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Original article

Spatio-Temporal Variability of the Resulting Long-Wave Radiation on the Surface of the Northwestern Pacific Ocean Based on the ERA5 Reanalysis Data

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Abstract
Purpose. The work is purposed at studying spatio-temporal variability of the resulting long-wave radiation reflecting the ocean heat loss, on the surface of the northwestern Pacific Ocean and the Far Eastern seas based on the ERA5 reanalysis data for 1998–2021.
Methods and Results. The ERA5 reanalysis data on the resulting long-wave radiation in the region limited by 42°−60°N and 135°–180°E, and including the Far Eastern seas and the northwestern part of the Pacific Ocean constituted the material for the study. The array of monthly averages with a quarter degree spatial resolution was analyzed using the standard statistical methods. Average long-term distributions of long-wave radiation were constructed for each month and by seasons; the amplitudes and phases of the annual and semi-annual harmonics, and the linear trend coefficients were calculated in each spatial cell, also the empirical orthogonal functions decomposition was performed. The highest values of long-wave radiation were observed in winter, primarily in the Sea of Japan and in the area east of Honshu Island. The heat flux from the ocean to the atmosphere reached its significant values in the same areas in autumn, as well as in the coastal strip along the entire continental coast. The most probable reason for such features in the distribution of long-wave radiation is the atmospheric circulation, namely, the steady northwesterly wind (winter monsoon) characteristic of a cold season. In the open ocean, heat loss is less, especially in summer, which is facilitated by dense clouds. Similar results were obtained by the method of empirical orthogonal functions: the values of the first mode spatial distribution decrease from west to east (in absolute value).
Conclusions. It was revealed that heat losses in the studied area occur mainly in autumn and winter in its western part – in the Sea of Japan, east of Honshu Island, and especially in a narrow strip along the entire mainland coast; but in winter in the areas north of 48°N (the Tatar Strait, the Sea of Okhotsk), they are damped by the ice cover. Unidirectional trends in the changes of long-wave radiation are pronounced relatively weakly, and differ in the same water areas in different seasons of a year.

Keywords: long-wave radiation, reanalysis, northwestern part of the Pacific Ocean, Far Eastern seas

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Introduction

Changes in the heat content of the ocean surface layer under the conditions of global climate changes, which are manifested most clearly in its sea surface temperature (SST) variation, are of great scientific interest, since they reflect complex processes of interaction between the atmosphere and the ocean, as well as advective and convective movements of water masses inside it. In relation to the water areas of the northwestern Pacific Ocean (NWPO) and the Far Eastern seas, they are also of great practical importance in terms of the habitat variability characteristics of pelagic fish, primarily such an important species for the economy of the Far Eastern region as Pacific salmon [1]. To study thermal conditions in the Sea of Okhotsk and adjacent water areas, a TeraScan receiving satellite station was installed in the Sakhalin branch of FSBSI VNIRO (SakhNIRO) in 1997. An SST database, which is the main component of the information basis of these studies [2], has been formed since 1998. Currently, there are comprehensive studies of heat content variations under the conditions of climate changes. For this purpose, the ERA5 reanalysis data on a wide range of influencing factors are used, of which the spatio-temporal variability of short-wave solar radiation has been studied so far [3].

Few works are devoted to the variations of different radiation balance components, in particular, the radiation of heat from the ocean to the atmosphere, and they concern mainly the tropical regions of the ocean [4−6]. From the point of view of this research, the most important was their study in selected areas of the northern part of the Pacific Ocean (above the 20° parallel) in 1948−2009 [7]. This study was based on NCEP/NCAR reanalysis data, considering heat losses for evaporation, turbulent heat flux, short wave radiation (SWR) and long wave radiation (LWR). In particular, a decrease in the heat flux radiated by the ocean into the atmosphere was noted in tropical regions, as well as in extratropical ones − eastward of 180°E which, according to the authors, was the cause for the increase in the resulting flow into the inner layers of the ocean in these areas.

In more detail, without averaging over areas, the spatio-temporal variability of SWR was studied in the work of the authors [3] based on ERA5 reanalysis data for 1998−2021 in the NWPO (northward of the 42nd parallel and westward of the 180th meridian). The choice of the temporal interval for data analysis in [3], as well as in this study, was determined by the SST database available at SakhNIRO. To assess seasonal and interannual variations, averaged distributions over the seasons of the year were considered, the amplitudes and phases of annual and semi-annual harmonics, linear trend coefficients, etc. were calculated. Since, for understanding variability of the ocean surface layer heat content, information on heat losses by the ocean, identification of the most important zones in this regard, is also important and interesting, a similar approach is applied in this work to the LWR data array.

This work is purposed at studying spatio-temporal variability of the resulting long-wave radiation flux on the surface of the NWPO and the Far Eastern seas based on reanalysis data for 1998–2021.

Materials and methods

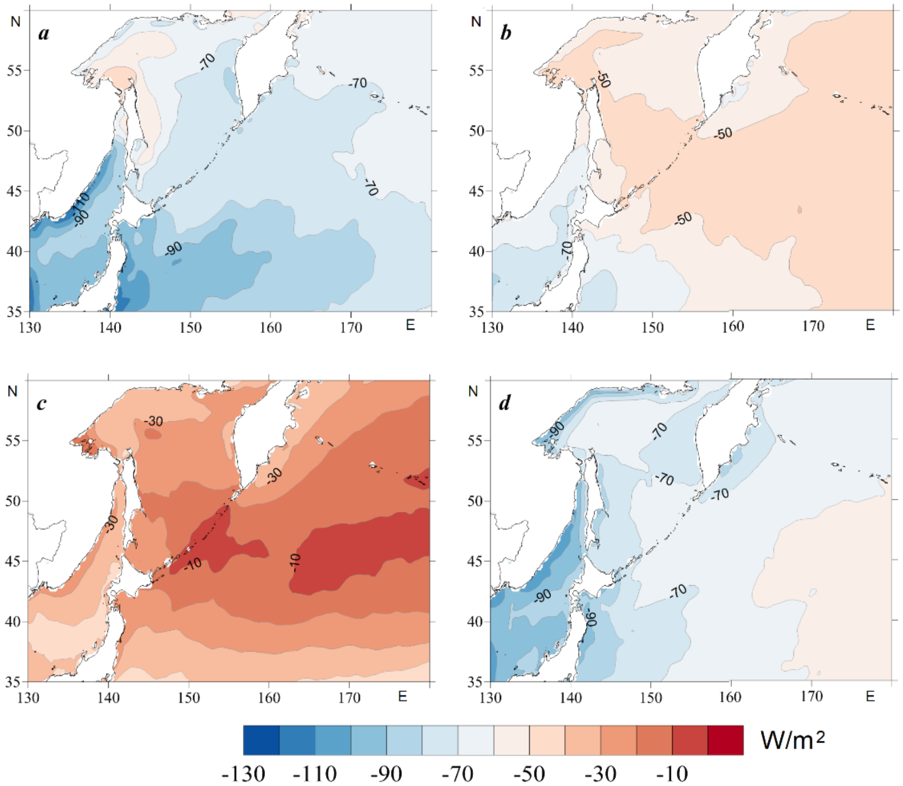
The materials for this study were the ERA5 reanalysis data on the resulting LWR, taking into account the cloudiness effect in the area limited by 35°–70°N, 130°–180°E coordinates. This area covers the waters of the Far Eastern seas (along the Bering Sea, only its western part, adjacent to the Russian coast) and the NWPO. The spatial resolution of the data was a quarter of a degree, the discreteness in time was 1 month. All LWR values are negative, which means the energy loss by the surface layer of the ocean due to heat radiation into the atmosphere.

This work aimed at studying the features of the LWR spatio-temporal variability (seasonal and interannual variations in different parts of the water area) as an important component of the radiation balance. For its implementation in each spatial cell for each month, the average long-term values of this parameter, reflecting seasonal changes in the flux of the resulting long-wave radiation, are calculated. To determine quantitative characteristics of flux seasonal variations of LWR, the amplitudes and phases of the annual and semi-annual harmonics were calculated. Linear trend parameters were found in each cell (for each month and each season). The sequence of LWR fields (temporal layers) was also studied using the method of decomposition in empirical orthogonal functions (EOF). This type of statistical analysis provides a simultaneous study of the main features of both seasonal and interannual variations [8]. According to the results of such decomposition, the interannual variability of the sea surface temperature, as well as short-wave solar radiation, is expressed mainly in the modulation of the annual harmonic (primarily in the variability of summer maxima) [2, 3]. Similar manifestations could also be expected in the variations of the time functions of the principal modes of the LWR decomposition in terms of EOF. To assess the nature of this modulation, samples were formed for December and July (periods of maximum and minimum resulting long-wave radiation), cyclic variations with periods from 3 to 11 years were determined from these samples.

Results and discussion

Seasonally averaged LWR distributions. Fig. 1 presents the spatial distributions of LWR averaged over the entire period under consideration (1998–2021) for the central months of different seasons in the Far Eastern seas and NWPO. This parameter reaches its highest (in absolute value) points in winter, January. The maximum values of the resulting long-wave radiation were found off the coast of Primorye (southward of 48°N), as well as in the influence zone of the warm Kuroshio Current near the eastern coast of Japan and its branch, the Tsushima Current, near the western coast. The lowest heat flux values into the atmosphere are observed in the western part of the Sea of Okhotsk and in the north of the Tatar Strait − areas traditionally covered with ice. Obviously, the ice cover prevents the ocean heat loss in winter.

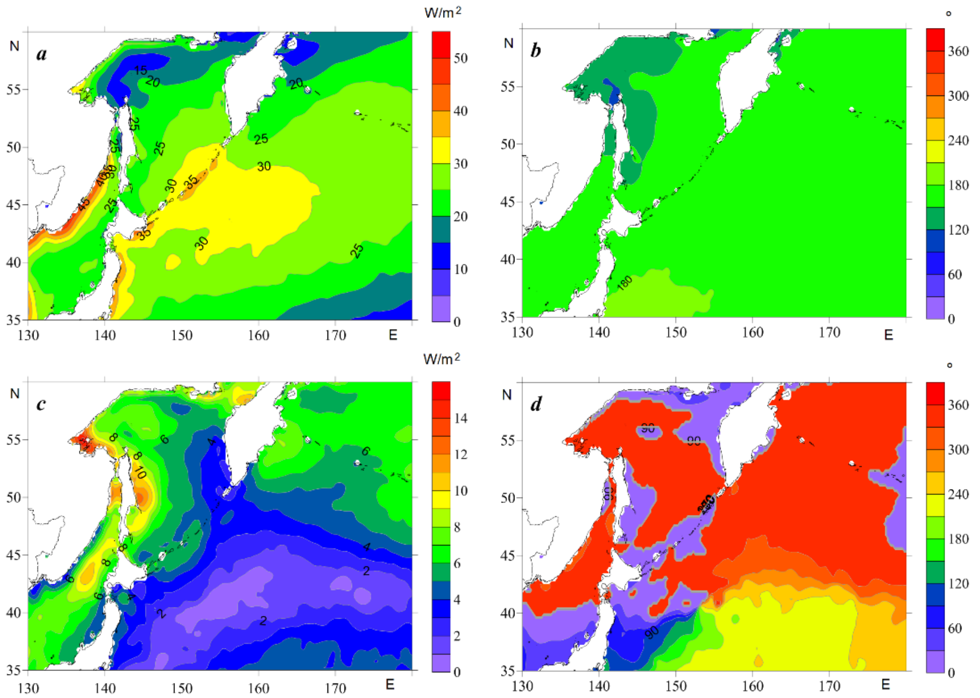
In spring, the LWR spatial distribution is more uniform, and the spatial differences in the parameter are small. In most of the studied water area, the parameter values are about −50 W/m^2; they are slightly higher in absolute value (about −70 W/m^2) in the water area of the Sea of Japan and near the eastern coast of Honshu Island.



F i g. 1. Average long-term spatial distributions of LWR, W/m^2, in January (*a*), April (*b*), July (*c*) and October (*d*)

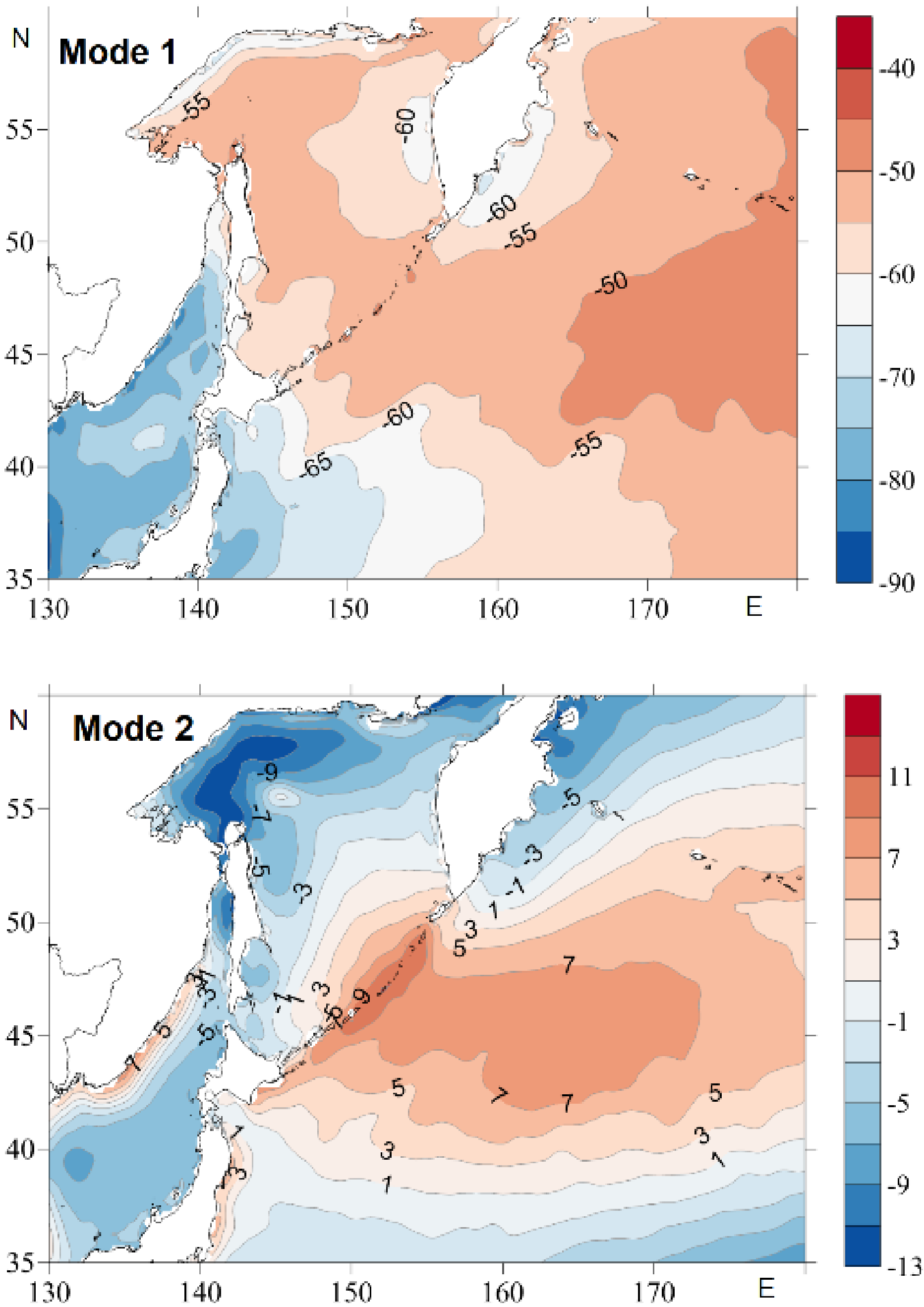
In summer, the flux of the resulting long-wave radiation significantly weakens, the LWR values in most of the region are −20…−30 W/m^2, the area with the lowest values (about −10 W/m^2) is elongated from the central part of the Kuril Islands to the east approximately along the 45°N parallel. This area is traditionally characterized by high cloudiness, which prevents heat from radiating into the atmosphere. The most significant flux of long-wave radiation was recorded in the northwest of the Sea of Okhotsk, off the coast of Kamchatka and, somewhat unexpectedly, along the southern boundary of the area under study. Perhaps, this feature is due to the nature of cloud formation, which is less dense here compared to the zone near the 45th parallel.

In autumn, the long-wave radiation flux reaches the values close to those observed in winter. The highest values (−90…−100 W/m^2) were found in a relatively narrow strip along the entire continental coast from the Peter the Great Gulf in the south to the Nevelskoy Strait in the north of the Sea of Japan, as well as along the western and northern parts of the coast of the Sea of Okhotsk. This feature is due to the action of a strong and steady northwestern wind (winter monsoon), which is characteristic of this time period, carrying cold air from the mainland, surging off and cooling the surface layer of water along the entire mainland coast of the region under consideration. This is in good agreement with the results of [2], which revealed an earlier cooling of water in the surface layer of the Sea of Okhotsk northwestern part compared to its main water area, which most clearly shows a significant effect of heat radiation into the atmosphere on the formation of the spatio-temporal SST variability. Probably, from the point of view of the processes under consideration, this area can be attributed to the energy-active zones of the ocean, by analogy with the area eastward of Honshu Island [9]. Also noteworthy is the decrease in the LWR flux in the direction from west to east; the minimum absolute values (about −50 W/m^2) were found in the southeast of the area under consideration, in the Pacific Ocean.



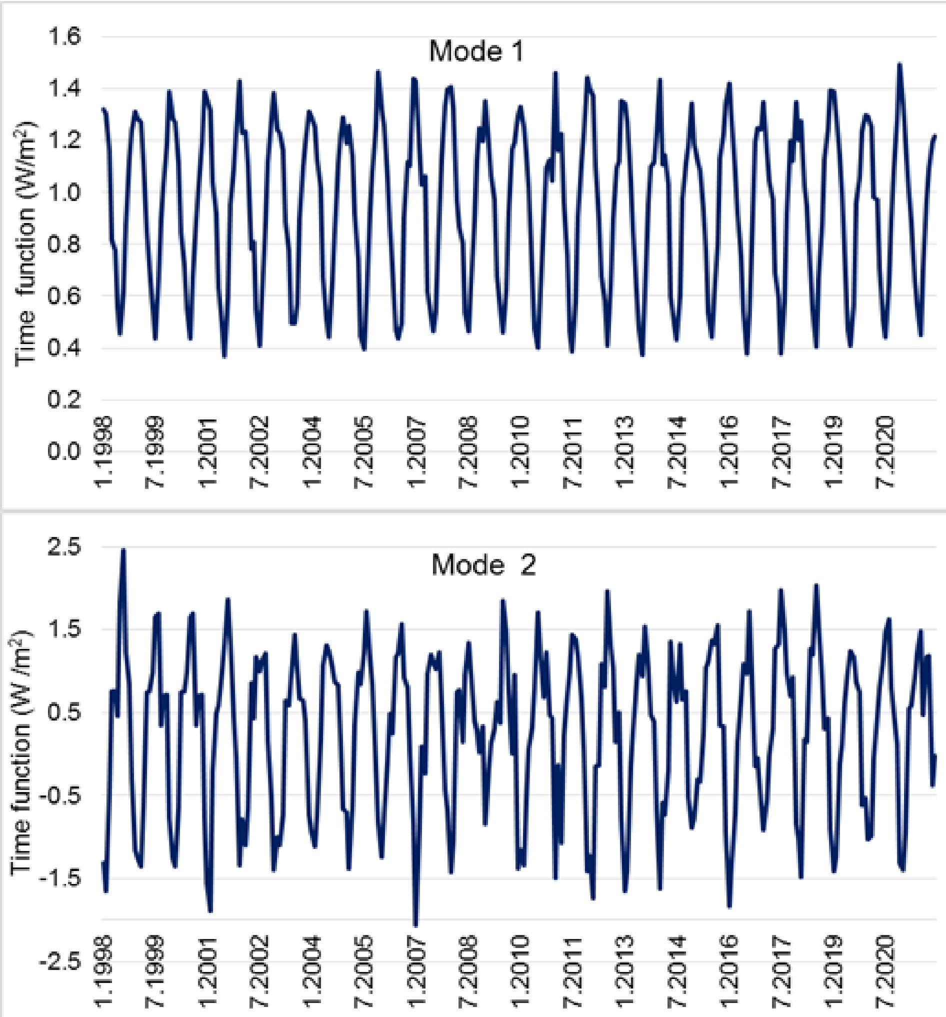
F i g. 2. Spatial distribution of amplitudes (*a*, *c*) and phases (*b*, *d*) of annual (*a*, *b*) and semi-annual (*c*, *d*) harmonics

Harmonic analysis of seasonal variations. To quantitatively characterize seasonal LWR variations, the amplitudes and phases of the annual and semi-annual harmonics were calculated (calculation was carried out by the least squares method in each spatial cell of the studied water area). Calculation results in the form of spatial distributions of these parameters are shown in Fig. 2. The highest values of the annual component amplitude were noted in the areas where the largest flux of the resulting long-wave radiation is observed in winter, i.e., in the coastal areas of Primorye, the eastern coast of Japan, and the Kuril Islands. In the northern part of the Sea of Okhotsk (in freezing areas) and at the southeast of the study area, it has the smallest value. Probably, in the first case this is due to a decrease in heat losses in winter due to the ice cover effect, in the second case – due to the effects of clouds.



F i g. 3. Spatial distribution of the first two modes of decomposition of the LWR fields sequence in EOF (dimensionless)

Variations in the phase of the annual harmonic are insignificant; only its decrease can be noted in the northwestern part of the Sea of Okhotsk and in the Tatar Strait compared to the main part of the area under study. This means that the maximum and minimum values of the heat flux from the ocean into the atmosphere are recorded approximately at the same time, with the exception of freezing regions (where maximum radiation occurs in November).



F i g. 4. Variations in the time functions of the first (*top*) and second (*bottom*) modes of the LWR decomposition in EOF

The spatial distribution of the amplitude and phase of the semi-annual harmonic is more complex. In the vast water area of the NWPO, the amplitude is small, its highest values (8–10 W/m^2) were noted in the western part of the Sea of Okhotsk in the traditionally freezing water area, especially in the area of the Shantar Islands (up to 15 W/m^2). In the Sea of Japan, except for the northern part of the Tatar Strait, we note a higher intensity of semi-annual variations in the center of its water area. It is difficult to provide a physical explanation for the causes of this phenomenon.

A noticeable phase shift is observed between the water areas northward and southward of 40°N parallel.

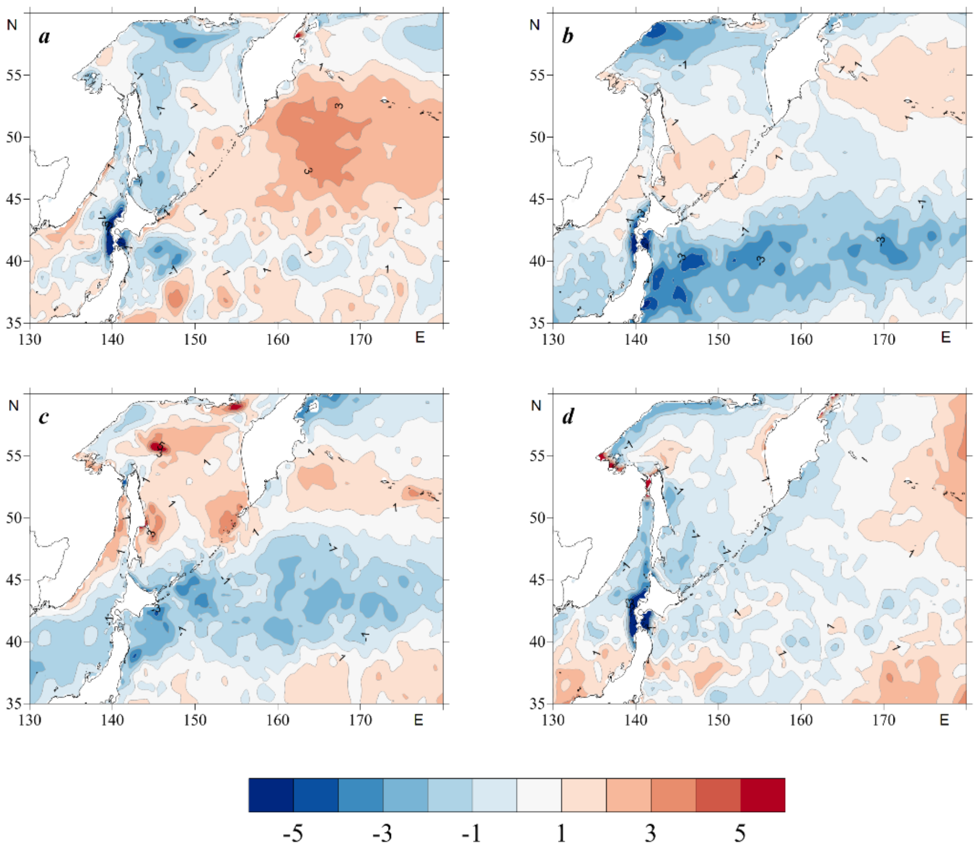
Decomposition of LWR in terms of EOF. To a large extent, the nature of seasonal variations is also reflected by the results of decomposing the sequence of LWR fields in terms of EOF, since the technique is focused on minimizing residual dispersion, and the annual variation of the studied parameter is the main one. The spatial distributions of the first two main decomposition modes (which explain 97.4% and 0.8% of the total parameter variance, respectively) are shown in Fig. 3, and the graphs of the time functions corresponding to them are given in Fig. 4.

The values of the first mode spatial distribution, which was taken to be dimensionless, are negative at all points of the water area (the time function is positive). The maximum absolute values of the spatial function were found in the Sea of Japan waters (except for the northern part of the Tatar Strait) and near the eastern coast of Honshu Island (−70…−90 W/m^2). This indicates, in particular, significant heat losses in these water areas in winter, which is not surprising because its reserves are obviously significantly larger than in the Sea of Okhotsk, and the ice cover in the area under study is absent, except for the mentioned top of the Tatar Strait. The lowest rates are identified in the remote part of the Pacific Ocean and the central Bering Sea. This indicates an important role of the continent, in particular, the air flows coming from it, in the processes of heat exchange between the atmosphere and the ocean.

In the time function variations, the annual variation clearly dominates with an amplitude of 0.4 W/m^2: it accounts for 96.8% of the dispersion. The phase amounts to 348°, which corresponds to the maximum value in December. The unidirectional trend in the time function variations is weakly expressed, the interannual variations are in the low-frequency modulation of the signal, which is more noticeable at the maxima. Based on the sample of December maxima, it turned out that there was not any pronounced periodicity. The three-year component manifested itself to the greatest extent, the influence zone of which covered a significant part of the Sea of Okhotsk with the maximum amplitudes on the northern shelf. For the July lows, the most interesting fact revealed was a clear relationship with the cyclic components of shortwave radiation and SST. In particular, the manifestation of an 11-year cycle in both parameters was noted on the northern shelf of the Sea of Okhotsk [3].

The spatial distribution of the second mode is characterized by an area with positive values in the center of the area under study (as well as in narrow strips off the coast of Primorye and the western coast of Honshu Island) and negative values along its periphery. The largest positive values of the spatial function were noted in the central part of the Kuril Islands (10–11), and the negative values were noted in the northwestern part of the Sea of Okhotsk (−11…−12). Time function variations also have a pronounced annual course with an amplitude of 1.2 W/m^2 and a phase of 188°, corresponding to a positive maximum in July (sometimes it is observed in August) and a minimum − in January (sometimes in February). The role of the second mode is relatively small, it is some correction to the LWR distribution determined by the first mode, so the modulation of its time function was not considered.

Linear trend coefficients. Fig. 5 demonstrates spatial distribution maps of the LWR linear trend coefficients, calculated seasonally (indicators are reduced to 10-year intervals). In winter, at most of the study region water area, positive trends were observed with relatively low rates (1–3 W/m^2 for 10 years), the highest values were noted in the NWPO eastward of the Kamchatka Peninsula. Weak negative trends (about −1…−2 W/m^2 over 10 years) were indicated in the northern and western parts of the Sea of Okhotsk (possibly, in these areas they are related to a decrease in ice coverage in this basin), as well as off the western and southern coasts of Hokkaido.



F i g. 5. Spatial distributions of the LWR linear trend coefficients (in W/m^2 over 10 years) in winter (*a*), spring (*b*), summer (*c*) and autumn (*d*)

In spring, positive trends (1–3 W/m^2 over 10 years) were indicated in the southern part of the Sea of Okhotsk and in the area of the Aleutian Arc, to a greater extent in the southern part of the Bering Sea and somewhat to a lesser extent in the adjoining part of the NWPO. The negative trends (−1…−4 W/m^2 over 10 years) are identified in the northern part of the Sea of Okhotsk and in the subpolar front region, along the 40°N parallel.

In summer, positive trends (with approximately the same values of the linear trend coefficient) are observed in most of the Sea of Okhotsk, in the northern part of the Sea of Japan, and in a small section of the NWPO near the Aleutian Islands. In the southern part of the Sea of Japan and in most of the NWPO water area, the trends are negative.

In autumn, unidirectional trends in variations in the resulting long-wave radiation flux are not expressed, the value of the linear trend coefficients in the main part of the study area is small.

In general, unidirectional trends in LWR variations in the area under study are not significant, and the values of the linear trend coefficient in the same water area regions change in different seasons. This is consistent with the results of [7], in which a trend towards a decrease in heat radiation into the atmosphere was indicated in the areas located either to the south or to the east of the water area under consideration.

Conclusion

As a result of the performed studies, it was revealed that the resulting long-wave radiation flux, which expresses the heat loss by the ocean, reaches the highest values in winter and autumn in the Sea of Japan, in the western part of the Sea of Okhotsk and in the NWPO part adjacent to Honshu's Island eastern coast. A narrow strip along the entire continental coast in autumn stands out. Obviously, this effect is due to the impact of the offshore northwesterly winds, which is characteristic of the winter monsoon. From the point of view of the process under consideration, this area can be regarded as an energy-active zone of the atmosphere and ocean in the water area under consideration (along with the previously identified area eastwards of Honshu Island). In winter, in the areas northward of 48° latitude, this phenomenon is less pronounced due to the ice cover effect.

The minimum absolute values of LWR are observed in July, sometimes in August, in the area extended from the central part of the Kuril Islands towards the east. The most probable cause for the low LWR flux is cloudiness.

The spatio-temporal variability of this parameter is described well by the first mode of decomposition in EOF, the spatial function values of which increase in absolute value from east to west. The variations of its time function are dominated by the annual variation with an amplitude of 0.4 W/m^2, the interannual variations are expressed in its low-frequency modulation. In the winter maxima variations, the role of the three-year component, which manifests itself in the eastern part of the Sea of Okhotsk, is most significant. In fluctuations of summer minima, the most interesting is the 11-year cycle, the influence zone of which is concentrated on the northern shelf of the Sea of Okhotsk and coincides with the manifestation area of a similar component of the short-wave solar radiation flux.

Unidirectional trends in LWR variations are weakly expressed, linear trend coefficients fluctuate within 1–4 W/m^2 over 10 years in absolute value and change significantly in the same parts of the water area in different seasons of the year.

Summing up the study results, we can state that the heat flux from the ocean to the atmosphere is affected by such factors as atmospheric circulation (especially the winter monsoon), ice cover and cloudiness. The obtained results are important for understanding the features of the formation of the surface water layer heat content in the region under study, since, together with the short-wave radiation considered by us in earlier works, it forms the radiation balance and determines the resulting heat flux in the surface layer of the ocean.

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Dmitry M. Lozhkin – processing and complex data analysis, construction of graphs and distributions, discussion of the work results

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.