Chapter

Analysis of Spatiotemporal Variability of Surface Temperature of Okhotsk Sea and Adjacent Waters Using Satellite Data

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Abstract

The chapter is divided into 5 parts. The first part describes what the satellite data is and describes the levels of its processing. In the second part, attention is paid to sea surface temperature anomalies, the conditions for the appearance of the most significant anomalies and their influence on the behavior and survival of aquatic organisms are described. The third part is devoted to calculating linear trends in ocean surface temperature from a 20-year series of satellite data. It is shown that the heat content of the surface layer of Okhotsk Sea decreases, most significantly in its northern and western parts. This trend is especially pronounced in the spring, which may be due to a decrease in ice cover and a more significant cooling of the waters due to winter convection. In the fourth part, periodic fluctuations in the temperature of the surface of the ocean are considered. It is demonstrated how, using the calculated trend and several basic harmonics, one can try to predict the temperature next year. And the last part concludes the chapter.

Keywords: satellite data, sea surface temperature, Tsushima current, Okhotsk Sea, regional effects of global warming, SST anomalies, trends, harmonic, cyclicity

1. Introduction

The study of the thermal regime of various water areas is one of the most important oceanological problems, since the spatio-temporal variability of water temperature reflects complex processes of formation, transformation and dynamics of water masses. In addition, temperature is one of the key parameters that determine the conditions for the existence and development of most species of aquatic organisms; therefore, the study of this problem is also of key importance for hydrobiology. The zoning of water areas by the nature of temperature conditions, as well as their forecasting, taking into account the peculiarities of seasonal and interannual variability, is an important scientific task, which also has a pronounced applied aspect associated with the fact that accumulations of some species of commercial fish are confined to the zones of separation of water masses with different characteristics.

Direct measurements are a traditional source of water temperature data. Their accuracy depends only on the accuracy of the device, and the discreteness depends on the specific task (in some cases it can reach a fraction of a second). They can also be used to construct vertical profiles with high vertical resolution. However, recently the number of expeditions has been steadily declining, and the data obtained through direct measurements are point and irregular and are not suitable for studying large-scale phenomena or for obtaining data from hard-to-reach places.

Satellite data, on the other hand, are regular and allow covering the entire water area of the studied basin. Therefore, they are very good sources for studying seasonal and interannual variations in the temperature of the surface layer (the thickness of which ranges from 1 to 10 meters). The disadvantage of these data is the strong dependence of accuracy on cloudiness (especially in the infrared and visible ranges). Ideally, they should be regularly compared with direct measurements in order to identify errors in data interpretation.

For scientific purposes, data are usually used from satellites located either in a geosynchronous (in a particular case, geostationary orbit) or in a heliosynchronous orbit. The advantage of the geostationary orbit is obvious: you can get a picture of the same area with discreteness of up to half an hour, and after pointing to the satellite, a constant correction of the antenna position is not required. It is very useful for telecommunication systems as well as for obtaining meteorological data. The disadvantage is the lack of coverage at polar latitudes.

This disadvantage is easily eliminated by satellites in a polar sun-synchronous orbit. A sun-synchronous orbit is important to science because it keeps the angle of incidence of sunlight on the Earth's surface more or less constant, although the angle will change with the change of seasons. Without a sun-synchronous orbit, you would have to account for changes in shadow and lighting angles, making it difficult to track changes over time. It would simply be impossible to collect the information needed to study climate change.

In 1997, a TeraScan satellite receiving station was installed at SakhNIRO, with the help of which data are received from the NOAA, Metop, Aqua and Terra satellites in a polar sun-synchronous orbit (**Figure 1** [1]). At the moment, a 21-year series of satellite data on the temperature of the surface of the Sea of Okhotsk and adjacent waters has been accumulated, which makes it possible to analyze the interannual variations of this parameter.

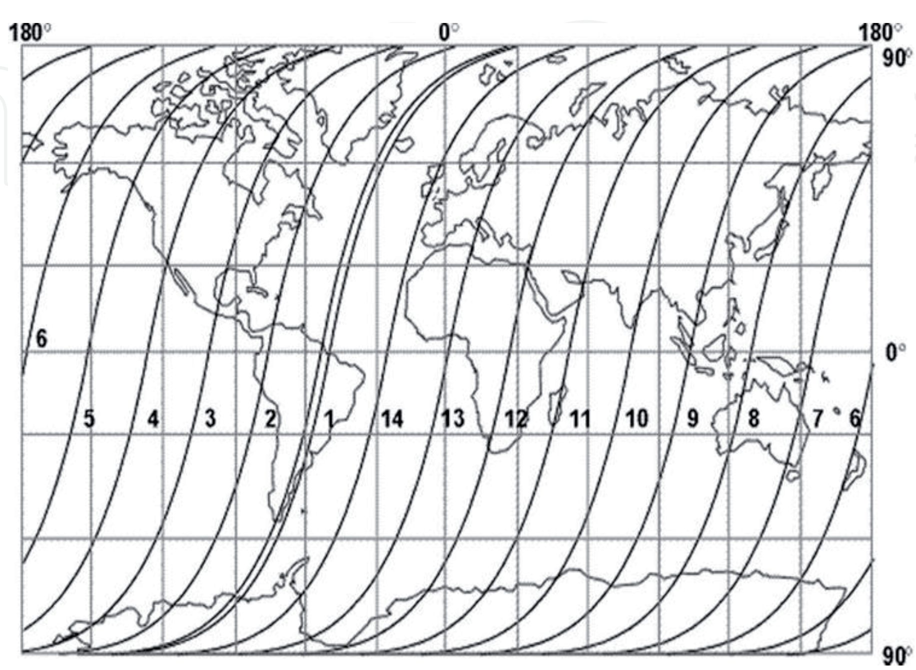

Figure 1.
Example of a sun-synchronous orbit for a NOAA satellite [1].

This chapter is organized as follows:

- Section 2 discusses satellite data
- Section 3 discusses Sea Surface Temperature (SST) anomalies
- Section 4 analyzes long-term data series using linear regression
- Section 5 presents results on periodic SST fluctuations
- Section 6 concludes the chapter.

2. Satellite data

What is satellite data? An electromagnetic (EM) signal with certain characteristics leaves the sea and contains information about the primary observable quantities, which are light, radiation temperature, roughness and sea level. This signal travels through the atmosphere, where it can be distorted, and where noise is added to the signal before it is received by a sensor that registers certain properties of the radiation and converts each measurement into a digital signal to be encoded and sent back to earth. The sensor geometry limits each individual observation to a specific instantaneous field of view.

In order to convert a digital signal received at a ground station into a useful one for scientific measurements with a certain accuracy and quality, the process of obtaining data by the sensor should be numerically transformed using knowledge about signal processing technology, physical and technical properties of the sensor, the physics of the atmosphere, and the interaction of EM radiation with the ocean and near-surface processes in the ocean. The process of extracting data from a unique observation location in space is at the heart of the satellite data feature.

Table 1 summarizes 5 levels of satellite data processing.

Using the TeraScan software, raw data received from satellites is automatically calibrated and atmospheric correction, as well as georeferencing of data and projection onto a standard map (selection of parameters, projections, etc., is performed

Level	Product description
0	Raw satellite data in binary format.
1	Image in measurement coordinates. Satellite data of individual calibrated channels.
1,5 (or 1A)	In special cases, a Level 1 product with atmospheric correction applied.
2	Atmospheric corrected and calibrated product containing upstream values or directly variable ocean response with reference to geographic coordinates, but most often not mapped.
3	Composite images of the obtained ocean variables transferred to a standard map, obtained by averaging over space and time of several flights in the form of a level 2 product. This product contains data from only one sensor and may have gaps.
4	An image representing the ocean variable averaged within each cell of the spatio-temporal grid, for the creation of which the gaps in the level 3 product data are filled with data analysis methods, incl. Interpolation. In the course of the analysis, it is possible to use several level 2 or 3 products from different sensors, and it is also possible to use data from field observations or model calculations.

Table 1.
A summary of various satellite data processing levels.

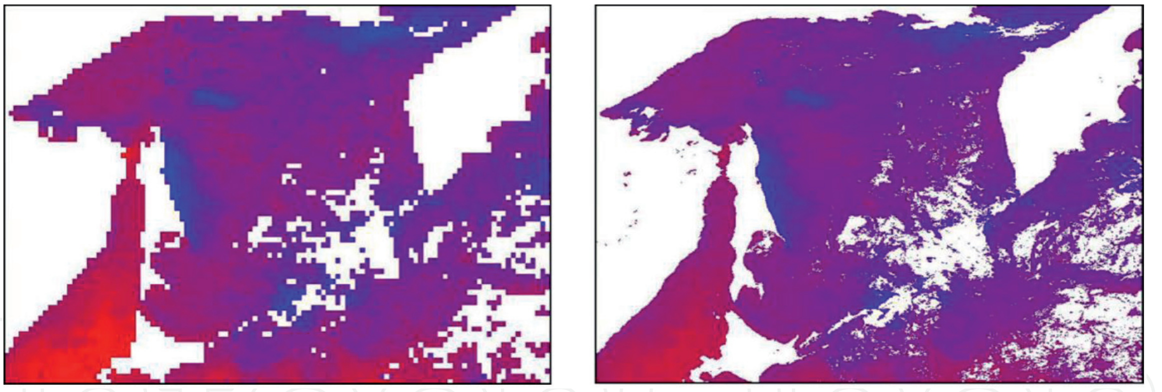

Figure 2.
An example of a ten-day average image with a spatial resolution of 0.25 × 0.25 degrees (left) and 2 × 2 km (right) [2].

once by the operator, after which it is performed in automatic mode). Then data with different spatial resolution (the maximum resolution for a set of satellites is 2 km, images with a spatial resolution of 250 m can be obtained on separate channels) are entered into the database, where the operator manually corrects each image (eliminates gross errors that most often appear in the case of the presence of semi-transparent clouds). After that, daily data averaging is performed. As the data accumulate, ten-day and monthly averaging is also performed (as shown in **Figure 2** [2]), as well as the calculation of anomalies (deviations from the long-term average value in a specified decade or month, obtained over a number of previous years).

The resulting data set should be carefully analyzed. Determination of the characteristics of unidirectional trends, as well as the amplitudes and phases of cyclic components and the possibility of using them to predict thermal conditions in the next season constituting the content of this study.

3. SST anomalies

There are two types of SST anomalies as for any parameter distributed in space and time. The first is the sharp deviation of the specified parameter from the mean values in the neighboring areas. Anomalies of this kind can be regular and even present on average long-term maps (**Figure 3** [3]). Typical examples from the point of view of SST are upwelling zones (quasi-stationary), mouths of large rivers, as well as zones of influence of warm and cold currents. Some anomalies of this nature may be unstable and dependent on weather conditions. Such anomalies determine the behavior of aquatic organisms, since each species has its own conditions of existence and development (some species need colder water, and some are more comfortable in warmer water).

The second type of SST anomaly is a deviation from the multiyear average. This type of anomaly depends entirely on the current conditions and reflects the peculiarities of the distribution of the parameter in a given year. From the point of view of SST, this may mean more or less intense heating or cooling than usual. The appearance of such anomalies can lead to a change in the timing of the fish's approach to spawning (**Figure 3** [3]) or to migration to places with more favorable conditions, and in the early stages of development it can lead to death from unfavorable conditions.

Let us consider in more detail the extraordinary conditions that took place in the spring of 2011, when the greatest delay in the release of juveniles from the Sakhalin SFHs was noted. The spatial distributions of sea surface temperature anomalies observed during the period under consideration, which is strongly characterized by unusual conditions (**Figure 4** [4]), are quite remarkable.

In the third decade of May (**Figure 4A**), significant negative deviations from the norm were noted along the entire eastern coast of Sakhalin Island and in the Aniva Gulf; they were the largest (up to 3°C) in the basin of the Mordvinova Gulf. Judging by the zone of negative anomalies stretching from the Terpeniya Peninsula along the line of the depth increase, which corresponds to the core of the East Sakhalin Current [5], they were caused by the outflow of cold water and ice-cover remains from the northeastern shelf. This opinion is confirmed by a satellite image on June 2, 2011 (**Figure 3** [3]), which clearly shows the transport of drifting ice from the north to the Terpeniya Peninsula and further towards the Mordvinova Gulf. Such a situation is observed relatively rarely: usually, under the influence of the southern winds characteristic of this period of the year, the ice that is transported from the Sakhalin Gulf is blocked at the northeastern tip of the island and does not move south of 52° N. A similar ice removal was observed in spring 2005 [6]. Then, due to the unusual distribution of the surface atmospheric pressure, the northeastern

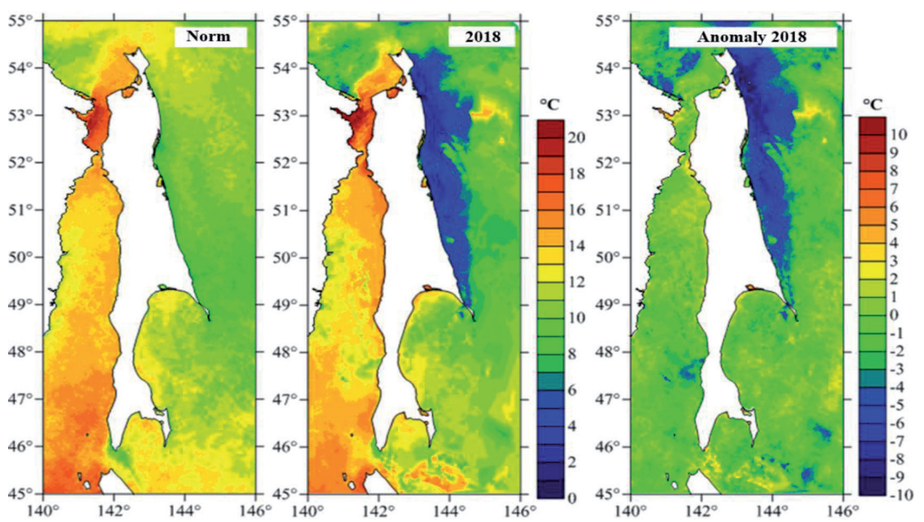

Figure 3.
An example of the long-term average distribution of SST, the actual temperature in the second decade of July 2018 and the 2018 anomaly relative to the multi-year average (these conditions led to a two-week delay in the approach of pink salmon to spawning rivers) [3].

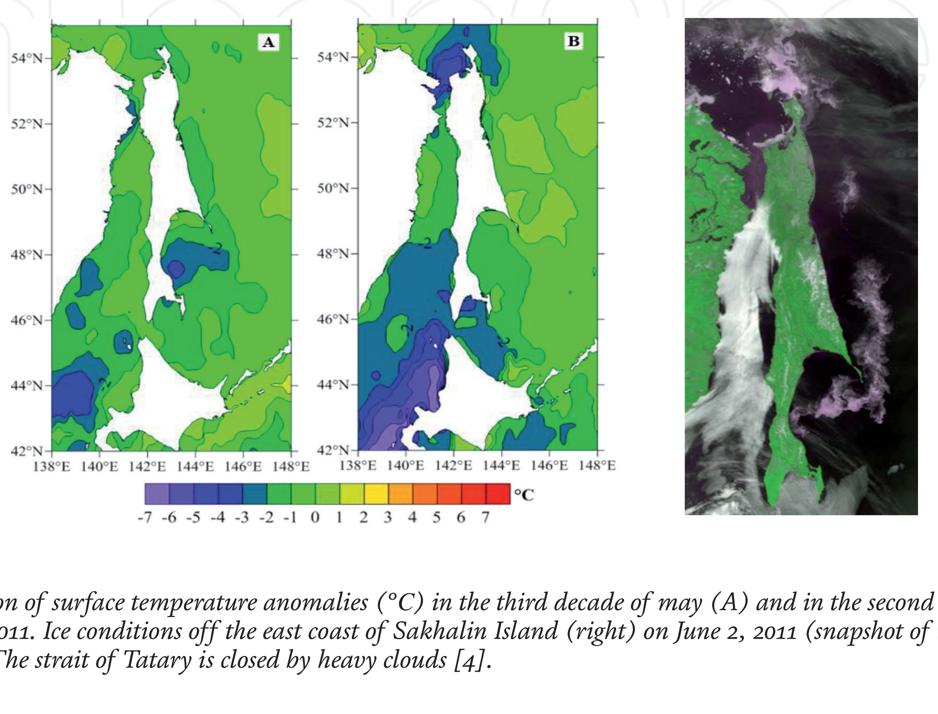

Figure 4.
Distribution of surface temperature anomalies (°C) in the third decade of may (A) and in the second decade of June (B) 2011. Ice conditions off the east coast of Sakhalin Island (right) on June 2, 2011 (snapshot of the aqua satellite). The strait of Tatary is closed by heavy clouds [4].

winds prevailed in the study region, which just contribute to the transport of drifting ice to the southeastern coast of Sakhalin Island, as well as to the estuarine regions of the Naiba and Ai rivers and to the Mordvinova Gulf.

In spring 2011, the distribution of surface atmospheric pressure also significantly differed from the characteristic one in the given period of the year. For example, in the third decade of May, the high-pressure region was located in the southern part of the Sea of Okhotsk, above the Kuril Basin (**Figure 5A** [7]). Usually this area is located in the eastern part of the sea, and air flows directed to the north are formed above this basin. When the pressure distribution has this structure, the atmospheric circulation typical for the summer monsoon is not formed; in principle, it was weakly expressed, since the pressure gradients were small and cold waters with low salinity moved freely to the south, transporting drifting ice.

Subsequently, the high-pressure region shifted from the sea to the Pacific Ocean. In particular, in the second decade of June, zonal, northeast-oriented air flows prevailed, which is not typical for the warm season (**Figure 5B** [7]).

However, it is unlikely that only the peculiarities of the synoptic conditions can explain the significant negative temperature anomalies of the sea surface in the northern part of the Sea of Japan, primarily in the main zone of the Tsushima Current influence, off the west coast of Hokkaido Island (up to 5–6°C). Another zone with approximately the same negative anomalies was noted in the zone of the influence of the Amur River runoff in the region of its mouth, in the western part of the Amur Estuary, and in a significant part of the Sakhalin Gulf, as well as on the northeastern shelf of Sakhalin Island (up to about 52° N). Pronounced negative anomalies were observed both on the southwestern and southeastern coasts of Sakhalin Island, as well as in the Aniva Gulf. It is difficult to explain the cause of such a heat deficit in the surface waters of a very wide basin: one of them could be a decrease in the intensity of the Tsushima Current, whose quasi-periodic fluctuations (a cycle with a period of 5–6 years is especially distinguished) have a significant influence on the climate of the Sakhalin-Kuril region [8]. It is also difficult to assess how often such situations can be observed which have led to a delay in the release of juveniles from Sakhalin SFHs lasting from 3 weeks to a month. Probably, due to the low temperature of coastal waters observed for a long time, there could be a mass death of juveniles of natural origin which rolled along the spawning rivers of the island.

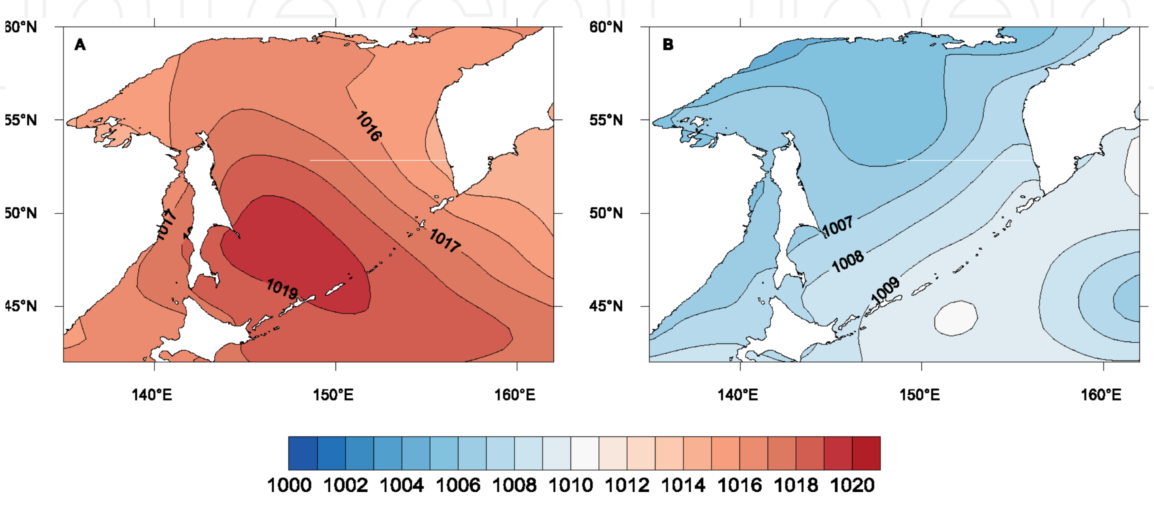

Figure 5.
Distribution of surface pressure (hPa) over the Sea of Okhotsk in the third decade of may (A) and the second decade of June (B) 2011 [7].

4. Linear trends

When analyzing long-term data series, a question arises – are there unidirectional tendencies of one or another parameter in the specified period of time? This is especially important in the context of global warming, the most noticeable results of which are an increase in winter air temperature in the Arctic latitudes and a decrease in ice cover (area of the water area covered with ice) both in the Arctic Ocean and in the Sea of Okhotsk.

In order to answer this question, in each spatial cell of the 1000 × 1022 matrix, covering the investigated water area (42–60°N and 135–163°E), the linear trend coefficients were calculated using the least squares method, meaning the temperature increase over the year … The calculation was carried out on a 20-year series of data for each month separately, for annual averages, as well as for average temperatures for the season. The seasons for the calculations are shifted by a month relative to the calendar ones due to the specifics of the region: January–March (winter), April–June (spring), July–September (summer) and October–December (autumn).

The linear trend coefficients calculated from the full annual series in the study region are mostly negative, and there are no regions with positive values in the Sea of Okhotsk (**Figure 6** [9]). Significant cooling of the surface layer (about 1.5°C over 10 years) was observed in the northern and western parts of the sea; most clearly this process is manifested in the northern part of the sea at some distance from the coast. A less pronounced decrease (at a rate of about 0.5°C over 10 years) is observed in the Kuril Islands and in the band along the western coast of Kamchatka beyond the shelf zone, as well as in the influence zone of the Amur River outflow (Amur Estuary, Sakhalin Bay, northern shelf of Sakhalin Island).

A significant decrease (more than 0.5°C over 10 years) was found in the northern part of the Strait of Tatary; further southward, the cooling rate of surface waters decreases and, south of 45° S, a slight increase in the temperature of the surface waters in the Sea of Japan was recorded. The warming process is more pronounced in the northwestern part of the Pacific Ocean, i.e., in the southeastern part of the study region.

Let us now consider the results of calculating the parameters of the linear trend in different seasons. In winter, there is not enough data for a reliable calculation in the northwestern part of the sea (the "Sea of Okhotsk fridge"), on the northern shelf of the sea, and on the northeastern shelf of Sakhalin. In many regions of the basin, where the ice cover is significantly influenced, the calculation is not reliable enough; nevertheless, some ideas of the trends in the thermal regime during the cold period can be put forward.

In the entire Sea of Okhotsk, especially in the northern and western parts of the sea, as well as in the Strait of Tatary of the Sea of Japan and in the regions of the Pacific Ocean adjacent to the Kuril Islands, there is a tendency for the temperature decrease in the surface layer. Signs of the opposite trend are recorded only in the southeastern part of the study region, in the Pacific Ocean, in the northern part of the Sea of Japan, and in the very southern part of the Strait of Tatary (south of 47° N).

The most pronounced decrease in the surface layer temperature is in the springtime. It covers the entire study region, including the northwestern part of the Pacific Ocean, and it is particularly significant in the northern and western parts of the Sea of Okhotsk (the rates of temperature decrease range from 1.0 to 1.5°C over 10 years and even higher in some regions).

The cooling of the surface layer in spring is the most evident consequence of a decrease in ice cover, since in the absence of the ice cover the cooling processes

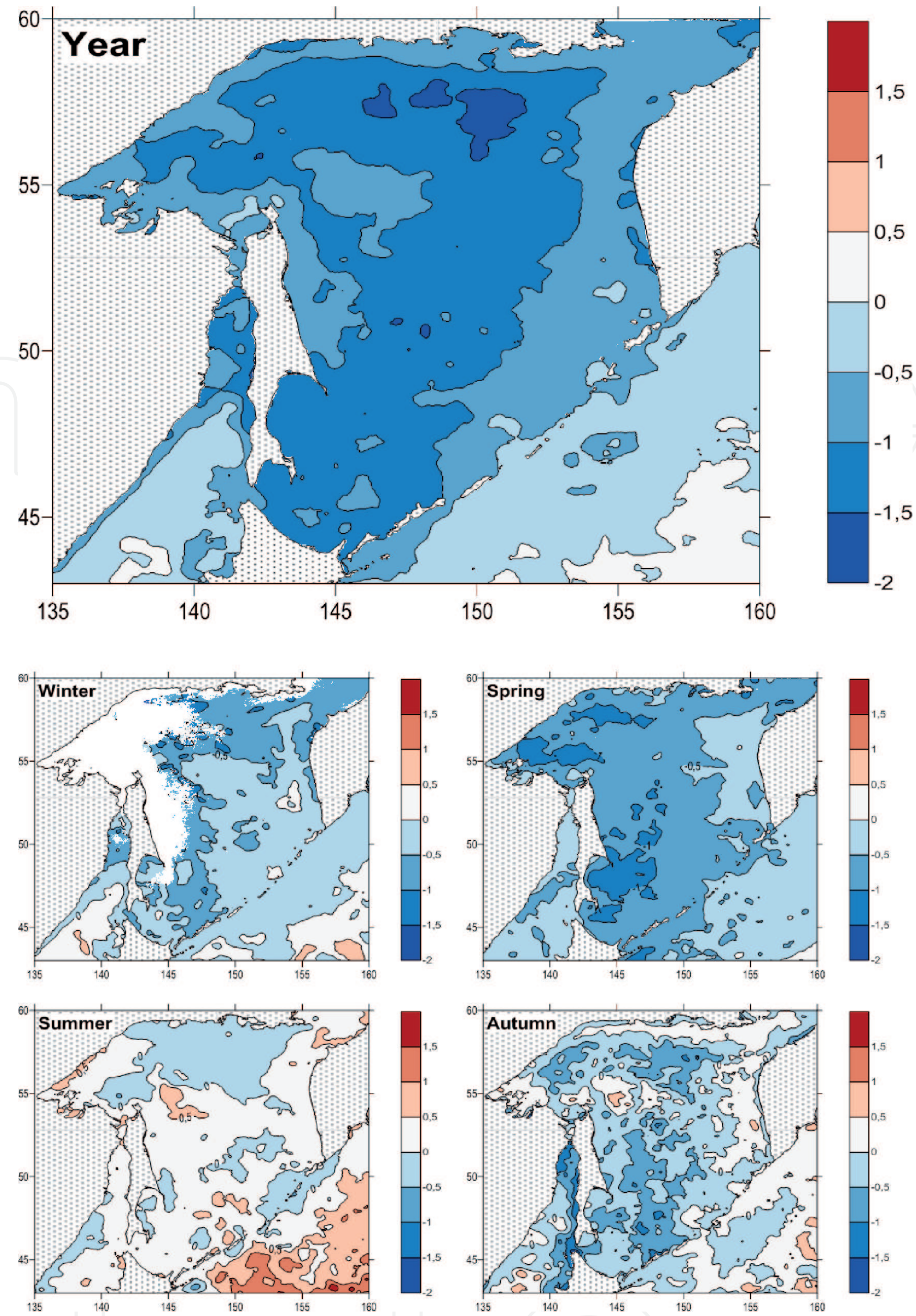

Figure 6.
Distribution of linear trend coefficients by number of average annual (above) and average seasonal values. The scale corresponds to degrees celsius over 10 years [9].

cover a layer of water thicker than in the presence of the ice cover. Undoubtedly, this has a significant impact on the climate of the region and, above all, on the weather conditions of Sakhalin, which are the most affected by this process.

While calculating the trends in sea surface temperature in individual months, it was found that the most intense cooling is observed in the month of May, especially in the northwestern part of the Sea of Okhotsk and along the entire eastern coast of Sakhalin Island from Cape Elizabeth in the north to Cape Aniva in the south. Exceptions are the western part of the Amur Estuary, which accounts for the bulk of the Amur flood, and the basin adjacent to Tauiskaya Bay. It is obvious that the hydrological regime of coastal areas experiencing the influence of the river outflow differs from that typical for the Sea of Okhotsk as a whole.

In summertime, the region is dominated by an increase in the sea surface temperature most pronounced in the northwestern part of the Pacific Ocean. In the Sea of Okhotsk, it is noted in its northwestern part, in the region of the Shantar Islands, in Sakhalin Bay, and in the Amur Estuary, to the east of the northern tip of Sakhalin Island, at the northwestern coast of the Kamchatka Peninsula, and near the Urup and Simushir islands.

In the northern part of the sea, near the Kuril Islands, on the southeastern coast of Sakhalin Island and along the Primorye coast in the Sea of Japan, there is a trend towards a decrease in temperature, although it is more moderate than in springtime. Moreover, in July, the tendency towards a decrease in the sea surface temperature still prevails in the study region; the trend changes only in the northwestern part of the Pacific Ocean. In August, in these regions, warming reaches the highest rates (about 1.5°C over 10 years); the temperature increase was noted in the central part of the Sea of Okhotsk, along the western coast of Kamchatka and off the southeastern coast of Sakhalin, in the Strait of Tatary and the Amur Estuary. In the northern part of the sea, on the northeastern shelf of Sakhalin, and in the Kuril region, the trend towards a decrease in sea water temperature continues.

In September, on the contrary, the intensity of warming in the Pacific Ocean decreases; the greatest warming rate was noted in the northern and northwestern parts of the sea (especially in the shelf zone between Ayan and Okhotsk settlements).

A diffuse pattern is observed in the fall. Relatively small negative trends prevail in the greater part of the Sea of Okhotsk; positive trends (also insignificant) are noted in the eastern part of the sea on the western shelf of Kamchatka and in a relatively narrow band along the northern coast. Smaller areas were also found in the Shantar Islands and Kashevarov Banks and in the southwestern part of the analyzed basin of the Sea of Japan.

The highest rates of the temperature decrease in the surface layer are observed in the Strait of Tatary, in its northern part, and along the western coast of Sakhalin, as well as in the Sea of Okhotsk, in the northern part of it, beyond the shelf, off the southeastern coast of Sakhalin, and also in the band between 145° and 150° E from the Urup and Iturup islands to the Kashevarov Banks.

It was found in the calculations for individual months that a positive trend prevailed in October, and the trend reversed in November and December.

In the work [10], it was found that, in the Sea of Okhotsk and in the region of the Kuril Islands, negative trends were also noted in the spring months; the largest positive trends were recorded in October. Similarity results become very interesting if we take into account the differences in the studied time periods and spatial characteristics of the regions in which the trends were calculated. In the Sea of Japan, no negative trends were identified in this work.

As a result of the analysis of data on the surface temperature of the Sea of Okhotsk over a 20-year period (1998–2017), it was found that the global climate change in this basin caused a decrease in the ice cover and a decrease in the temperature of the upper water layer during the winter–spring period. The negative trends in temperature in the spring in the northern and western parts of the study region, as well as in the Strait of Tatary of the Sea of Japan (from 0.5° to 1.5°C over 10 years), are especially large. This effect in the reduction of the ice cover, both in time and in space, is the most evident and can be explained by an increase in the depth of winter convection. The predominance of a decrease in sea surface temperature, although less pronounced, was also noted in winter and autumn, and generally throughout the year.

In summer, the region is dominated by an increase in sea surface temperature, most pronounced in the northwestern part of the Pacific Ocean. In the Sea of Okhotsk, it was noted in its northwestern part, east of the northern tip of Sakhalin Island, off the northwestern coast of the Kamchatka Peninsula, as well as in some other regions. Moreover, in July, the main role belongs to the processes of cooling of the surface layer; the change in the trend occurs in August and continues in September–October.

These processes play a significant role in the climate variations in the Sea of Okhotsk; in particular, a decrease in the temperature of sea water is noted in the coastal waters of Sakhalin Island. In addition to the weather conditions, the results are important for studying the habitat conditions of commercial fish species and invertebrates in the basin, which is of great fishery importance.

5. Periodic fluctuations

If you look closely at the graph of the course of the mean monthly SST (**Figure 7** [11]), then in addition to seasonal fluctuations, you can notice interannual variations. They are especially pronounced in August, when the mean monthly water temperature reaches its maximum value, and are expressed in the modulation of the annual harmonic. Moreover, these oscillations are of a quasiperiodic nature, most likely associated with certain phenomena in the atmosphere and hydrosphere.

Any periodic oscillations can be described by knowing their amplitude, phase and period. Using the least squares method, you can find the corresponding amplitude and phase for each selected period. Thus, it is possible to establish a kind of "influence zones" of harmonics with a certain period, i.e. areas in which the amplitude of one or another harmonic exceeds a certain threshold value. And in order not to interfere in the calculations with long-term components (the period of which exceeds half the length of the series), the trend obtained according to the method described in the previous section was subtracted from the initial data.

The distribution of the amplitudes of temperature fluctuations in the studied region is rather complex. Having determined in each spatial cell the period corresponding to the largest amplitude and displaying the obtained data on the screen, we have established several main periods that play a significant role in interannual SST variations in most cases. For a series of 21 years, it is not entirely correct to calculate fluctuations with a period exceeding 11 years. Short-period fluctuations are unstable and generally have little information. Thus, the spatial distributions of harmonic amplitudes with a period from 3 to 11 years were considered in detail.

In most of the studied water area, the main role was played by variations with a period of about 5.5–6 years (on the graphs for points 2, 5 and 8 in **Figure 8**, you can see that the largest amplitude at these points corresponds to a period of 66–68 months), the spatial distribution of the amplitude with a period of 6 years is shown in **Figure 9** [12]. The zone of its influence is the most extensive and occupies

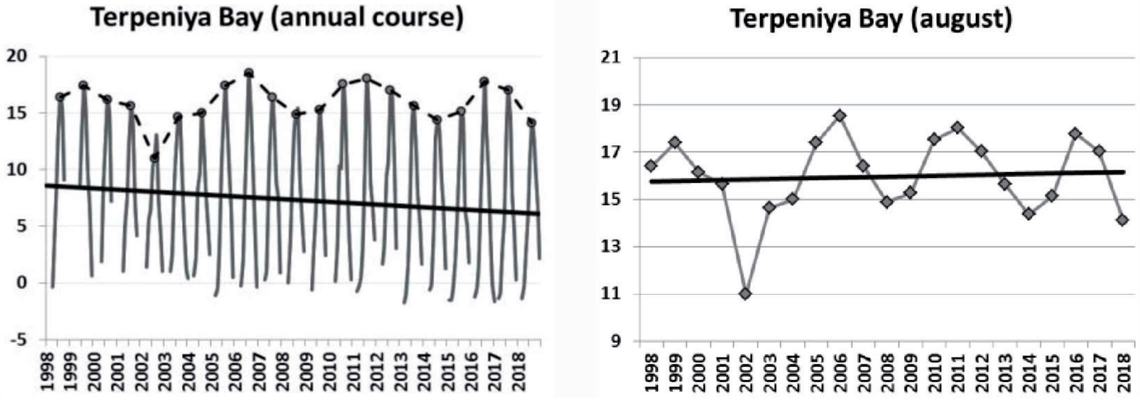

Figure 7.
Annual variation of average monthly temperature (left) and average temperature in august (right) [11].

the southern half of the Sea of Okhotsk and the northern part of the Sea of Japan, up to the Amur estuary. The amplitude of this harmonic in the zone of its influence ranges from 1 to 2°C. In the vicinity of the Kuril Islands, off the western coast of about. Hokkaido, off the northeastern coast of about. Sakhalin, the amplitude is slightly lower (from 0.5 to 1°C). Further to the north, starting from 52 N, its influence decreases and practically disappears.

In [8], based on the EOF decomposition of the sea surface temperature in the North Pacific Ocean, it was shown that an oscillation with a similar period is characteristic of the entire region influenced by the Kuroshio Current and its branch, the warm Tsushima Current. This is evidenced by the large amplitudes in the zone of the indicated currents and in **Figure 9**. Consequently, as a result of this study, it was possible to estimate the boundaries of the influence of this component in the Sea of Okhotsk, which runs parallel to the islands of the Kuril ridge and divides this basin into two practically equal parts. The entire northern Sea of Japan is significantly affected by this cycle.

As seen from **Figure 8**, at most points, one can also note peaks in the range of periods from two to three years. The highest values of the amplitude of the 3-year harmonic can be noted in the northwestern part of the Sea of Okhotsk, at a distance from the coast, as well as near the northwestern coast of Kamchatka and in the strip from 47 to 49^0 N. and from 147 to 149^0 E. in the area of the Kuril deep-water basin and in the northwestern part of the Pacific Ocean. However, the amplitudes of these oscillations are somewhat lower than those of the six-year harmonic (from 1 to 1.5°C). At a distance from these regions, the amplitude gradually decreases to zero.

The spatial distribution of the amplitudes of the cyclic component with a period of 5 years differs markedly from that considered above for a period of 6 years. The zone of its influence is noticeably narrower, it is concentrated mainly on the northern shelf of Hokkaido, in the region of the South Kuril Islands (vast waters both on

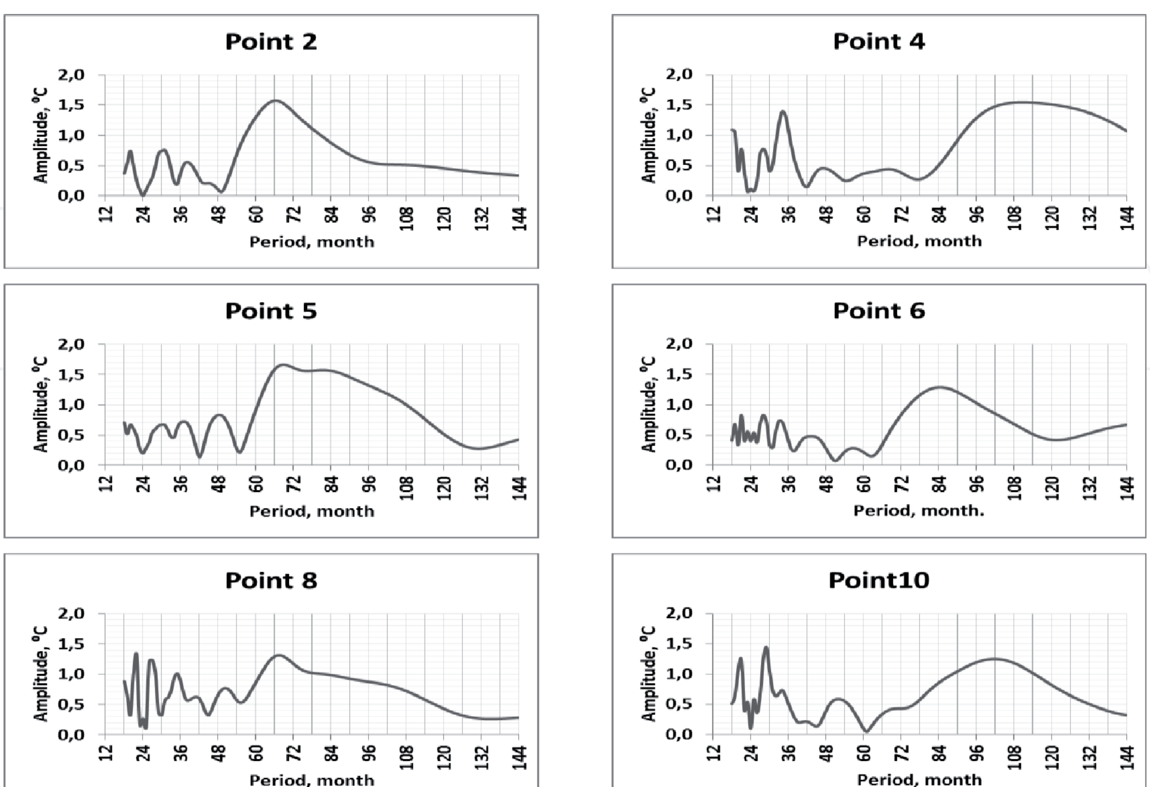

Figure 8.
*Examples of graphs of the dependence of the amplitude of the harmonic (in °C) from its period (in months). The location of the points is shown in **Figure 9** [12].*

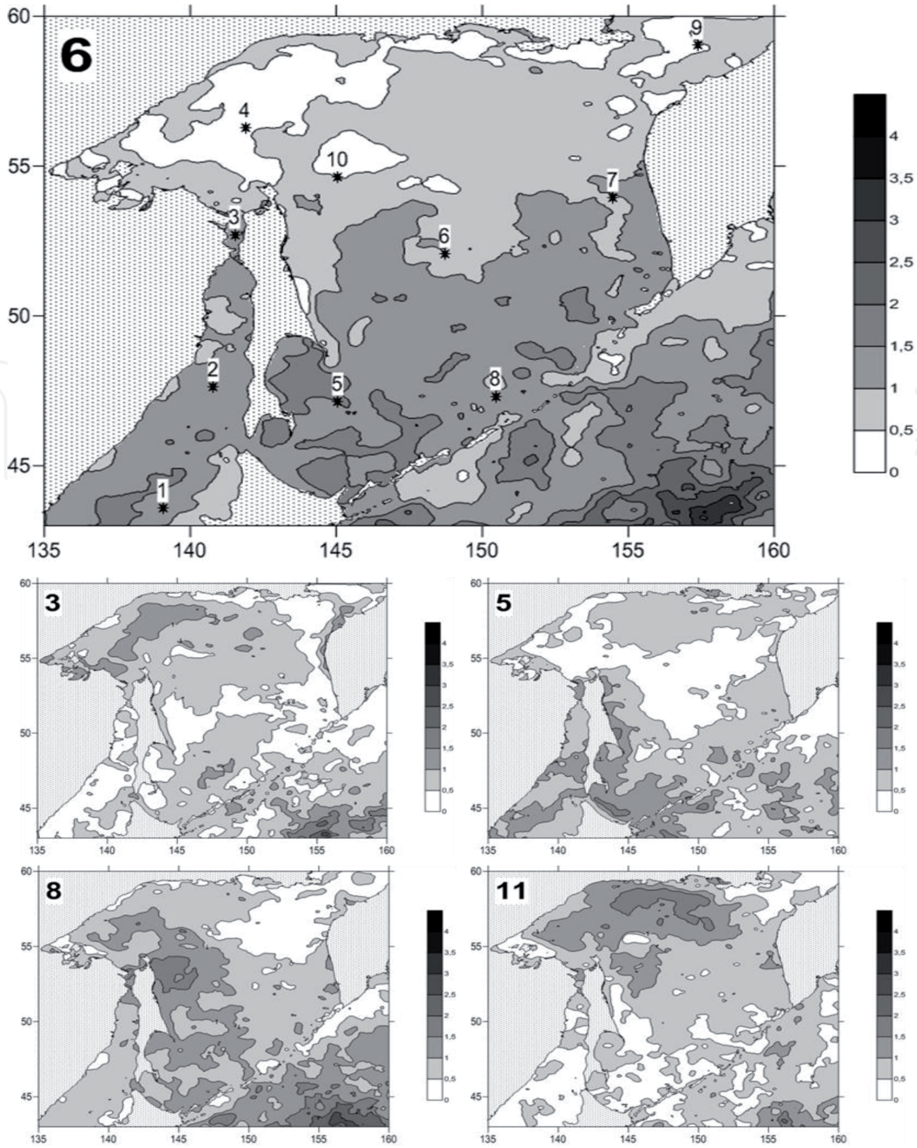

Figure 9.
Distribution of amplitudes (in °C) of interannual fluctuations in the mean monthly sea surface temperature (august) with a certain period (indicated in years in the upper left corner of the image) [12].

the Sea of Okhotsk and on the ocean sides), and, surprisingly, on the northeastern shelf of Sakhalin, where the influence of a lower frequency component was not noted. In the Tatar Strait, its role is also noticeable, but expressed to a lesser extent than the 6-year harmonic.

In the western part of the Sea of Okhotsk and the northwestern part of the Pacific Ocean, a cyclical component with a period of about 8 years is significantly manifested. The zone of influence of the Amur river runoff in summer is clearly distinguished in the spatial distribution - the Amur estuary, the southern and eastern parts of the Sakhalin Bay, the area between the Schmidt Peninsula and the Kashevarov Bank [13]. It is interesting that in the area of the Kuroshio Current manifestation, this component has large amplitudes, in the Tsushima Current zone in the Sea of Japan - insignificant, while on the northern shelf of Hokkaido and on the Sea of Okhotsk side of the Southern Kuril Islands, where the warming effect of the Soya Current affects, the amplitudes are significantly.

The lowest frequency of the considered harmonics with a period of 11 years is manifested in the northern part of the Sea of Okhotsk; in other parts of the study area, its role is insignificant. It is rather difficult to put forward a reasonable hypothesis that could explain such significant differences in the very long-term variations in SST in different parts of the same basin. It can only be assumed that due to the comparative shallowness of the northern region, the effect of the winds of the southern rumba and the greater number of sunny days than in the southern part, due to the lesser influence of cloudiness, the influence of the solar cycle is more noticeable here.

Attention is drawn to the fact how the zones of manifestation of harmonics shift with a period of 5 to 11 years. If the zone of influence of the 5-year harmonic is focused near the islands of Sakhalin, Hokkaido and the Southern Kuriles, then with an increase in the period, the region with the highest amplitude shifts clockwise (towards the northeastern coast of Sakhalin and further to the northern part of the Sea of Okhotsk). This interesting fact is also difficult to give a reasonable explanation, it requires additional study.

In work [8], a method was developed for predicting thermal conditions for a year in advance in certain areas of the studied water area (this method was also used to recover data gaps associated with the influence of cloudiness or technical reasons), which consisted in calculating the temperature in a given square in time t according to the formula:

$$T(t) = at + b + \sum_{k=1}^{N} c_k \cos(\omega_k t - \varphi_k) \tag{1}$$

where a and b are the parameters of the linear trend, ck are the amplitudes, and φk are the phases of the cyclic components (harmonics) of sea surface temperature variations. An essential feature of the method is the fact that the amplitudes and phases of the main cyclical components are calculated by the least squares method, with their periods ranging from 18 to 144 months with a step of 1 month. For each cell, a set of 3–4 harmonics was determined, which make the largest contribution to the interannual variations in SST. Since they are not orthogonal, for forecasting using formula (1), it is necessary to subtract the calculated wave from the initial series before determining the parameters of the next one in order to avoid double inclusion of coherent components (in [14, 15]) such a technique was called "Sequential spectra method").

Based on the parameters of the obtained cyclic components, a retrospective forecast of thermal conditions for the summer of 2018 was carried out (observational data for 1998–2017 were used to calculate the parameters of harmonics and a linear trend). The calculation was carried out for each spatial cell according to formula (1), taking into account the trend and four harmonic components with the highest amplitudes. For the forecast, periods from 18 to 144 months were covered. The calculation results are presented in **Figure 8** in the form of graphs of forecast curves and real variations in sea surface temperature, including the predicted values that took place in the summer of 2018. **Figure 10** shows the spatial distribution of the difference between the predicted and actual temperatures for August 2017 and 2018. The forecast was built for a year ahead along the entire previous series.

The curves, which are the sum of the trend and the first four harmonics, generally repeat the actual interannual temperature fluctuations. The correlation coefficient of the initial and predicted series at the selected points exceeds 90%. Note that even the first two harmonics in many cases provide a correlation coefficient of more than 70%. Despite the fact that 2018 was anomalous in terms of thermal conditions (the Tsushima Current and its Okhotsk branch of the Soya Current were weakened, a heat deficit was felt in the zone of influence of the Amur River runoff), and in some other areas, even in such water areas, the forecast can be considered acceptable. An example of a similar situation is given for the Tatar Strait, where the predicted value was higher than the actual one, but the general course was predicted correctly, and the error was not so great. For the northern part of the Sea of Okhotsk, the northeastern shelf of Sakhalin Island, and a number of other areas,

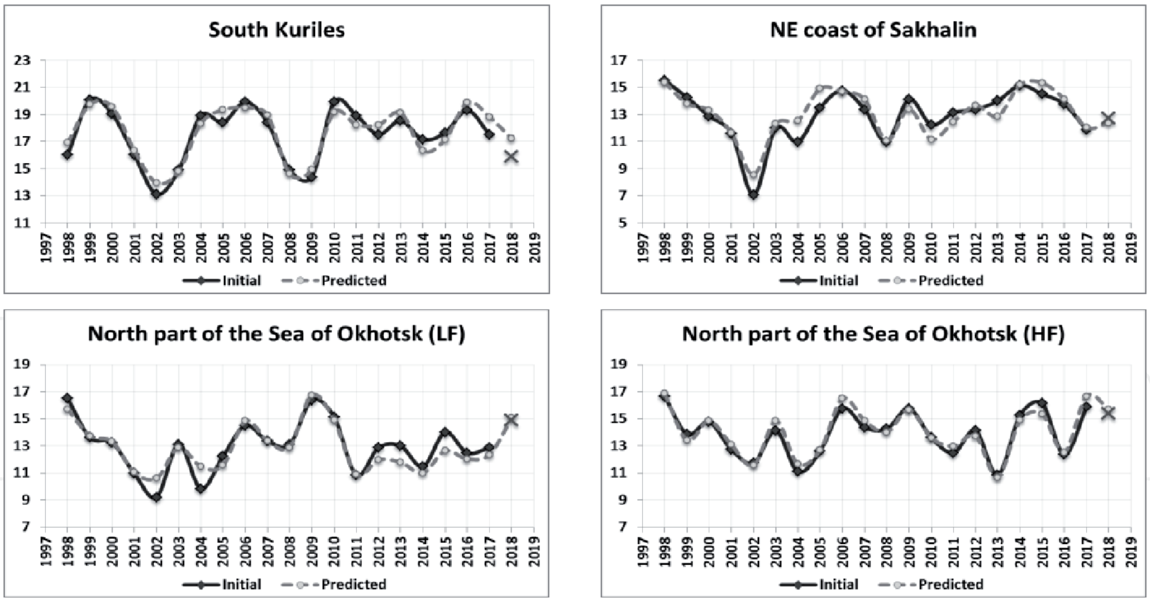

Figure 10.
Examples of temperature forecast graphs (in °C) for the next year. The dashed line shows the prognostic curve. The forecast is carried out for the period from 1998 to 2017. The actual temperature in 2018 is marked with a cross [11].

good agreement was observed between the calculated and real values of the surface layer temperature.

Let us consider some of the parameters of the graphs below. The standard deviation of the initial and predicted series correspond to each other and range from 1.5°C (Tatar Strait) to 2°C (South Kuriles). The average displacement of the predicted series relative to the initial one ranges from 0.4 to 0.6°C. The forecast error is 1.7°C in the Tatar Strait, 1.3°C near the Southern Kuriles, 0.3–0.4°C in the northern part of the studied water area.

More detailed studies devoted to predictability and the limits of applicability of the approach used will be carried out later. However, we can already say that for a significant part of the Sea of Okhotsk regions and adjacent water areas, the forecast of the surface layer temperature with a one-year lead time is quite successful, although the abnormally cold temperatures that took place in a number of areas in 2018 are rather difficult to predict.

Let us take a closer look at **Figure 11**. The forecast for August 2017 turned out to be quite successful, the discrepancy between the actual and predicted temperatures in most of the water area does not exceed ±2°C, with a standard deviation of SST of about 1.5-2°C (only in the northwestern part of the Pacific Ocean is the standard SST deviation is within 2-4°C). At the same time, the forecast for August 2018 contains a large area within which the temperature estimate was greatly overestimated (over 4°C). The map of SST anomalies for August 2018 [16] also contains areas of low temperatures (3-4°C lower than the average multiyear norm), which coincide in space with areas of unsuccessful forecast. This area is located in the zone of influence of the Tsushima Current, and the forecast inaccuracies are due to the fact that the weakening of this current occurred two years earlier than the expected date. Indeed, in **Figure 8**, we see that in the Tatar Strait and the Southern Kuriles, the distance between two neighboring SST minimums decreased to 3–4 years, while its quasiperiodic oscillations with a period of about 6 years are described in the literature [17].

As a result of the analysis of the data set on the surface temperature of the Sea of Okhotsk and adjacent waters, the main cyclical components responsible for the interannual variations of this parameter and the "zones of influence" of each

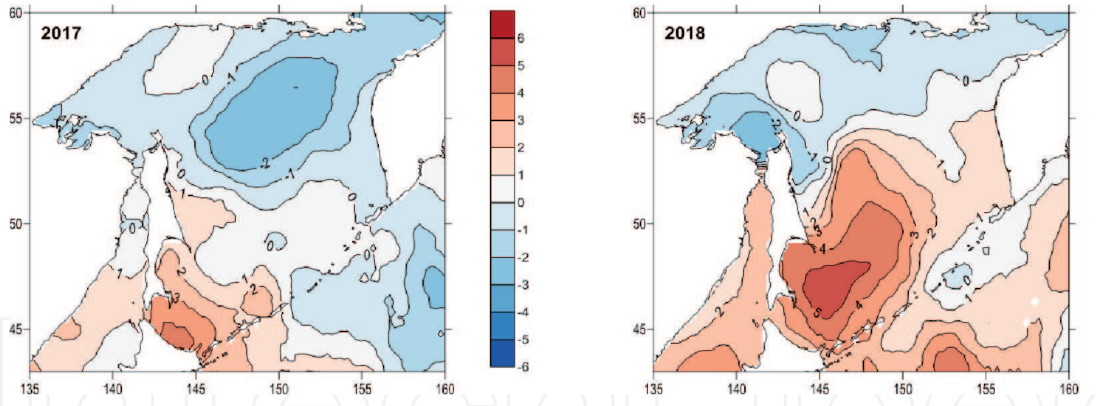

Figure 11.
Difference between predicted and actual temperatures [11].

harmonic were determined. It is shown that the main contribution to these variations comes from components with a period of about 6 years, as well as 3, 5, 8, and 11 years.

The zone of influence of the fundamental harmonic is the most extensive and occupies the southern half of the Sea of Okhotsk and the entire northern part of the Sea of Japan; its amplitude is within 1–2°C. In the vicinity of the Kuril Islands, off the western coast of Hokkaido Island, off the northeastern coast of Sakhalin Island, the amplitude is slightly lower (0.5–1°C), and in the northern part of the Sea of Okhotsk its influence is insignificant. Most likely, this component is associated with fluctuations in the Kuroshio Current and its branch, the Tsushima Current [17].

The highest values of the amplitude of the 3-year harmonic (1–1.5°C) can be noted in the northwestern part of the Sea of Okhotsk, at a distance from the coast, as well as off the northwestern coast of Kamchatka, in the region of the Kuril deep-water basin and in the northwestern parts of the Pacific Ocean.

The area of manifestation of the component with a period of 5 years is noticeably narrower, it is concentrated mainly on the northern shelf of Hokkaido, in the region of the South Kuril Islands (both from the Sea of Okhotsk and the ocean side), and on the northeastern shelf of Sakhalin. In the Tatar Strait, its role is also noticeable, but expressed to a lesser extent than the 6-year harmonic.

In the western part of the Sea of Okhotsk, in the zone of influence of the Amur River runoff, as well as in the northwestern part of the Pacific Ocean, a cyclical component with a period of about 8 years is significantly manifested.

The lowest frequency of the considered harmonics with a period of 11 years is manifested in the northern part of the Sea of Okhotsk; in other parts of the study area, its role is insignificant.

Together with the parameters of the linear trend [9], the amplitudes and phases of the main cyclical components (in each spatial cell, 4 harmonics with the highest amplitudes were used) can be used to predict thermal conditions for the next summer. The retrospective calculation for 2018 gave generally satisfactory results, despite the abnormally cold conditions of this year, noted in a number of areas of the studied water area. The possibility of predicting thermal conditions is of practical importance, primarily for assessing the conditions for the approach of Pacific salmon to spawning. And the results obtained show that in some areas of the water area, one can count on a fairly accurate forecast even for such an unstable parameter as the ocean surface temperature.

In general, the success of the forecast is influenced by how pronounced the cyclical components with a certain period in a given area. Identification of the zone of influence of various harmonics allows you to determine the boundaries of the regions in which the applicability of this method can be expected. As for the accuracy of the forecast, one should pay attention to the presence of large areas in which the modulus of the difference between the predicted temperature and the actual one was of the order of two standard deviations. This fact shows that this method does not guarantee the success of the forecast in cases where strong temperature anomalies are observed. It can only be used to obtain a primary estimate of the ocean surface temperature (or another parameter that experiences quasiperiodic oscillations) based on a sufficiently long series. The 21-year series is not enough to estimate low-frequency components (with a period of 30–50 years), which could also affect the quality of the forecast. For a better forecast, you can combine this method with an assessment of the current conditions, adjusting the forecast in the direction of increasing or decreasing temperature, depending on the current meteorological conditions.

6. Conclusion

This chapter shows how satellite data, going through all levels of processing, become useful products for both science and applied environmental prediction problems. Assessment, and later predicting the dynamics of various environmental parameters, will help reduce damage to nature and identify the degree of influence of anthropogenic factors on the future of the Earth. Based on our analysis results, it seems that the existence of global warming phenomenon has already been proven, but its influence on different parts of the planet is heterogeneous and is not traced in all seasons in the same way. In the spring, there is a tendency to a decrease in the temperature of the surface layer of the Sea of Okhotsk, this tendency continues until August, where it changes to warming condition.

Periodic fluctuations of physical parameters are also not homogeneous in space. It is possible to identify areas where the main oscillation period is 3, 5, 6, 8 and 11 years. Using the sequential spectra method gives a relatively good estimate for the next year's ocean surface temperature. However, to improve the quality of the forecast, it is necessary to improve the quality of the initial data, comparing data from various sources and filling in the gaps associated with the presence of clouds and ice cover, as well as improve the interpolation algorithms to avoid losing sight of mesoscale phenomena.

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References

[1] TeraScan System Training Guide (http://www.seaspace.com)

[2] Puzankov, K. L. Issledovaniye okhotomorskogo regiona pri pomoshchi sputnikovoy sistemy TeraScan [study of the Okhotsk region using the TeraScan satellite system] // Sakhalinskaya molodezh' i nauka: Materialy 1-y mezhvuz. nauch.-prakt. konf. studentov i molodykh uchen. Sakh. region (March 11-12, 1997). - 1997. – Issue 2, pp. 135-137. (In Russian).

[3] Tshay Zh. R., Shevchenko G. V. Otsenka ekstremal'nykh termicheskikh usloviy v period neresta tikhookeanskikh lososey u poberezh'ya o-va Sakhalin [assessment of extreme thermal conditions during the spawning period of Pacific salmon off the coast of Sakhalin Island] // Geodinamicheskiye protsessy i prirodnyye katastrofy, Yuzhno-Sakhalinsk, May 27-31, 2019, P. 184. (In Russian).

[4] Lozhkin DM, Tshay ZR, Shevchenko GV. Satellite monitoring of temperature conditions near the mouths of spawning Rivers in the southern part of Sakhalin Island. Izvestiya - Atmospheric and Ocean Physics. 2019;**55**(9):1166-1171

[5] Vlasova GA, Vasil'ev a S, Shevchenko GV. Prostranstvenno–Vremennaya izmenchivost' Struktury i Dinamiki Vod Okhotskogo Morya (Spatial and Temporal Variability of the Structure and Dynamics of Waters of the Sea of Okhotsk). Moscow: Nauka; 2008

[6] Shershneva OV, Shevchenko GV, Novinenko EG. Temperature conditions in the areas of juvenile release from salmon fish-breeding plants from the mouth of rivers in Sakhalin and the Iturup Island. Izv. TINRO. 2007;**150**:217-225

[7] https://rda.ucar.edu/

[8] Shershneva OV, Shevchenko GV. On the prediction of thermal conditions in the Sakhalin–Kuril region according to satellite data. Izv. TINRO. 2005;**142**:161-187

[9] Lozhkin DM, Shevchenko GV. Trends in the sea surface temperature in the Sea of Okhotsk and adjacent basins based on the satellite data in 1998-2017. Izvestiya - Atmospheric and Ocean Physics. 2019;**55**(9):1133-1137

[10] Shatilina TA, Tsitsiashvili GS, Radchenkova TV. Assessment of the statistical significance of water temperature variability in the sea of Japan and the Northwest Pacific in 1982-2007, Resursy kolyuchego kraba, perspektivy ispol'zovaniya i usloviya obitaniya: Trudy Sakhalinskogo nauchno–issledovatel'skogo instituta rybnogo khozyaistva i okeanografii (Brown king crab resources, usage prospects and habitat conditions: Transactions of the Sakhalin research Institute for Fisheries and Oceanography). Yuzhno-Sakhalinsk: SakhNIRO. 2011;**12**:180-190

[11] Lozhkin D. M., Shevchenko G. V. Lineynyye trendy i tsiklicheskiye variatsii temperatury poverkhnosti Okhotskogo morya i prilegayushchikh akvatoriy po sputnikovym dannym [linear trends and cyclical variations in the surface temperature of the Sea of Okhotsk and adjacent waters according to satellite data] // VII nauchno-prakticheskaya konferentsiya molodykh uchonykh s mezhdunarodnym uchastiyem «Sovremennyye problemy i perspektivy razvitiya rybokhozyaystvennogo kompleksa». - 2019. – pp. 257-262. (In Russian).

[12] Lozhkin DM, Shevchenko GV. Cyclic Sea surface temperature variations in the sea of Okhotsk and adjacent water

areas according to satellite data in 1998-2018. Issledovaniye Zemli iz kosmosa. 2020;(1):44-51

[13] Rostov ID, Zhabin IA. Gidrologicheskie osobennosti priust'evoy oblasti reki Amur [hydrological conditions of the Amur River near-mouth area]. Meteorologiya i Gidrologiya. 1991;(7):94-99 (In Russian)

[14] Ivanov VV. Periodicheskie kolebaniya pogody i klimata [periodic weather and climate variations]. Uspekhi fiz. nauk. 2002;**122**:777-811 (In Russian)

[15] Ivanov VV. Issledovanie variatsiy srednemesyachnoy temperatury vozduha s pomosch'yu posledovatel'nykh spektrov [study of monthly mean air temperature variations with consecutive spectra]. Meteorologiya i Gidrologiya. 2006;(5):39-45 (In Russian)

[16] http://www.sakhniro.ru/

[17] Shevchenko G., Tshay Z., Puzankov C. EOF and wavelet analysis of satellite SST data in the northern Pacific // Proceedings of the Third PICES Workshop on the Okhotsk Sea and Adjacent Areas. Sidney, B.C., Canada, 2004. P. 13-18. (PICES Scientific report; N 26, 2004).