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Original article

Spatial and Temporal Variability of a Latent Heat Flux in the Northwest Pacific Ocean Based on the ERA5 Reanalysis Data

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Abstract
Purpose. The paper is aimed at studying the spatial and temporal variability of a latent heat flux – one of the important components of heat balance in the Northwest Pacific Ocean and the Far Eastern seas based on the ERA5 reanalysis data.
Methods and results. The ERA5 reanalysis data on a latent heat flux in the area limited by the coordinates 42°–60°N and 135°–180°E and including the Far Eastern seas and the Northwest part of the Pacific Ocean constituted the material for the study. The array of monthly averages at a quarter-degree spatial resolution was analyzed using the standard statistical methods. The average long-term distributions of latent heat flux values for each month were constructed; the amplitudes and phases of annual and semi-annual cycles, and the linear trend coefficients were calculated in each spatial cell, and the decomposition was performed using the empirical orthogonal functions. The range of seasonal variations is significant in the zone of warm currents, and it decreases sharply in the northern part of the area under study in the Pacific Ocean as well as in the Okhotsk and Bering seas. The interannual variations are manifested in the quasi-cyclic changes of the envelope based on the maximum values with a period of about 6 years. The unidirectional trends in the interannual latent heat flux variations are weakly shown.
Conclusions. Among the seasonal variations of a latent heat flux, the annual cyclicity is predominant and most pronounced in the southern part of the Northwest Pacific Ocean (the area influenced by the warm Kuroshio Current) off the Japan Sea coast of the Honshu Island in the Tsushima Current zone. This is conditioned by a significant evaporation increase in these areas during a cold season that, in its turn, is related to a sharper temperature contrast as well as to the impact of a winter monsoon characterized by the strong and stable northwesterly winds bringing dry cold air from the continent. The latent heat flux values are positive in some areas of the studied area in a warm period that indicates the important role of water vapor condensation in the areas with high cloudiness and in the zones of quasi-stationary upwellings.

Keywords: heat balance, latent heat flux, annual cycle, linear trend, empirical orthogonal functions, Northwest Pacific Ocean

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Introduction

The Northwest Pacific Ocean and the Far Eastern seas represent an active fishing area of the Russian fishing companies in the Far Eastern region. A significant number of pelagic fish species, such as Pacific salmon, saury and Far Eastern sardine, are caught here. Most of these species are sensitive to the thermal conditions of their habitat. Changing climate conditions determine the importance of the study of various factors influencing the temperature of the surface water layer in these areas, including the spatial and temporal variability of the heat balance and its elements. One of the important components of this balance is the latent heat flux (LHF). Its data can be obtained on several web pages giving reanalysis materials of various hydrometeorological parameters.

Latent heat flux refers to its costs for phase transitions during the atmosphere and hydrosphere interaction – losses in the ocean during evaporation and melting of ice and intake during condensation and ice formation (heat flux from the atmosphere to the ocean is considered to be positive, and in the opposite direction – negative) [1]. Moreover, the heat flux from the ocean during evaporation is considered one of the most important components of the heat balance. In addition to the evaporating surface temperature, this flux magnitude is significantly influenced by air temperature and humidity, as well as wind speed. Despite this parameter importance for climate research, spatial and temporal variability of latent heat flux in the Northwest Pacific Ocean is rarely considered as an independent characteristic. Important results were obtained in [1], although more attention was paid to the tropical regions (as in [2, 3], which indicates the special role of this zone in the interaction between the atmosphere and the ocean) and the northeastern part of the Pacific Ocean. In this regard, the study of sensible and latent heat fluxes in the northwestern part of the Sea of Japan during the cold season is specially noted [4]. The information basis for this study was the NCEP/NCAR reanalysis data which allow a detailed analysis of the spatial and temporal variability of the heat balance components. The present paper uses a different data source, namely the ERA5 reanalysis materials, available at https://climate.copernicus.eu/climate-reanalysis.

It is known that in the Northwest Pacific Ocean, in the zone of warm Kuroshio Current influence, one of the most energetically active regions of interaction between the atmosphere and the ocean is located, between which very intense heat exchange occurs across the interface [5]. The region under consideration also contains the Far Eastern seas, in which significant heat fluxes are caused by the ice cover formation and ice melting. Interannual variations of these fluxes associated with global warming processes are also of interest.

The present paper is aimed at studying the spatial and temporal variability of the latent heat flux, one of the important components of heat balance in the Northwest Pacific Ocean and the Far Eastern seas, based on the *ERA*5 reanalysis data for 1998−2022.

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[1] Budyko, M.I., 1956. *The Heat Balance of the Earth's Surface*. Leningrad: Gidrometeoizdat, 256 p. (in Russian).

Materials and methods

The ERA5 reanalysis data were taken as the materials for the research on the latent heat flux over the Northwest Pacific Ocean and the Far Eastern seas for 1998–2022. All fluxes of this product are calculated using the corresponding ECWMF model described at https://www.ecmwf.int/en/publications/ifs-documentation.

As noted above, this flux (LHF) reflects the heat exchange associated with phase transitions of water in the surface layer (evaporation, ice formation and melting). The data are given in joules per square meter which means the amount of flux per month through a cell with an area of 1 m^2. The area under study was limited to coordinates 35°–70°N, 130°–180°E, the spatial resolution of the data was 1/4°, the time resolution was 1 month. The main attention at this stage of the work was focused on the spatial and temporal variability features of the heat balance – determining factor in the formation of thermal conditions in the surface layer of the ocean.

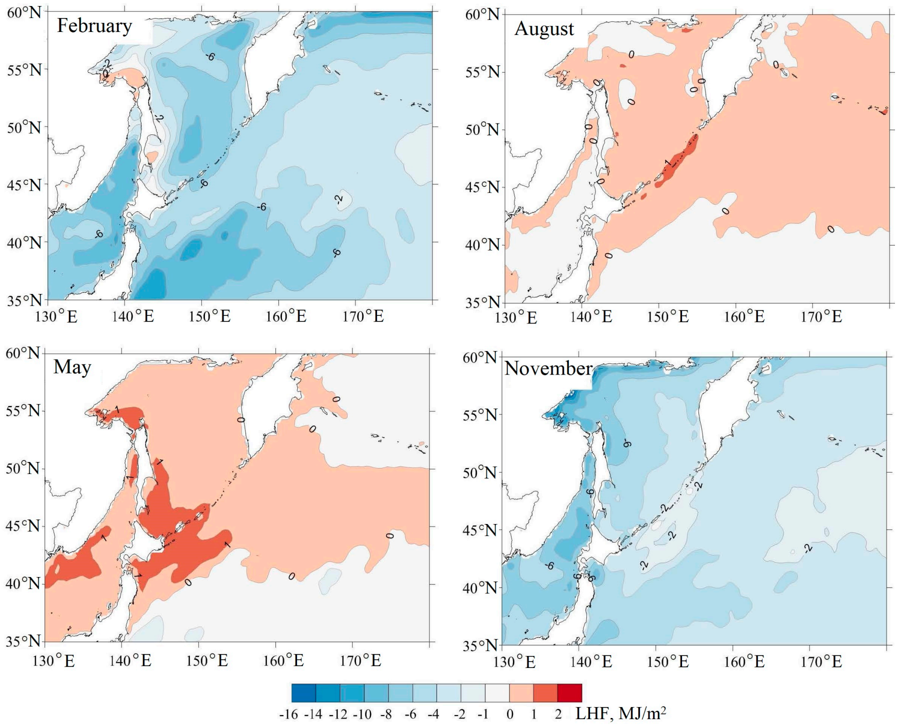
The average long-term values of this parameter reflecting seasonal changes in the latent heat flux are calculated for every month in each spatial cell. To determine the quantitative characteristics of seasonal variations, the amplitudes and phases of annual and semi-annual cycles using the least squares method (LSM) were found. Linear trend parameters were determined using LSM (for each month and each season) in each cell. The method of empirical orthogonal function (EOF) decomposition was also used to study the sequence of LHF time layers; this type of statistical analysis permits simultaneous study of the main features of both seasonal and interannual variations. The interannual variability of the studied parameter is expressed mainly (in addition to unidirectional trends) in the low-frequency modulation of the annual cycle which makes the main contribution to the time functions of the two main modes of the EOF expansion.

Results and discussion

Averaged LHF distributions by season. Fig. 1 shows the average long-term spatial distributions of LHF for different seasons. February was chosen to characterize winter conditions, May – spring, August – summer and November – autumn.

In winter (the distributions of the studied parameter in January and March are identical to those presented in the figure with a slight decrease in its values in absolute value), LHF values are negative throughout the region and have the largest absolute values on the southern boundary between the 140th and 150th meridians, where the warm Kuroshio Current departs from the coast of Honshu and acquires its eastern direction (about −25 MJ/m^2). In general, intense latent heat flux is characteristic of the zone between parallels 35° and 40°N both in the Northwest Pacific Ocean and in the Sea of Japan, in the zone of influence of the warm Tsushima Current, although in the latter case to a lesser extent.

LHF values fluctuate within rather narrow limits from −6 to −10 MJ/m^2 over most of the region under study. The lowest flux values (from 0 to −2 MJ/m^2) are in the frozen waters of the northwestern and western parts of the Sea of Okhotsk and in the northern part of the Tatar Strait (the Sea of Japan). This is typical not only for February, when the ice cover reaches its maximum development and prevents heat exchange between the atmosphere and the ocean, but also for December, when high flow intensity could be expected.



F i g. 1. Average long-term spatial distributions of LHF in the region under study

Latent heat flux values decrease primarily in the southern part of the Northwest Pacific Ocean (they change slightly in the main part of the region) in spring. LHF becomes positive in the southwestern part of the Sea of Okhotsk and in the Northwest Pacific Ocean area adjacent to Hokkaido and the South Kuril Islands in May, although it has a small value from 0.05 to 0.2 MJ/m^2. This can be determined by moisture condensation in areas with traditionally high clouds.

The area with positive LHF values expands in June; it covers large areas in the area of the Kuril Island Ridge, as well as in the northern and western parts of the Sea of Okhotsk. Areas with positive values (up to 0.5 MJ/m^2) reach their maximum sizes in the Sea of Okhotsk and in a wide band (42°–50°N) stretching east from the Kuril Ridge to the Aleutian Islands in July. The latent heat flux intensity decreases to its minimum values for the year (about −6 MJ/m^2) at the southern boundary. Areas with positive values narrow noticeably in August; they are noted mainly in the area of quasi-stationary upwellings in the central part of the Kuril Ridge, Kashevarov Bank, the Yam Islands, etc. Positive values are noted only in a small area in the Middle Kuril region in September.

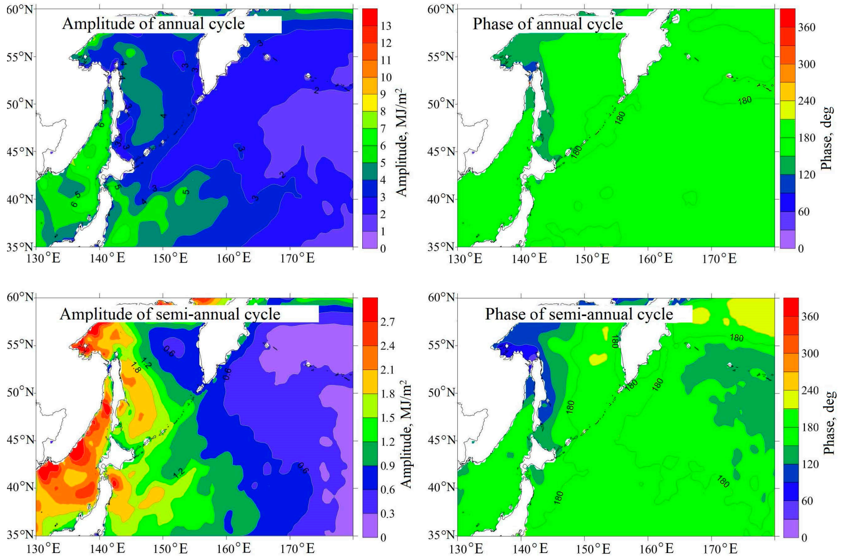
In autumn, the LHF spatial distribution is similar to winter; the only values that are absent are those close to zero noted above in frozen areas. The maximum absolute values were noted on the southern boundary of the studied region and they increased from October to December and exceeded 30 MJ/m^2.

It is important to emphasize that the highest LHF values were found in autumn and winter in areas with the highest sea surface temperatures (SST), in the zone of influence of the warm Kuroshio and Tsushima Currents, associated with an increase in the temperature contrast between the atmosphere and the ocean surface in the cold season (the similar effect was also noted in the western part of the Barents Sea, in the zone of influence of the warm Gulf Stream [6]). This is largely determined by the effect of the winter monsoon characterized by high wind speeds carrying drier and colder air from the mainland than the summer monsoon brings from the central regions of the Pacific Ocean. The results obtained are consistent with the conclusions of [5, 7] in which the area east of Honshu is noted as one of the most energetically active areas of the atmosphere and ocean. Positive values of the parameter in areas of quasi-stationary upwelling also have a simple physical explanation, since moisture condensation can appear in them due to the lower temperature of the ocean surface.

Harmonic analysis of seasonal variations. Figure 2 shows the spatial distributions of the amplitude and phase of the annual and semi-annual cycles. Annual cycle amplitude usually characterizes the scale of seasonal variations as it takes high values in areas where these variations are most intense and is minimal where the annual cycle is weakly expressed. The figure shows seasonal fluctuations in latent heat flux with pronounced latitudinal variability: they are maximum near the eastern coast of Honshu and minimum in the northern part of the area under study, in the Bering Sea and on the northern shelf of the Sea of Okhotsk. The nature of the spatial variability of the amplitude in the Sea of Japan is somewhat different as the maximum values are noted off the Honshu western coast, in the zone of warm Tsushima Current influence, and the minimum are noted off the Primorye coast. High values of the amplitude of the annual cycle in the zone of influence of the warm Kuroshio and Tsushima Currents show a significant decrease in evaporation in these areas during the summer monsoon characterized by lower wind speeds and higher air humidity compared to the winter monsoon. These differences are not so noticeable in the average long-term LHF distributions for different seasons.

The phase of the annual cycle in the main part of the study area (the Northwest Pacific Ocean, the Bering Sea and the eastern part of the Sea of Okhotsk) fluctuates within 150–160° (1 month accounts for 30°, so the obtained value corresponds to the maximum in July), its values decrease to 130–140° in the Sea of Japan and in the western Sea of Okhotsk and up to 110–120° in the northern part of the Tatar Strait and north of the Sakhalin Island.

Noticeable amplitudes of the semi-annual component were noted in areas with a complex annual cycle which is not well described by the annual cycle. Such areas include the northwestern part of the Sea of Okhotsk, coastal zones off the coast of the Sakhalin, Hokkaido and Honshu Islands (from the eastern side).



F i g. 2. Spatial distribution of amplitudes and phases of the annual and semi-annual LHF cycles

Linear trend coefficients. Much attention is usually paid to identifying unidirectional trends when studying hydrometeorological parameters under global climate change. In this regard, such an analysis was also carried out for the latent heat flux in the Northwest Pacific Ocean and the Far Eastern seas (Fig. 3). A weakly expressed tendency towards an increase in latent heat flux was noted in the Bering Sea, the northern and northeastern parts of the Northwest Pacific Ocean and in the eastern part of the Okhotsk Sea in winter and spring. The same weak tendency towards its decrease was observed in the Pacific Ocean south of the 45°N parallel, in the northern part of the Sea of Okhotsk and the Sea of Japan. Minor negative trends in most of the area under study were observed in summer. The most intense interannual changes were detected in autumn. Significant negative trends were found in the area of the Sangar Strait and in general off the coast of Japan, positive ones – in the Amur Estuary, near the Shantar Islands and in the Pacific Ocean along the southern boundary of the region under study. In general, relatively weak unidirectional trends in changes in LHF in the Far Eastern seas and the Northwest Pacific Ocean can be observed. It indicates an insignificant impact of global warming on interannual changes in the latent heat flux in this region. This is consistent with the low values of the linear trend coefficients in variations in ocean surface temperature in the studied region (with multidirectional trends in the Sea of Okhotsk and the Bering Sea) and surface atmospheric pressure which indicates relatively weak changes in the atmospheric air circulation [2].

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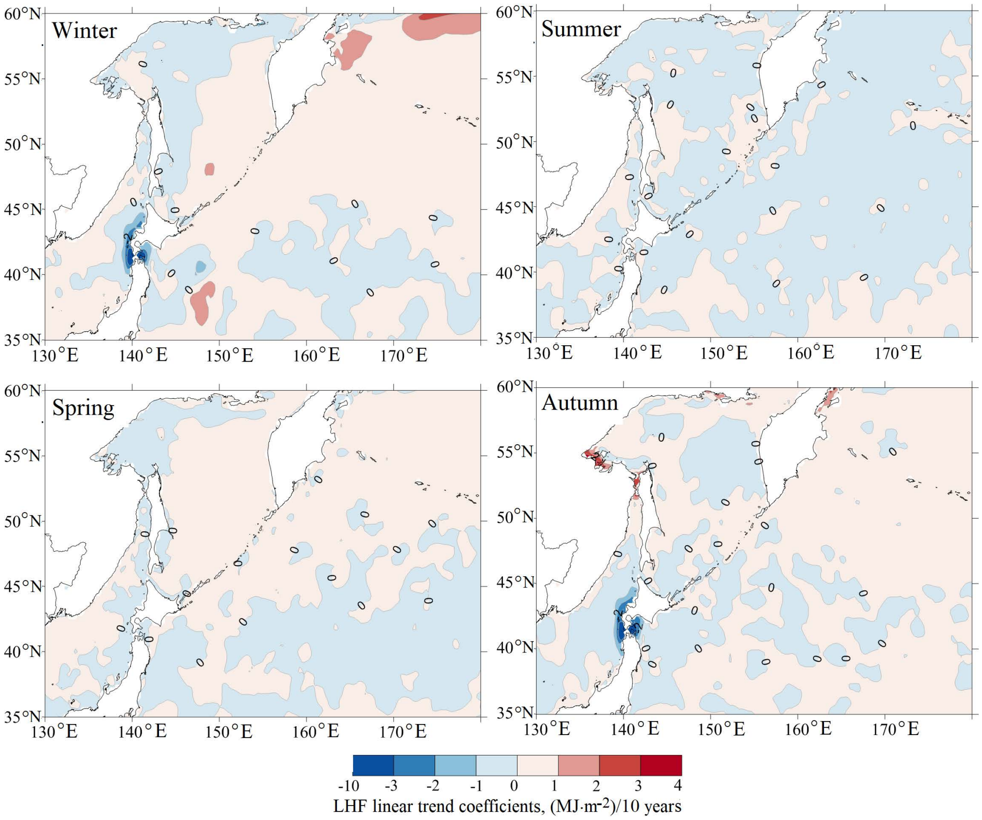
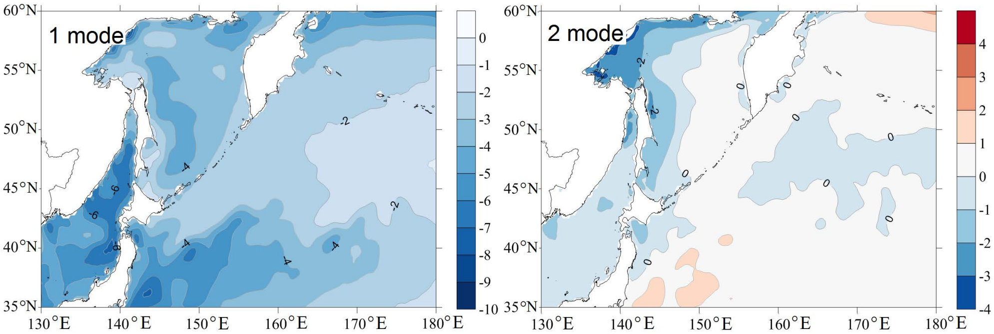


F i g. 3. Spatial distributions of the *LHF* linear trend coefficients in different seasons of a year

Decomposition of LHF in terms of EOF. The EOF decomposition method is often used for a detailed study of the spatial and temporal variability of hydrometeorological fields [8]. Fig. 4 shows the spatial functions of the first two modes of decomposition of the sequence of the LHF time layers using this method. The first mode is the main one accounting for 94.5% of the total variance of the parameter. Its spatial distribution (all values are negative, assumed to be dimensionless) is quite simple; values of ~ −5 are noted in vast areas of the northeastern part of the Northwest Pacific Ocean, in the Bering Sea, in the eastern and central parts of the Sea of Okhotsk. In the north-west of the latter, the smallest absolute values from −2 to −3 were identified and the highest ones were noted in the Sea of Japan off the western coast of Japan (from −10 to −12) and in the south of the considered part of the Northwest Pacific Ocean (up to −20 at Honshu eastern coast).

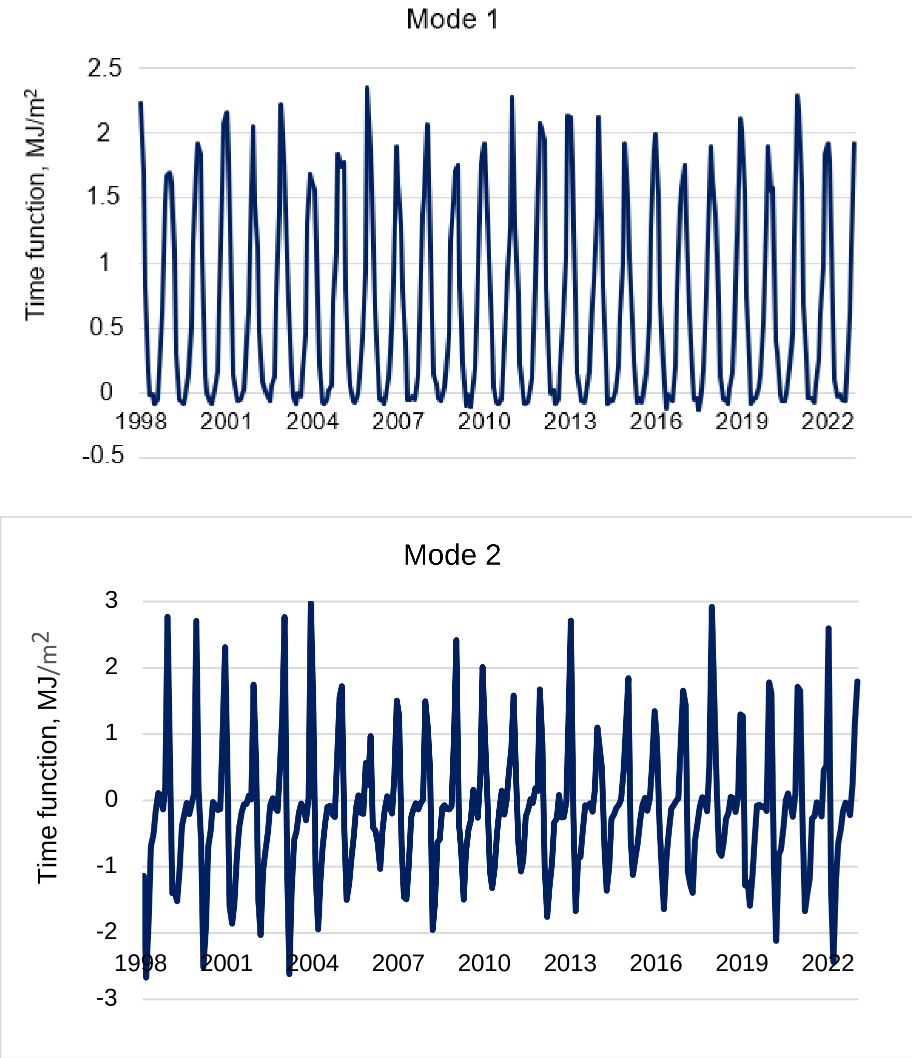


F i g. 4. Spatial distribution of the first two modes of decomposition of a sequence of the *LHF* time layers using EOF (dimensionless)

The time function of the main mode (Fig. 5) has a pronounced annual variation with maximum values in December and January (a little more and a little less than 1.5 MJ/m^2) and minimum values in July and June (about 0.2 MJ/m^2). It is well described by the annual cycle with an amplitude of 0.7 MJ/m^2 and a phase of 334° which corresponds to the above noted maximum in December. It is characterized by low-frequency modulation, most pronounced for winter maxima, with a period of about 6 years. The highest function values in December 2020 (1.84 MJ/m^2) and 2005 (1.79 MJ/m^2) stand out noticeably.

In general, the spatial distribution and temporal function of this mode reveal the most general patterns of the LHF distribution: the presence of areas with the most intense evaporation in the cold season in the zones of influence of the warm Kuroshio and Tsushima Currents and low LHF values in the northern part of the region under study including in frozen areas.

The distribution of the spatial function of the second mode (it accounts for 1.4% of the LHF dispersion) is significantly more complex. It characterizes the parameter variations that are not in phase, which are described by the first mode discussed above. Therefore, it has a nodal line dividing zones with the opposite sign. The area with positive values occupies part of the Northwest Pacific Ocean south of the 45°N parallel with maxima near the Honshu eastern coast (~ 2). Positive values of the function were also revealed in the eastern part of the considered area of the Bering Sea and in a narrow strip near the Middle Kuril Islands. In the rest of the Northwest Pacific Ocean (north of the 45th parallel) and in the waters of the Far Eastern seas, the spatial function is negative, the maximum absolute values are noted in the western part of the Sea of Okhotsk and in the Sea of Japan (from −1 to −2), extreme values are found in a small area off the Hokkaido southern coast (~ −3).



F i g. 5. Variations in time functions of the first (*top*) and second (*bottom*) modes of decomposition of a sequence of the *LHF* time layers using EOF

The time function of this mode is described by a combination of annual and semi-annual cycles with amplitudes of about 1 and 0.4 MJ/m^2. The average annual variation of this function is characterized by maximum values in November (1.3 MJ/m^2) and October (1.1 MJ/m^2) and minimum values in April and May (−1.1 MJ/m^2). This means that in autumn the second mode provides a positive correction to the main component in the southern part of the region under study and a negative correction in the northern and especially in its northwestern sections. In spring, the contribution of this opposite nature mode is observed. The interannual variability of the time function of the second mode is more significant compared to the first one and is not regular.

Conclusion

The analysis of an array of average monthly LHF values for 1998–2022 showed the following characteristics of the spatial and temporal variability of this parameter.

The LHF values are universally negative and reach their highest absolute values in the zone of influence of the warm Kuroshio and Tsushima Currents in the cold season (autumn and winter). This is determined by the influence of the winter monsoon characterized by stable and strong winds from the northwest and close to it carrying cold dry air from the mainland. The latent heat flux is insignificant in the northern part of the study area, including in frozen areas.

During the warm period in zones of warm currents, the LHF values decrease significantly in absolute value, which is probably determined by the summer monsoon winds, which are characterized by relatively low speeds and high humidity of the air flow. At the same time, the latent heat flux is positive in a number of areas, although small in magnitude. This indicates the important role of condensation in areas of high cloudiness and in zones of quasi-stationary upwelling.

Calculation of the annual cycle amplitudes showed the greatest range of seasonal variations in the zone of warm currents and its sharp decrease in the northern part of the Northwest Pacific Ocean and the Sea of Okhotsk, as well as in the Bering Sea. This component with an amplitude of 0.7 MJ/m^2 and with high values in December and January (about 1.5 MJ/m^2) and minimum values in July and June (0.2 MJ/m^2) plays a major role in variations in the time function of the EOF main mode. Interannual variations are expressed in quasi-cyclic changes in the envelope along maximum values with a period of about 6 years. Unidirectional trends in interannual LHF variations are weakly expressed.

The results obtained can be used to study the variability of thermal conditions in the surface layer of the Northwest Pacific Ocean and the Far Eastern seas to improve forecasts of the timing and conditions of feeding and spawning migrations of Pacific salmon, as well as other species of pelagic fish.

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Contribution of the co-authors:
Georgiy V. Shevchenko – analyzing and summarizing the research results, paper preparation

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

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