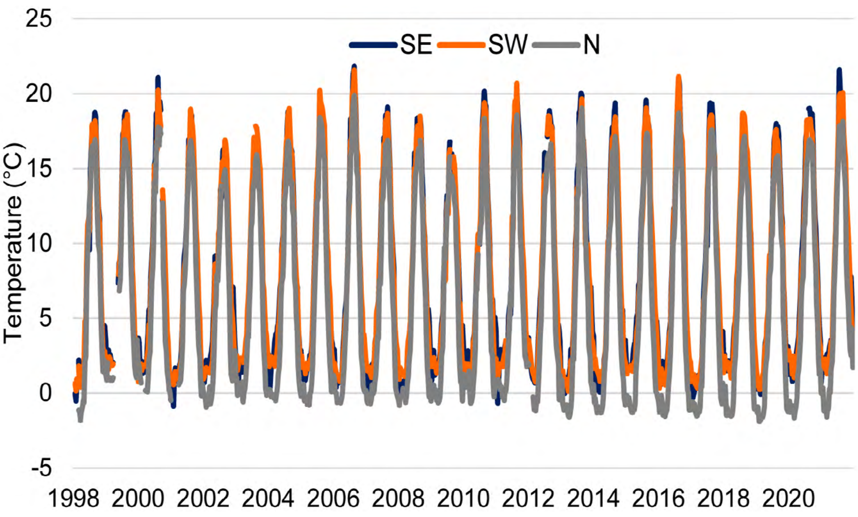

Fig. 2. Graphs of SST variations (in °C) averaged over the northern, southeastern, and southwestern parts of the Tatar Strait

of the strait was divided into three parts: northern, north of the 49° parallel; southeastern, south of the mentioned parallel and east of the 141° meridian; and southwestern, west of it. Obviously, the northern part is significantly different in its thermal regime from the southern part, as it is much colder. We also assumed the area east of the 141st meridian, including the shelf area and the mainland slope off the southwest coast of Sakhalin, to be under the stronger influence of the Tsushima Current than the western one, largely exposed to the cold Liman Current.

Fig. 2 shows graphs of the SST variations in the three specified areas. It can be seen that in the northern area the surface temperature is noticeably lower than in the southern one, especially in winter. The SST values were expected to be noticeably higher in he southeastern area than in the southwestern one. In most cases this is true, but the differences are small, and in some cases summer maximums are higher in the southwestern area (2002–2003, 2011). Perhaps, the division into the areas was not optimal, but the division by the 140° meridian was not more successful either. But these circumstances are not so significant, it is important that the interannual variations expressed in the modulation of annual course are the same in all areas and, therefore, are determined by the same reasons. They show pronounced quasi-cyclic components, visually estimated with a period of 6–7 years. We will focus on the nature of interannual fluctuations below, but first consider the seasonal SST variability.

Season variations of SST

Table 1 presents the average long-term SST values for each month in the three above-mentioned areas of the Tatar Strait. In all areas the maximum is observed in August, and its value is 16.6 °C in the north, 18.25 °C in the southwest and 18.35 °C in the southeast. Warm conditions were also noted in September (the averaged SST value is significantly higher than in July, and about 1 °C lower than in August). Minimum temperatures were detected in the north and southwest in March, and in the southeast in February – thermal effect of the Tsushima Current already begins to affect here in March, and the value is higher than not only February, but also January indicators.

The standard deviation value, which characterizes the parameter variability, was also calculated. It is much less in the cold period of the year than in warm (1.5-2 times), that is quite natural. September is stands out sharply with low values against this background, which indicates significantly more stable thermal conditions in all three areas in this month than in others. The physical cause of this interesting phenomenon is difficult

Table 1. Average long-term SST values (in °C) in different parts of the Tatar Strait for different months of the year

Month	North	Southwest	Southeast
January	0.01	1.74	1.54
February	–0.46	1.54	1.35
March	–0.72	1.36	1.58
April	0.06	2.34	2.72
May	3.24	4.98	5.26
June	8.49	9.49	9.61
July	13.44	14.70	14.83
August	16.61	18.25	18.35
September	15.52	16.98	17.04
October	9.93	12.16	11.76
November	3.72	7.11	6.45
December	0.54	3.26	3.77

to explain, given that the wind field usually restructures from the summer monsoon to the winter in the third decade of September and meteorological conditions are difficult to call stable.

The time functions of the SST variations in each area are well described by a combination of annual and semi-annual harmonics. The amplitudes and phases of these components calculated by the least squares method are given in Table 2. Thus, the amplitude of the annual harmonic in the northern area was 8.6 °C, it accounted for 93 % of the parameter variance, the amplitude of the semi-annual harmonic was significantly smaller (2.3 °C), and its contribution was 6.8 %.

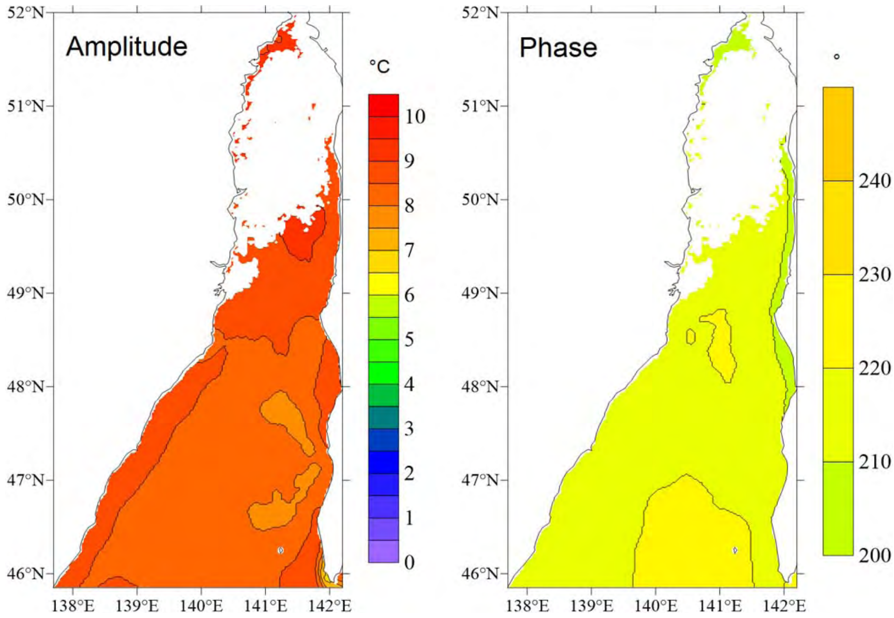

Fig. 3. Spatial distribution of the amplitude (in °C) and phase (in °) of the annual SST harmonic in the Tatar Strait.

In the southwestern area, the amplitudes of these harmonics were smaller (8.3 and 2.0 °C), with the shares of 94.5 and 5.4 %, respectively. In the southeastern area, the amplitudes of season variations were exactly the same as in the southwestern one, and their shares were similar (94.3 and 5.4 %).

The amplitude of the annual harmonic varied significantly over the years. The lowest value for all areas was recorded in the cold year of 2002 (7.6; 7.4 and 6.8 °C in the northern, southwestern and southeastern areas, respectively), and the highest one was in the heat year of 2006 (9.5; 9.2 and 9.4 °C, respectively).

Figure 3 shows the spatial distributions of amplitude and phase of the annual harmonic calculated for the period of 1998–2021. For the northern part of the strait, these values were not determined correctly due to the data omissions because of the ice cover influence, so the obtained values referred only to the southern part of the northern area.

In general, there are little variations in these parameters across the Tatar Strait. The annual harmonic amplitude ranges from 7.9 °C (two small spots in the Cape Lamanon area) to 9 °C in the north, close to the area where values could not be calculated due to ice influence. The phase

Table 2. Amplitudes (H) and phases (G) of the annual and semi-annual harmonics in different parts of the Tatar Strait

Period	North		Southwest		Southeast	
	H, °C	G, °	H, °C	G, °	H, °C	G, °
Year	8.6	213.9	8.3	217.5	8.3	215.8
Half year	2.3	67.9	2	75.1	2	73.7

of this component also varied in narrow limits: on the main part of the water area of the strait from 217 to 221°, which meets the maximum in the first half of August. In the narrow band along the west coast of Sakhalin, the phase values are slightly lower, from 206 to 209°.

The amplitude of the semi-annual harmonic is minimal in the southeast of the strait, in the area adjacent to La Pérouse Strait (about 1.5 °C), and its maximum is near the coast of Sakhalin in the area from 49.5 to 50.5° N, where it reaches 2.5 °C. The phase of this component in most of the strait ranges from 65.5 to 75°, and only near La Pérouse Strait it increases to 100°.

Interannual variability of the thermal conditions

Under modern conditions, when global warming plays a major role in climate change on the Earth, the most common question arises, when studying variations in thermal conditions in sea areas, as to whether they have unidirectional trends. To answer this question, linear trend coefficients were calculated in each spatial quarter degree cell of the Tatar Strait. Calculations were performed separately for a full year, seasonally and per month. Figure 4 presents the calculation results for different seasons, linear trend coefficients are reduced to values for 10 years.

In winter, the trends are predominantly negative and reach the highest values (in absolute magnitude) in the northern, freezing part of the strait at some distance from the shore: (–0.5... –1) °C/10 years. This is an amazing fact, it is somewhat contrary to the idea that ice coverage (the proportion of the water area covered by ice) is decreasing in this area as a result of the increase in air temperature in winter [19].

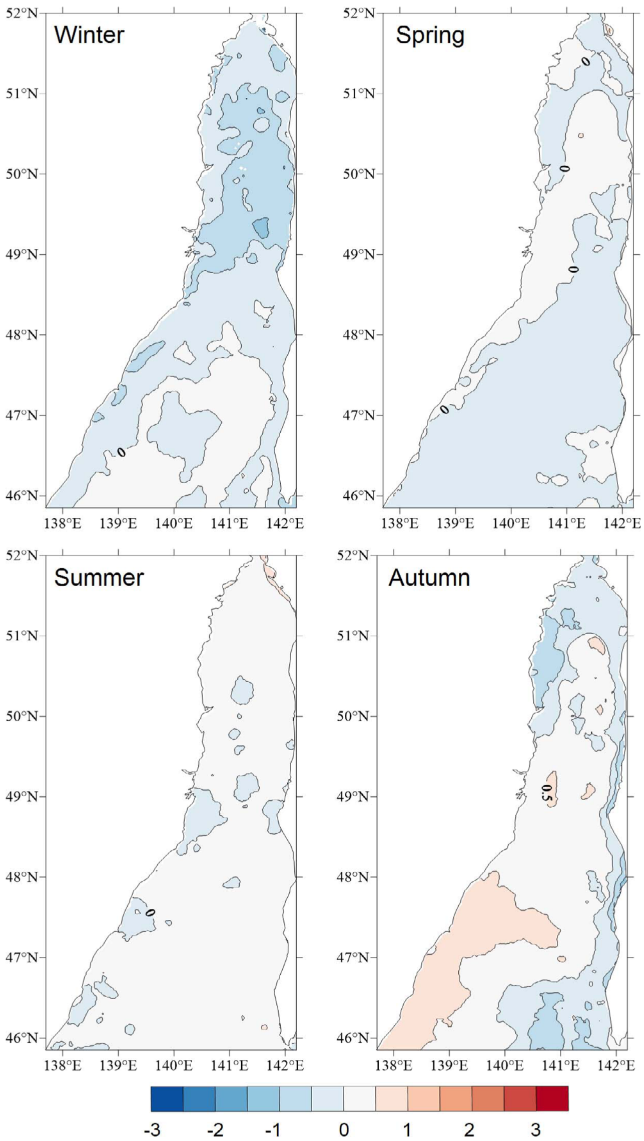

Fig. 4. Spatial distribution of SST linear trend coefficients (in °C/10 years) in different seasons in the Tatar Strait.

In the southern part of the strait, unidirectional trends are weakly pronounced, south of the 48° parallel, the linear trend coefficient is mostly positive but small in magnitude.

In spring, the situation is opposite: insignificant positive trends prevail in the northern part of the strait, and negative trends prevail in the southern one. This complicates the explanation of negative trends in the freezing area in winter by an increase in the depth of winter convection, since a similar phenomenon in the Sea of Okhotsk brought to the most significant negative trends just in spring, in April and May, and this had a quite convincing explanation [13]. This emphasizes the complexity of the processes related to the response to global warming in different basins.

In summer, small positive values of linear trend coefficient in the range from 0.05 to 0.1 °C /10 years are observed in almost the entire water area of the strait, and only in some areas they increase up to 0.2 °C/10 years. Negative values are observed in small areas, and they do not exceed 0.05 °C/10 years in absolute value.

The most complex picture of unidirectional changes in the SST was found in autumn. Significant negative linear trend coefficients – (−0.3... −0.7) °C/10 years have been identified in the northern part of the strait and in the coastal zone near the west coast of Sakhalin Island; and an area, where the temperature of the sea surface steadily increases at a rate of (0.5–0.7) °C/10 years, is identified in the southwest of the studied area near the mainland coast. A possible reason for such a complex picture of the SST variability may be a change in the intensity of the wind effect, but this issue requires special research.

Let's turn now to the graph of the SST variations in three areas of the Tatar Strait (see Fig. 2). It visually shows well-pronounced variations of thermal conditions in summer (maximum envelope). It is clear that in 2000, 2006, 2016 and especially in 2021 the conditions in the Tatar Strait were significantly warmer than in the "ordinary" years, when the water temperature is close to the average long-term values. Cold conditions in the studied area were found in 2002, 2009 and 2019, differences in the average SST values by areas reached 5 °C.

The quasi-rythmic components, for which the methodology proposed in the paper [21] was used, are traced in the variations of the SST maxima.

To determine the contribution of the cyclic component with a given period in each spatial cell of the area by means of the least squares method, its amplitude and phase for August samples were calculated. This component was further subtracted from the original series, and the significance of the harmonic contribution was determined using relation of the variance of the residual series to the variance of the original one for all cells over the Tatar Strait. The cyclic component periods were set from 3 to 12 years with the increment of 3 months.

The smallest fraction of the residual variance was obtained for a harmonic with a period of 6 years. The amplitude of this component throughout the water area of the strait was close to 1 °C (slightly smaller than this value in the area between the 49° and 51° parallels and somewhat higher outside this area).

Significant SST anomalies

In fact, the warm and cold years noted above were determined by visual estimates, meanwhile the identification of the large-scale (both in terms of size and area) SST anomalies (i.e. deviations from long-term averages called norms) is of considerable interest. It is related to the fact, that such situations, called by some experts “thermal catastrophes”, represent a serious danger to marine biota. A methodology [22] has been developed in order to estimate such situations. It consists in identifying the area, where the anomaly has exceeded twice the standard deviation σ. Deviations from the norm usually adhere to a normal distribution, for which the value 2σ corresponds to the boundary, within which, 95 % of the parameter values lie. Therefore, going beyond its boundaries testifies to the extraordinary conditions, extraordinary thermal conditions of the environment state in this case. If such anomalies are observed on a significant part of the studied area, the situation is very serious and deserves careful study.

For each month of each year of observation, long-term average values (norms) in each spatial cell and standard deviation were calculated. Spatial distributions of σ value were analysed for different months, especially for the warm season (it was already noted above, that in September the value of this parameter averaged over the areas was about 1.5 times less than in August). In June, the distribution of σ is homogeneous, the parameter variations are small: it varies from 1.1 to 1.4 °C in most of the studied water area. Only in narrow coastal bands, both near the west and the east coast of the strait its values increase up to 1.5–1.6 °C. In July, in the northern part of the studied water area, the character of the distribution of σ practically does not change, and σ increases to 2.4 °C south of the 48° parallel. On the contrary, in August, higher values of σ are found in the northern part of the strait, and in the southern one they are similar to those in June.

The difference between the current monthly average and the norm (the anomaly itself) was compared with the double standard deviation, the area occupied by such significant anomalies was calculated. Graph in Figure 5 shows the percentage of the area of the significant anomaly in relation to the entire water area of the Tatar Strait.

The most interesting situations are when such anomalies occupied a large part of the studied basin. In most cases, they manifested themselves in small areas, accounting for 2−3 % of the water area of the strait, and rarely exceeded the mark of 10 %. The most important situation, when the area of anomalies was at least 15 % of the strait area, were selected for the detailed analysis. There were nine such cases, positive anomalies were observed in five of them, and negative ones – in four

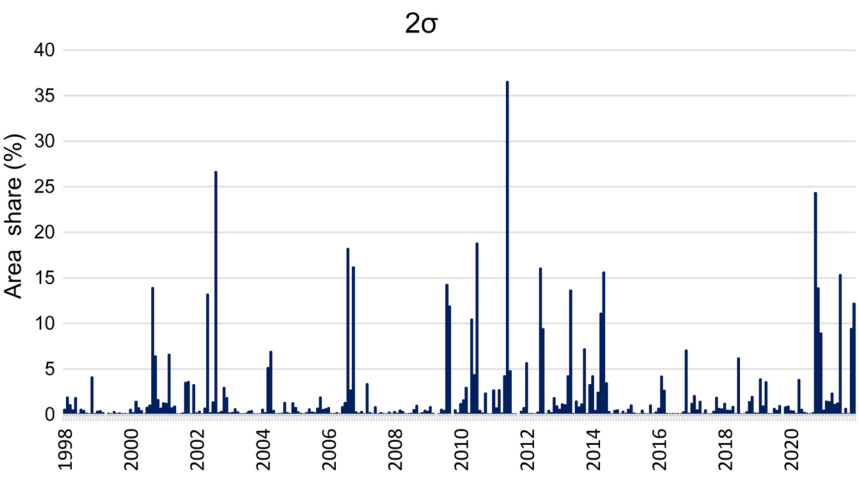

Fig. 5. Percentage of the area (in relation to the entire Tatar Strait) in which the SST anomaly exceeded 2σ.

Table 3. Information on the most significant SST anomalies in the Tatar Strait

Month, year	Percentage of the area, %	Sign of anomaly
August 2002	26.61	–
August 2006	18.17	+
October 2006	16.16	+
July 2010	18.77	–
June 2011	36.51	–
June 2012	16.03	+
May 2014	15.59	–
October 2020	24.29	+
July 2021	15.30	+

cases (Table 3). In two cases (August 2002 and October 2020), the percentage of the area where the anomaly exceeded 2σ was about a quarter, and in June 2011 it was more than a third of the entire area of the strait.

Figure 6 presents spatial distribution of three the most significant negative and positive SST anomalies.

In August 2002, negative deviations from the average long-term values were observed throughout the Tatar Strait, that allows this year to be attributed to the "cold". They were most significant in the northern part of the strait, near its summit the anomaly reached −7 °C. Significant deviations from the norm (up to −6 °C) were detected in the southeast, near La Pérouse Strait. The anomalies were more moderate in the main part of the water area, ranging from −3 to −5 °C, and were weakest near the mainland coast, ranging from −2 to −3 °C. The percentage of the area where the anomaly exceeded the threshold value of 2σ was more than 26 %.

In July 2010, the spatial distribution of the anomaly was similar. The most significant deviations from the norm (about −5 and even −6 °C in certain areas) were observed along the entire east coast of Sakhalin Island, especially in its northern and southern areas. In the central part of the strait, anomalies are not so great (from −2 to −3 °C), they are even less at the shore of the mainland, especially in the area adjacent to the Sovetskaya Gavan (Port of Vanino), where their value is about −0.5 °C. Anomalies exceeding the threshold value of 2σ, occupied about 19 % of the strait, mainly in its eastern part.

In June 2011, negative anomalies were observed throughout the strait. On the main part of the water area, they fell in the range from −3 to −4.5 °C and were the most pronounced, up to −5.5 °C, in the southeastern area. The lowest values were found in the northern part of the strait, in the area of Alexandrovsk-Sakhalinsky, at some distance from the coast (about −1.7 °C). Anomalies exceeding the value of 2σ were noted on 36.5% of the studied area, which indicates unusual thermal conditions in the Tatar Strait.

In August 2006, the positive SST anomalies were detected throughout the Tatar Strait. This year, including the visual assessment on the basis of the graph of average monthly values (see Fig. 2) in the various areas of the studied water area, was considered to be among the most «warm» years. The most significant anomalies were found in the northern and central parts of the strait, ranging from 2.5 to 3.5 °C. In the southern part (near the coast of Primorye south of the 48° parallel, and in the southwestern Sakhalin south of 47° N) the anomalies are somewhat smaller, from 1.3 to 2.8 °C. The area occupied by anomalies exceeding the threshold value of 2σ, was more than 18% of the water area of the strait.

In June 2012, significant positive anomalies were detected in a wide band adjacent to the mainland south of 49° N. In the northern part of the strait and off the west coast of Sakhalin, the anomaly values range mainly between 1 and 2 °C, except for a few spots in the area of Uglegorsk, Cape Lamanon and Crillon Peninsula.

The increased temperature background also persisted in July, primarily in the western part of the strait (the area, where deviations from the norm exceeded 2σ, occupied about 9.5 % of its entire water area). As shown below, this situation is reflected in the time functions of the second and fourth modes of EOF expansion of the SST fields.

Significant positive SST anomalies were also observed in October 2020, mainly along the west coast of Sakhalin. Their value was 4–5.5 °C, and in the area between Boshnyakovo and Pilvo they were especially pronounced (6–6.5 °C). Along the mainland coast, the anomalies are somewhat smaller, but also significant (2.5–3.5 °C)), they were slightly smaller only in the central part of the strait south of 47° N (1–2 °C). The area, where the

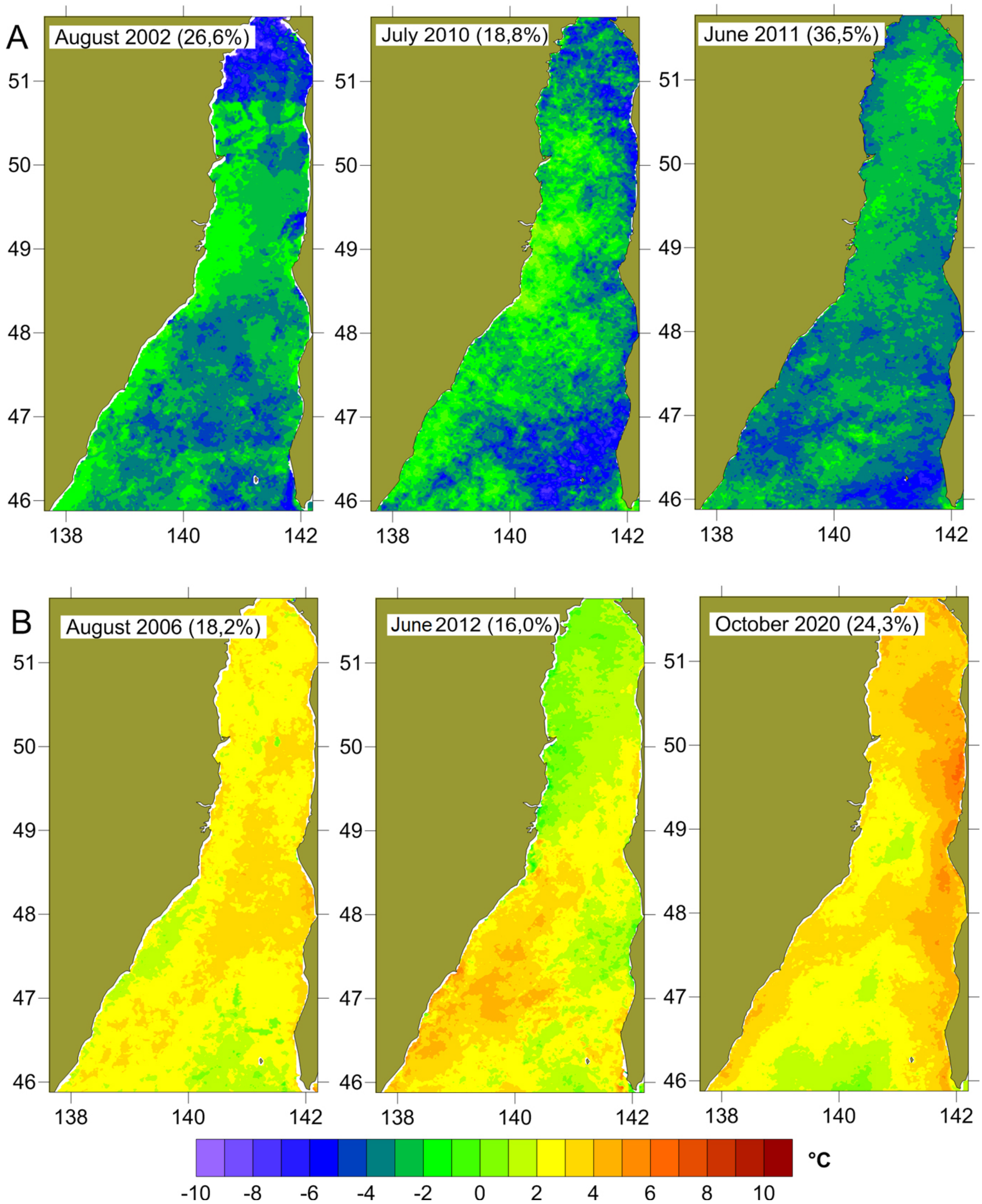

Fig. 6. Spatial distribution of the SST anomalies in "cold" (A) and "warm" (B) years in the waters of the Tatar Strait.

deviations from the norm exceeded 2σ, was about a quarter of the area of the Tatar Strait.

EOF expansion of the SST field

The method of expansion of hydrometeorological fields in empirical orthogonal functions (EOF [20]) was used to determine the features of seasonal and interannual variability. The series with a monthly time averaging were analyzed using this method. The calculation results in the form of spatial distributions of 4 main modes (they account for 97.37; 1.02; 0.28 and 0.16 % of the SST dispersion in the Tatar Strait) are presented in Fig. 7, and their corresponding time functions are shown in Fig. 8. Spatial functions were assumed to be dimensionless and time ones to have a dimension of °C.

In the EOF expansion of seasonally pronounced hydrometeorological fields (sea water or atmospheric air temperature variations are among the most prominent examples of this kind) the first mode is usually associated with seasonal trend and provides an overwhelming contribution to the total variance of the parameter, which, however, does not devalue the role of the higher components.

Thus, the spatial structure of the first mode (Fig. 7) practically repeats that of the SST average distribution in summer, and its time function has a very high correlation with the trend of monthly temperature values in the entire strait (r = 0.996). For this reason, it makes no sense to consider the main component of EOF in detail, except that the time function is well described by a combination of annual and semi-annual harmonics with amplitudes of 0.9 and 0.2 °C, it reaches maximum values in August–September and minimum in February–March.

The first mode characterizes the fluctuations of the parameter, which are cophased throughout the area, though with different intensity in its different parts, that is described by the spatial function of the mode.

The second mode reflects the SST variations, that do not fit into the idea of a parameter changes identical within the entire area, which are reflected by the main mode. Therefore, there are areas with different signs in the spatial distribution, which are separated by a nodal line (the contribution of this mode is insignificant near it). However, its general nature is similar to that of the first mode distribution, it indicates that the second mode in its pure form is an amendment to it. Positive values are typical for shallow areas of the northern part of the Tatar Strait and narrow bands along the coast of the mainland and Sakhalin Island, a maximum of 1.5 is reached in the north, near the Nevelsky Strait. Negative values are typical for the zone of influence of the Tsushima Current, the largest absolute value (about −2) is on the southern boundary of the Tatar Strait. Interannual variability consists in the annual trend modulation, which has already been discussed above.

The average curve of the time function (long-term average values for different months) has positive values in the summer months from June to September with a maximum in August. In the remaining months, this function is negative with the highest absolute values in November–December and March–April. This means that in summer the second mode adjusts the main component, this amendment is positive in the northern part of the strait and coastal zones, and negative in the deep water southern areas. In the cold season, the situation is opposite: in the north its contribution is negative, and in the south it is positive.

In the time function of this mode (the graphs of all time functions are shown in Fig. 8) there are significant interannual variations, while its annual trend is generally maintained. The maximum positive values (respectively, the maximum contribution of the mode to the whole SST field is in accordance with the above characteristics) were noted in July 2012 and 2015, August 2006 and September 2017.

Absolute maximum negative values were found in November 2002, 2005, December 2013 and 2015.

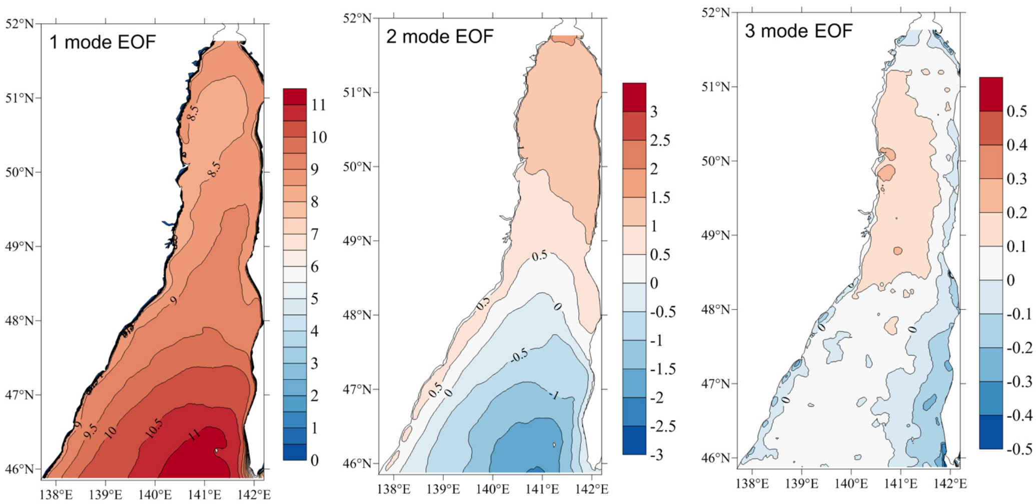

Fig. 7. Spatial distribution of the first three modes of EOF expansion of the SST field (dimensionless).

The third mode is one of the most interesting, very unexpected results, which should be considered in detail, were obtained using it. This is primarily due to a sharp change in the nature of the time function, which relates to 2013–2014. Before that, this function was characterized by a pronounced seasonal trend with maximum values in the summer months (up to +1.5 °C in August) and insignificant negative values in the winter ones (the exception was 1998 with fluctuations of rather random character). Negative but small in magnitude values were observed in summer during two noted transition years, but, since 2015, the seasonal trend character became opposite: a pronounced minimum (up to −2.3 °C in August) is in the summer months, and positive values, which are insignificant in magnitude, are in the cold period. The average value of the time function has also changed sharply, more than 1.4 °C (from 0.46 °C in the first interval to –0.97 °C in the second one), which, according to the method [23], allows to consider the revealed phenomenon as a "regime shift".

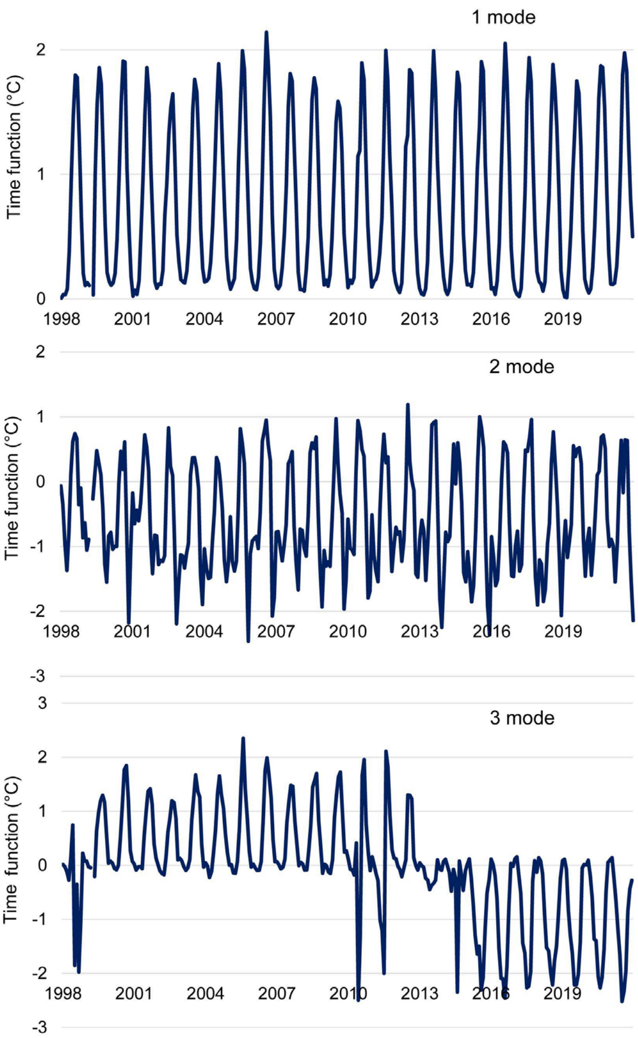

Fig. 8. Graphs of the time functions of the first three modes of EOF expansion of the SST field.

The spatial function of the third mode was characterized by small in magnitude values in the main part of the water area of the strait. The area with positive values occupied the central and western sections of the northern part of the strait, with maximum values of 0.21–0.22 in the vicinity of Cape Surkum. Negative values were found in the narrow coastal zones along the coast of Sakhalin, as well as the mainland south of the 48.5° latitude and in the northernmost section. For the most part, the spatial function values at the coastal area ranged from −0.07 to −0.15, and they reached extreme levels of −0.32 only near La Pérouse Strait.

This means that in the period up to 2013, the third mode provided a positive amendment to the main SST field of about 0.3 °C in magnitude in the northwest of the strait and negative one from −0.15 to −0.4°C in the coastal waters. Since 2015, on the northwestern part of the water area, the amendment changes the sign and increases in absolute magnitude (up to −0.4 °C) in the summer months. In the coastal zone of southwestern Sakhalin, it also changes the sign, becomes positive (from 0.2 to 0.6°C on various parts).

Thus, the total change in SST, conditioned by the contribution of the third mode and associated with the inverting of its time function in 2013–2014, is about 1 °C. For the water areas adjacent to the west and southwest coast of Sakhalin Island, it means warming in the summer months, from July to September. Such a significant change can be considered as a shift of the thermal regime in the eastern part of the Tatar Strait in 2015–2021 compared to the period of 1999–2012. This result is of great applied relevance: in the northern part of the strait, these changes are confined to the traditional zone of commercial accumulation of several species of shrimp, and in the southwest coast of Sakhalin – to the area, where herring and capelin catches have grown significantly in recent years. The authors of [24] attribute this growth to an increase in the temperature background in this area. Note that this area also contains most of the salmon fish farms of the coast of the Sea of Japan of the island. The revealed effect may be of some importance for the survival of salmon fish juveniles in their early marine life.

The spatial distribution of the fourth mode is also interesting, it has zones of different signs near the east and west coasts of the strait (up to +0.6 and −0.6 respectively), and the node line runs from north to south along its central part.

The time function character of this mode is very complex, the annual harmonic clearly dominates at its certain time intervals, but at some periods its influence decreases. The presence of several significant positive (July 2012 and 2013) and even more pronounced negative emissions (October 2001, 2014, 2016, October–November 2021) draws attention. The significant positive anomalies in June and July 2012 were mentioned above. In the first case, some feature was observed in the graph of the time function of the first mode (in the form of a line bend), in the second one, it was in the form of maximums of time functions of the second and fourth modes.

Conclusion

Calculation of the seasonal averaged SST distributions as well as analysis of the spatial function of the first EOF mode showed the SST distribution structure, which was characterized by higher values in the southeast of the water area and lower ones in the northwest, to be generally maintained throughout the year. The only significant difference is the formation of a band of colder water along the west coast of Sakhalin (from the Alexandrovsky Bay to the Chekhov-Ilyinskoye shallow water) in autumn. It is associated with coastal upwelling caused by winds of the northern and northwestern rhumbs typical for the cold season (winter monsoon). The average annual trend of the parameter is well described by the combination of annual and semi-annual harmonics with amplitudes of about 8.4 and 2 °C, their spatial distribution on the studied water area is uniform.

Calculation of linear trend coefficients revealed a downward tendency in surface temperature in the Tatar Strait, most pronounced in winter (in the northern part of the basin) and spring (−0.5… −1 °C/10 years). This may be due to the increased depth of winter convection in the traditionally freezing part of the strait under conditions of a decrease in ice coverage [13].

The study of the considerable SST deviations from the long-term averages showed that the remarkable anomalies, exceeding twice the standard deviation of the parameter in the cell, were formed in this basin, and on a significant part of its surface area (in nine cases more than 15 % of the area). The number of positive and negative anomalies was about the same. The most significant anomalies were found in the northern and southeastern parts of the strait.

Quasi-cyclical fluctuations with a period of about six years and an amplitude of about 1 °C are distinguished in the variations of the average curves of the SST trend (as well as in the time function of the EOF main mode) over the various areas of the Tatar Strait. The EOF expansion of the SST field reveals an interesting fact, associated with the sharp change in the nature of the time function of the third mode, which occurred in 2013–2014. Until 2013, this function was characterized by maximum values in the summer months and small negative values in the winter ones, but, since 2015, seasonal trend has taken an opposite character. Such changes can be characterized as a climatic shift in the studied area. It is most pronounced in the northwestern part of the strait and in the southwest coast of Sakhalin Island (about 1 °C). Several shrimp species and commercial fish populations may be significantly affected.

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