

Original article

Manifestations and Characteristics of Marine Heat Waves in the Northwestern Pacific Ocean

I. D. Rostov ✉, E. V. Dmitrieva

*V. I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch of Russian Academy of Sciences,
Vladivostok, Russian Federation*
✉ rostov@poi.dvo.ru

Abstract

Purpose. The purpose of the study is to determine the characteristics and trends of interannual variability of marine heat wave (MHW) parameters in the northwestern Pacific Ocean over the past two decades, as well as to analyze their causal-and-effect relationships with large-scale and regional processes in the ocean and atmosphere.

Methods and Results. Analysis in the study was done using the NOAA climate datasets. Standard methods for identifying marine heat waves and assessing their amplitude-frequency characteristics at the regular grid points were applied. The obtained results made it possible to characterize in detail the spatial-temporal variability of marine heat waves including their frequency, duration, intensity, and integral parameters (cumulative intensity and composite intensity index). Besides, they permitted to reveal the interannual and seasonal trends in three denoted regions located in different latitudinal zones of the area under study, and to determine statistical relations between the marine heat wave characteristics and the large-scale and regional processes in the ocean and atmosphere.

Conclusions. The study area of the Pacific Ocean shows a stable increase in sea surface temperature, namely on average by ~ 0.5 °C over 10 years with a growing trend from south to north (from 0.3 to 2 °C). The interannual fluctuations of sea surface temperature (periodicity is 2–5 years) are related to the changes of *ENSO* (*NINO.W*) index. Over the past two decades, the annual average frequency of marine heat waves was ~ 3 events per year increasing by 1.8 events per decade, and its average duration was ~ 14 days, with a positive trend of 5.9 days/10 years. The performed investigations have made it possible to reveal statistically significant relations between the marine heat wave parameters and the large-scale climatic modes, as well as a close correlation ($R > 0.7$) with the changes in surface air and ocean surface temperatures in the region.

Keywords: northwestern Pacific Ocean, climate changes, marine heat waves, climate indices, correlation relationships

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Introduction

The northwestern Pacific Ocean is characterized by complex climatic and oceanological conditions. Strong boundary currents, significant meridional gradients and spatiotemporal variations in water temperature and salinity, as well



as the influence of monsoons and typhoons, are observed here; all the above-mentioned factors form a specific climate. These conditions have a significant impact on coastal ecosystems, shipping, fisheries, and other types of activities in the region.

Marine heat waves (MHWs) are discrete extreme events manifested as strong positive temperature anomalies on the surface or in the upper layer of the ocean. They arise as a result of atmospheric and/or oceanic processes [1] and are characterized by several key parameters: occurrence frequency, duration, intensity, evolution rate, and spatial extent [2]. Marine heat waves can cover areas ranging from several kilometers to several thousand kilometers and last from five days to several months [3]. Such phenomena can have a devastating impact on marine ecosystems and provoke negative socio-economic consequences [4]. Qualitatively, MHWs are defined [5] as discrete periods of prolonged anomalously warm water at the surface at a specific location, while quantitative definitions are based on ocean temperatures exceeding fixed, seasonally varying, or cumulative threshold values.

The MHWs formation is determined by a complex of local processes in the upper mixed layer. These processes are regulated by climatic regimes and their remote relationships [6] through “atmospheric bridges” [7]. The mechanisms of their formation and maintenance are complex and diverse, depending on the balance of heat sources and other factors [8]. Special metrics for the quantitative assessment of MHWs make it possible to compare events in different regions and at different times [2, 9].

Satellite observations show that over the past decades, in most areas of the World Ocean, including the northwestern Pacific, there has been a significant increase in the frequency, duration, and intensity of MHWs, primarily due to the gradual warming of its surface [3]. The greatest changes in MHW characteristics in the future are expected in the western tropical Pacific and the Arctic Ocean [10]. As global warming progresses, the upper mixed layer of the ocean becomes thinner, making it more susceptible to extreme warming [11]. This leads to more abrupt temperature fluctuations and an increase in the frequency and intensity of MHWs, especially in shallow marginal seas [12, 13].

Since approximately 2013, the warming rate in the North Pacific has increased significantly compared to other basins [14]. The combined impact of MHWs, harmful algal blooms (HABs) [15], increased stratification, ocean acidification, and decreased oxygen concentration poses a serious threat to coastal ecosystems [16]. The degree of their impact on marine organisms and ecosystems is largely regulated by regional conditions [17] and climatic regimes [18].

The northwestern region of the Pacific Ocean stands out for its increased vulnerability due to its high content of dissolved inorganic carbon and low oxygen levels. This region became one of those where noticeable changes in environmental conditions occurred in recent decades [19, 20]. The strongest, longest, and most extensive events, with catastrophic consequences for marine ecosystems and various sectors of the region economy, have occurred here in the last decade. The shallow semi-enclosed region of the continental shelf of the East Asian marginal seas is recognized as an important hotspot for MHW distribution with associated HABs [21]. Record marine heat waves were observed in the summer and autumn of 2020 [22, 23], and in July – August 2021, intense MHWs covered vast areas, including

the Sea of Japan and part of the Sea of Okhotsk. The distribution of MHWs was closely related to heat fluxes on the sea surface, indicating the leading role of atmospheric forcing in their formation. One month after the decline of the most intense MHWs off the southeastern coast of Hokkaido, a HAB outbreak occurred [23, 24]. This event was synchronized with the deepening of the mixed layer at the final stage of MHW development and was accompanied by the upwelling of nutrients from deeper layers. In the summer of 2022, unprecedented in duration (168 days) MHWs in the subarctic zone reached an intensity of 4.6 °C and covered more than 1.5 million km², affecting the Sea of Okhotsk, the western part of the Bering Sea, and the East China Sea [25].

The most intense MHWs in the region are observed in summer, when the upper mixed layer is thinnest. The maximum variability of sea surface temperature (SST) anomalies, intensity, and duration of MHWs in the study area were observed in the Kuroshio – Oyashio Extension region (35–44°N, 141–175°E), where the summer monsoon has a significant influence [26]. It was established that extreme MHW manifestations intensified during El Niño periods, and their intensity depended on the thickness of the upper mixed layer and had a seasonal cycle [27].

Most cases of MHW generation in the region are associated with the formation of persistent subtropical anticyclones and anomalously weak winds. This leads to a reduction in cloud cover, increased incoming solar radiation, weakened ocean heat loss, and increased net heat input into the surface layer. Wind weakening also increases stratification and reduces the mixed layer depth, contributing to extreme surface warming.

These processes are modulated by low-frequency climatic modes – primarily the phases of El Niño – Southern Oscillation (ENSO) [27], the Pacific Decadal Oscillation (PDO), and the Indian Ocean Dipole (DMI), which enhance the meridional transport of heat from the tropics to temperate latitudes. Excess heat is generated by increased convection and the input of latent heat from extreme precipitation, and its further transport is carried out via planetary Rossby waves [28].

It should be noted that MHW manifestations on the surface of the tropical western Pacific are relatively weak [29, 30], but they intensify in the subsurface layer (50–300 m) [14] and are largely due to dynamic factors [14, 27, 31].

In 2010–2016, intense summer MHWs were observed in the Oyashio region [32]. Their intensity was enhanced by the axial migration of the Kuroshio Extension [26], frontal shifts, changes in heat advection, and the impact of warm anticyclonic mesoscale eddies [27, 32], which detached from the main current every summer during this period. These local MHWs off Hokkaido had a serious negative impact on fisheries [33].

In general, the factors determining the onset and termination of MHWs are diverse and depend on the region, season, and scale of the event [34]. Oceanic advection plays a key role in the formation of small-scale MHWs, while for large-scale events, atmospheric processes are the main driver. As the spatial scale of MHWs increases, they tend to become less intense but more prolonged [6]. During extreme warming events, vertical mixing weakens and stratification intensifies, which reduces the supply of nutrients to the surface and worsens oxygen conditions [35]. At the same time, more frequent MHW occurrences were observed in coastal areas of the East Asian seas and along the Kuroshio Current axis [28, 36, 37].

Despite the recognized importance of studying MHW events, the spatiotemporal features of their manifestation, regional characteristics, and their relationship with local processes in the monsoon climate of the region are studied insufficiently. The purpose of this work is to determine the characteristics and trends of interannual variability of marine heat wave parameters in different climatic zones of the northwestern Pacific Ocean between the equator and 45°N over the past two decades, as well as to clarify the possible causal relationships of these events with large-scale and regional climatic processes.

Data and methods

As the primary source of information applied was the optimally interpolated daily sea surface temperature data (NOAA OI SST, V2) at grid points of $0.25 \times 0.25^\circ$ for 1982–2024 (<https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>).

To identify and analyze marine heat waves, the detection method proposed in [2] was applied. An MHW event was defined as a period during which sea surface temperature exceeds the seasonally adjusted 90th percentile climatological threshold for at least five consecutive days. Events separated by an interval of less than three days were combined into one. Data for 1988–2018 were used as the baseline climatic period, and processing was carried out using MATLAB software [38]. At each grid node, as well as averaged over the region, key MHW metrics [2, 9] were determined:

- frequency – number of MHW events per year (F);
- duration – number of days between the start and end of MHW (D , days);
- mean intensity of a single MHW event – average SST anomaly over the entire event period calculated as the deviation from the climatic norm (I_{mean} , °C);
- maximum intensity – the highest SST anomaly value recorded during the event (I_{max} , °C);
- cumulative intensity for a single event (I_{cum} , °C);
- integral composite intensity index, considering the number, duration, and strength of all recorded events over the entire period (ICI , °C·day);

For the analysis of associated atmospheric conditions and climatic factors, the following were used:

- reanalysis data on surface air temperature and atmospheric pressure (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>);
- time series of climate indices *NPGO*, *PDO*, *IPO*, *NINO.WEST* [23] and the Indian Ocean Dipole index (*DMI*) (<https://psl.noaa.gov/data/gridded/index.html>, <https://psl.noaa.gov/data/climateindices/list/>).

The Western Pacific Subtropical High (*WPSH*) index from the China Meteorological Agency (CMA) website was also applied (https://cmdp.ncc-a.net/download/precipitation/diagnosis/NWP_high/wpsh_idx.txt).

Based on the data on the interannual variability of SST and MHWs, three distinct regions located in different latitudinal zones of the area were identified: northern (N), central (C), and southern (S). Subsequently, by simply averaging the grid data over the entire area of these regions, the long-term course of key MHW characteristics in each of them was calculated.

Modern warming trends in the northwestern Pacific Ocean

Over the past two decades, stable positive statistically significant linear trends in interannual sea surface temperature changes have been observed (Fig. 1, *a*), on average, in the study area. Trend values increase from south to north: from 0.3 °C per 10 years in the southern region to 2 °C per 10 years in the western part of the northern region, and overall across the region they amount to ~ 0.5 °C per 10 years.

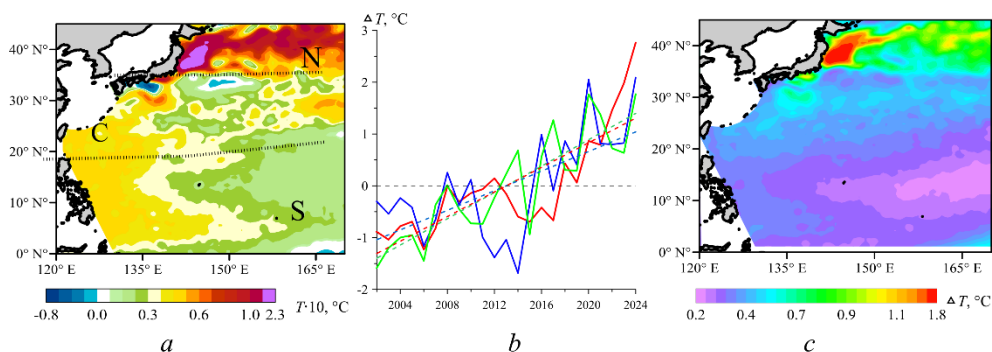


Fig. 1. Trends in annual average SST anomalies for 2002–2024 – *a* (N – northern, C – central and S – southern regions); interannual variability of SST anomalies – *b* (solid lines are SST anomalies, dashed lines – linear trends, red lines correspond to the northern region, blue lines – to the central region, and green ones – to the southern region); SST standard deviations for the denoted period – *c*

The northern region, located in the latitude band between 35 and 45°N (Fig. 1, *a*), covers the waters of the southern periphery of the western subarctic cyclonic gyre cell and the northern band of the subtropical anticyclonic gyre. Here lie the area of interaction, mixing, and continuation of the cold Oyashio and warm Kuroshio currents, the boundaries, and the interstructural zone of the subarctic front (Oyashio-Kuroshio Transition Zone – OKTZ [26]). Here, in the region of western boundary currents and their extensions, sharp horizontal SST gradients lead to the fact that even minor spatial shifts in the axis of currents and the position of frontal zones are transformed into large (in area and intensity) SST anomalies. It is here that the most noticeable trends in SST increase are observed [30]. To the south lie the central and southern regions, including the waters of the subtropical and tropical climatic zones, the boundary between which runs approximately along 20°N [39], with corresponding types of thermohaline water structure and current patterns.

The southern region is located in the area of the tropical warm basin of the western Pacific Ocean (WPWP), where SST values are above 28 °C year-round.

Annual average indicators of marine heat wave characteristics and their temporal variability

Marine heat waves began to manifest themselves in the early 1980s against the background of interannual and seasonal changes in the temperature regime. They were characterized by significant spatiotemporal heterogeneity and gradually covered an increasing area of the selected regions (Fig. 2). The interannual course of the amplitudes of climatic averages and the 90th percentile in the seasonal temperature cycle is similar for each of the regions. Their amplitude decreases in the direction from the northern region to the southern one. In 2002, MHWs were

not expressed at all on the ocean surface in the selected areas of the grid domain, where conditions for the manifestation of such waves apparently had not yet formed (Fig. 3, *a, c, e*). In contrast, in 2022, daily average SST values noticeably exceeded the 90th percentile, demonstrating a response to MHW events (Fig. 3, *b, d, f*). At the same time, the periods of onset, termination, and duration of MHW events differ in each of the regions, and in the central region they were observed only in summer (Fig. 3, *d*). In 2022, the northern region recorded the longest MHW duration compared to other regions (Fig. 3, *b, d, f*).

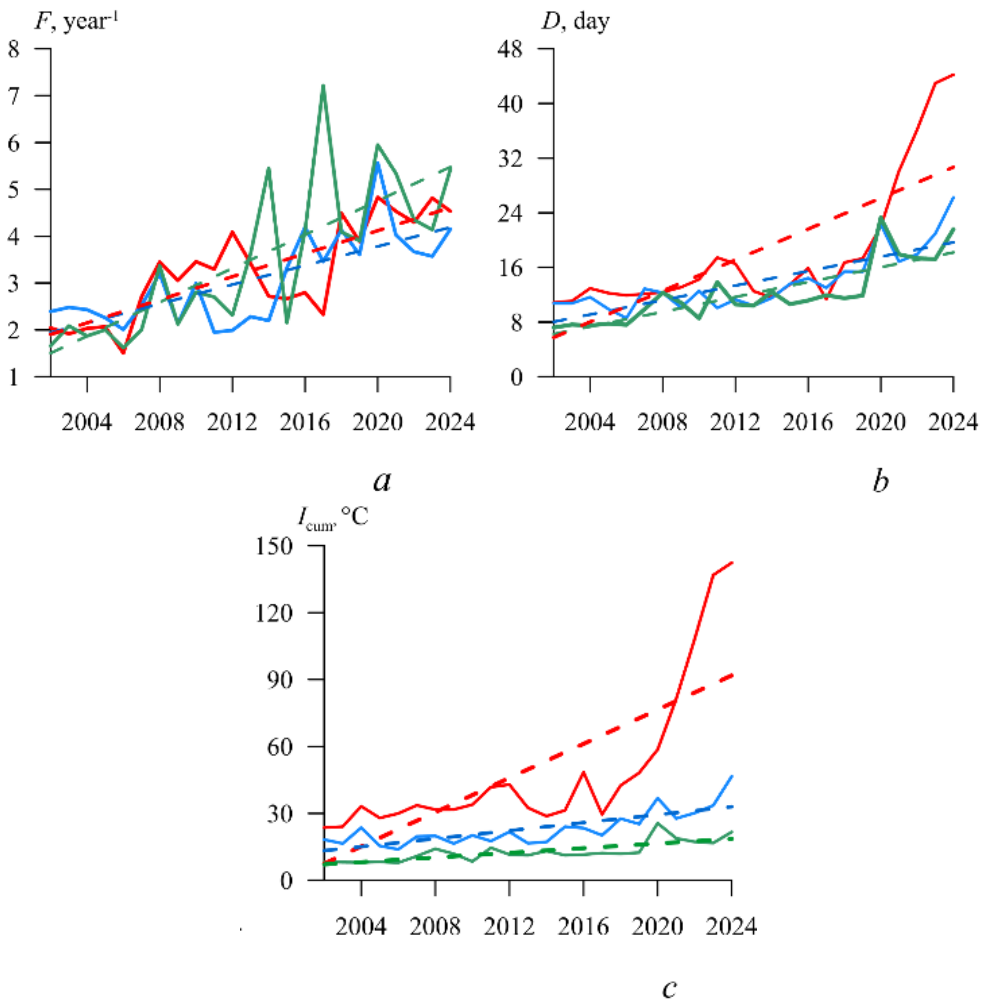


Fig. 2. Regionally averaged annual mean values of frequency (*a*), duration (*b*), and cumulative intensity (*c*) of MHW events for 2002–2024 (solid line is MHW parameter, dashed lines are linear trends, red lines correspond to the northern region, blue lines – to the central region, and green ones – to the southern region)

Preliminary estimates showed that if in the early 2000s the number of grid nodes where MHWs of varying intensity and duration manifested themselves occupied ~ 60% of the area, then by 2020 these events covered almost the entire area.

At the same time, the frequency of MHW events, their duration, and cumulative intensity (Fig. 2) in the region increased during this period with a significant trend, which caused catastrophic consequences for marine ecosystems and various sectors of the region economy [24].

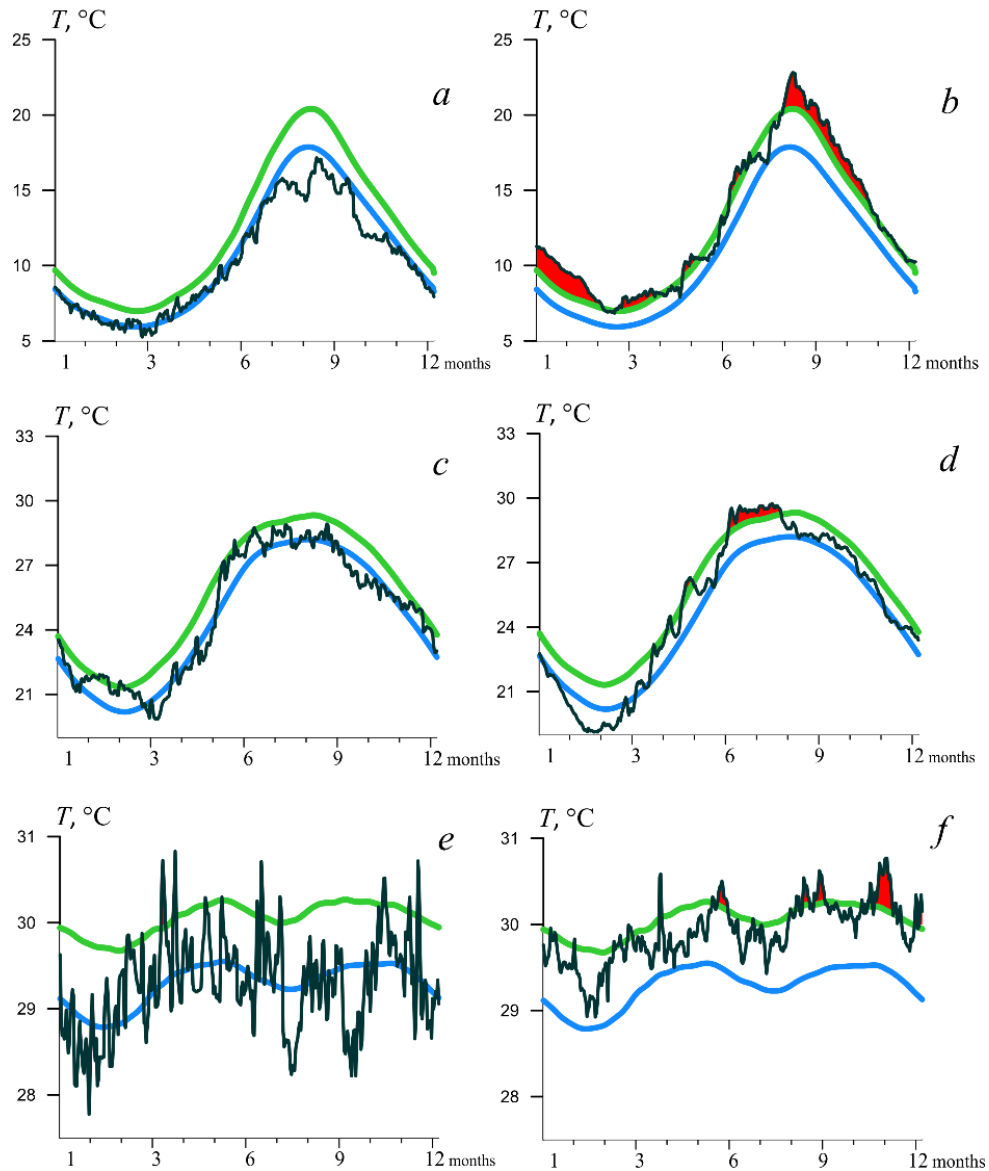


Fig. 3. Changes in the daily average SST values (black lines), climatological average SST values (blue lines), and threshold values of the 90th percentile (green lines) averaged over $2^{\circ} \times 2^{\circ}$ grid cells for the central part of the denoted regions: northern – 42°N (*a, b*), central – 27°N (*c, d*), and southern – 4°N (*e, f*) in 2002 (on the left) and in 2022 (on the right). SST values exceeding the 90th percentile threshold are highlighted in red

In general, according to averaged data for 2002–2024 for the entire study region of the northwestern Pacific Ocean and the identified subregions, interannual changes in MHWs were characterized by the following quantitative estimates (Table 1).

Table 1

Characteristics of interannual changes in the annual average SST and MHW values in the northwestern Pacific Ocean and in the denoted areas in 2002–2024

Parameter	SST	F	D	I_{mean}	I_{max}	I_{cum}
<i>Northern region</i>						
Average	13.7	3.3	18.2	2.4	3.0	49.7
Maximum	15.7	4.8	44.2	2.8	3.8	142.3
Trend b	0.8	1.2	11.3	0.2	0.4	38.3
<i>Central region</i>						
Average	23.4	3.1	13.9	1.6	2.0	23.2
Maximum	24.1	5.6	26.3	1.8	2.2	46.6
Trend b	0.3	1.0	5.3	0.0	0.0	8.9
<i>Southern region</i>						
Average	28.7	3.4	12.2	1.0	1.3	12.9
Maximum	29.1	7.2	23.3	1.1	1.4	25.6
Trend b	0.3	1.8	5.4	-0.1	-0.1	5.2

Note: Statistically significant (95 %) linear trend estimates are shown in bold.

According to our research, the following features of key MHW metrics were established:

- the average annual frequency of MHW events at grid nodes, on average across the entire region, was ~ 3 events per year. It differed little in the selected regions and increased on average at a rate of 1.8 events per decade. In the southern region, an absolute maximum F (7.2 per year) was noted in 2017. The largest positive trend in F was also observed there (Table 1). In the northern and central regions, the largest maxima of F (~ 5–6 events per year) were recorded in 2020;

- mean duration of individual events, on average across the entire region, was ~ 14 days, varying in the northern, central, and southern regions in the interannual course from ~ 12 to 18 days, with a trend of 5.9 days per 10 years for the entire area. The largest values of the D trend were 11.3 days per 10 years and were observed in the northern region;

- the largest average values of mean, maximum, and cumulative intensity and their trends were also noted in the northern region, which is consistent with the results of other studies [26];

- relationship between the duration of MHW events and their frequency is characterized by high correlation coefficients ($R = 0.7$);

- composite intensity index, reflecting the integral influence of the frequency, duration, and intensity of MHWs, correlates closely with the interannual changes in SST in the study regions ($R > 0.9$). It is especially high in the anomalously warm years 2020 and 2024 (Fig. 2, c).

We should note high stability of average annual characteristics of marine heat waves in the selected regions, despite the differing SST trends, since the main mechanisms of MHW formation in these regions are associated with the dominance

of the same synoptic processes over the region waters – blocking anticyclones and stagnant baric fields, and the duration of such situations and synoptic recurrence sets the natural time scale of MHWs.

Spatial structure of MHW manifestations

Spatial distribution of MHW characteristics in the area under study is given in Fig. 4. Their regional features over the past two decades are as follows:

- average maximum frequency of events (~ 5 per year) for the period 2002–2024 is noted in the area off the eastern coast of Honshu Island (Fig. 4, *a*);
- duration of individual events varies from 8 to 45 days (in the northern part of the area, Fig. 4, *b*), and on average across the entire area is 15 days;
- mean and average maximum intensity of MHWs (Fig. 4, *d*, *e*) in the region is 1.4 and 2.8 °C, respectively (Fig. 4, *d*, *e*), and their maximum values are especially pronounced in the waters located northeast of Japan;
- composite intensity index has the highest values in the northern region and also northeast of Japan (Fig. 4, *c*). Its maximum values coincide with the distribution of the cumulative index (Fig. 4, *f*). Both indices are important indicators of the MHW potential impact on marine ecosystems, and in 2020–2024 they reached their maximum values.

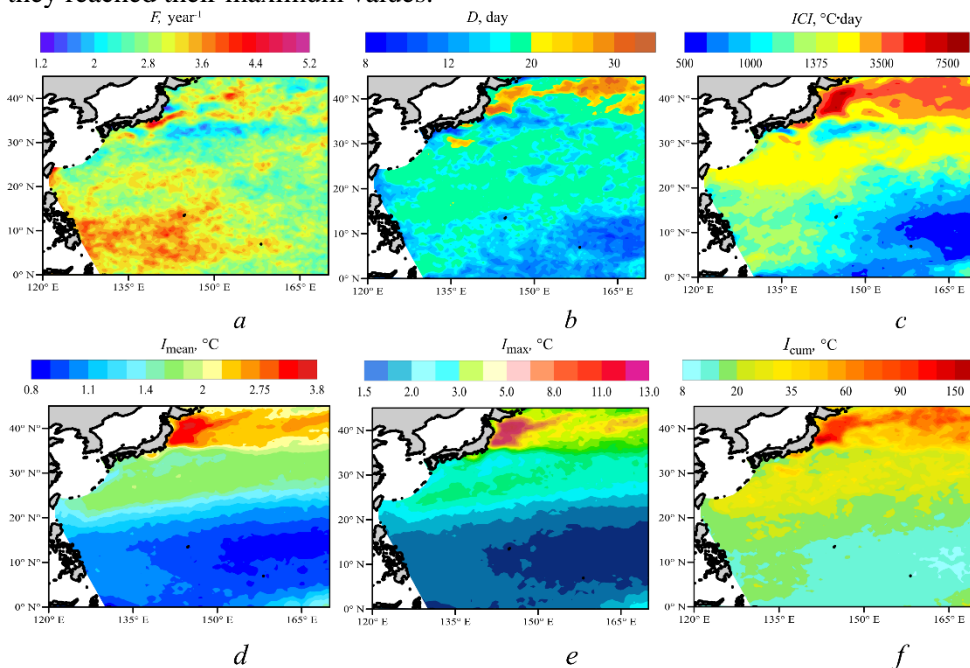


Fig. 4. Spatial distribution of the MHW long-term average annual characteristics for 2002–2024: MHW event frequency – *a*; duration – *b*; composite intensity index – *c*; mean intensity – *d*; average maximum intensity – *e*; and cumulative intensity – *f*

The increase in the values of the considered characteristics could have had a significant impact on recent cases of massive HAB events in the area of the Pacific coast of Honshu and Hokkaido islands (Japan), data on which are regularly received from various research organizations into the international database (<https://haedat.iode.org/index.php>). HAB events that occurred in 2021, in the context

of environmental conditions and MHW development, have already been considered earlier [23, 24]. Dangerous changes in environmental conditions caused by outbreaks of harmful algal blooms of the species *Karenia*, *Cochlodinium*, *Alexandrium*, and *Noctiluca scintillans* were recorded again in 2022–2024 in the waters of various Japanese prefectures located on the Pacific coast in the eastern and southern parts of Honshu Island. During this period, MHWs were well expressed, and their manifestations were observed annually from March to December (Fig. 5). The total annual duration of MHWs varied in the range of 123–255 days.

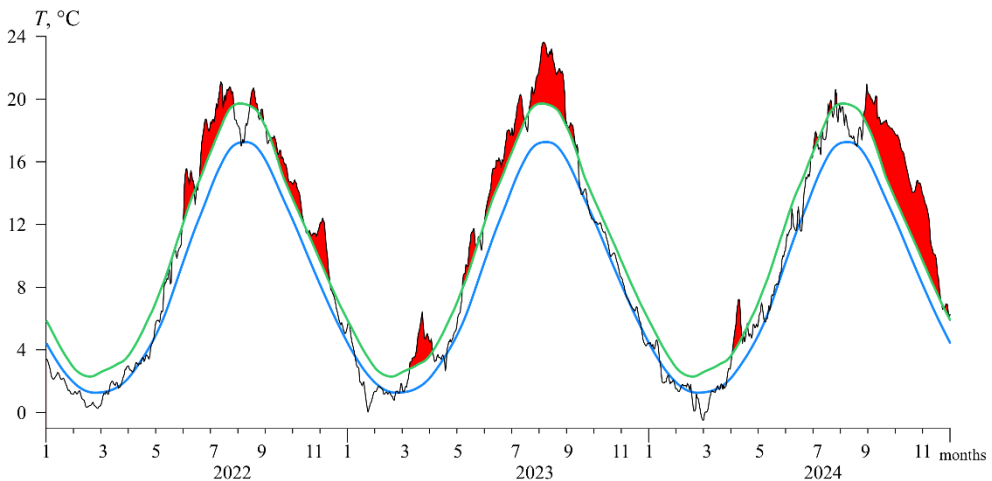


Fig. 5. Changes in daily average SST values (black lines) off the Pacific coast of the Honshu and Hokkaido islands in 2022–2024, climatological mean SST values (blue lines) and threshold values of the 90th percentile (green lines); SST values exceeding the 90th percentile are highlighted in red

Correlation relationships between changes in MHW parameters and climatic characteristics

A mutual correlation and regression analysis of the interannual variations in the time series of MHW characteristics with climatic indices and other indicators characterizing the dynamics of the atmospheric and oceanic climate system in the study area was carried out. In general, for the region, correlation relationships between MHW parameters and the leading modes of large-scale processes in the ocean and atmosphere are well expressed, such as the Pacific Decadal Oscillation, the North Pacific Oscillation of the Subarctic Gyre (*NPGO*), the Interdecadal Pacific Oscillation (*IPO*), and the Western Pacific Subtropical High (*WPSH*), as well as the *ENSO* indicator in the northwestern part of the tropical Pacific (*NINO.W*). These indices reflect various aspects of atmospheric and oceanic circulation that modulate thermal conditions in the ocean, and the correlation relationships between these indices and MHW characteristics are based on various physical mechanisms, including changes in ocean circulation, heat advection, atmospheric processes, and vertical mixing. At the same time, the value and sign of the corresponding correlation coefficients depend on the trend of changes, seasonality, and phase of oscillations of the considered indices, which changes sign in the interannual course. Correlation analysis also indicates a close ($R > 0.7$)

relationship between most MHW characteristics and changes in surface air temperature and SST in the region (Table 2).

Estimates of correlation coefficients between changes in various parameters differ significantly across the study areas (Table 2), which is due to their climatic differences and the selective sensitivity of waters to temperature stressors. Thus, the consistency of fluctuations in average annual surface air temperature (SST_a) and SST increases from south to north: the R value increases approximately twofold – to 0.8 in the central and to 0.88 in the northern region, where the seasonal temperature cycle is most pronounced (Fig. 2). At the same time, the correlation between SST and most MHW characteristics remains high and statistically significant in all regions. However, the relationships of MHWs with both SST and air temperature fluctuations gradually weaken in the direction from the northern region to the southern one. In the southern region, correlation coefficients for most MHW characteristics and SAT are statistically insignificant.

A change in the sign of the correlation between SST and MHW intensity (I_{mean} , I_{max}) is also observed – from negative in the south to positive in the north (Table 2). This asynchrony can be explained by a change in the dominant mechanism of heat wave formation. In the tropics (negative correlation), the main driver is atmospheric processes, and the conditions for MHW formation are determined by the interaction of background SST with colder deep layers. In middle and high latitudes (positive correlation), the accumulation of heat in the ocean column due to enhanced flux from the atmosphere, advection of warm waters, and shallow mixed layer depth (MLD) plays a key role [12]. A shallow MLD forms stable stratification, which contributes to the concentration of heat at the surface and leads to anomalously high temperatures in the surface layer. Thus, a high background SST serves as an indicator of significant ocean heat content, which directly determines more intense and prolonged MHWs. The spatial distribution of regression coefficients of MLD with the mean intensity of MHWs indicates close negative relationships between these parameters in all study regions: a decrease in the mixed layer depth is accompanied by an increase in I_{mean} (Fig. 6, *a*). Over the past two decades, trends in decreasing MLD thickness were most pronounced in the northern region (-6.7 m/10 years), while on average across the area they amounted to -1.8 m/10 years (Fig. 6, *b*). It is in the northern region that the highest values of frequency, duration, intensity, and cumulative MHW characteristics are observed.

Almost all MHW parameters in the selected regions show significant positive relationships with the $WPSH$ and $NINO.W$ indices. $WPSH$ index characterizes intensity and position of the western part of the Pacific subtropical high. The high-pressure area located north of $10^\circ N$ blocks the westerly flow, which leads to a decrease in cloud cover and weakening of winds [29].

The strengthening, expansion, and westward shift of the $WPSH$ observed over the past 30 years suppresses cloudiness, weakens monsoon circulation, and increases insolation. As a result, the warming of surface waters intensifies, heat accumulates in the ocean, and the frequency, duration, and intensity of MHWs increase [28]. Statistically significant correlations between $WPSH$ and MHW parameters in all regions confirm this relationship (Table 2).

Table 2

Correlation coefficients (R) between MHW characteristics and climatic parameters for 2002–2024

Parameters	F	D	I_{mean}	I_{max}	I_{cum}	ICI	TIIO / SST
<i>Northern region</i>							
R/SAT	0.81	0.79	0.43	0.57	0.78	0.83	0.88
R/SST	0.87	0.94	0.68	0.75	0.94	0.97	–
$R/WPSH$	0.46	0.59	0.55	0.63	0.61	–0.60	0.61
$R/NINO.W$	0.71	0.71	0.66	0.73	0.71	0.74	0.78
$R/NPGO$	0.41	–0.52	–0.38	–0.46	–0.53	–0.52	–0.49
<i>Central region</i>							
$R/SSTa$	0.84	0.62	–0.26	–0.09	0.56	0.73	0.80
R/SST	0.91	0.87	0.02	0.16	0.85	0.95	–
$R/WPSH$	0.77	0.81	–0.19	–0.04	0.73	0.82	0.76
$R/NINO.W$	0.64	0.76	–0.16	–0.04	0.70	0.70	0.62
$R/NPGO$	–0.63	–0.64	0.10	–0.01	–0.62	–0.67	–0.57
<i>Southern region</i>							
$R/SSTa$	0.47	0.26	–0.11	0.05	0.26	0.41	0.45
R/SST	0.92	0.84	–0.57	–0.38	0.83	0.93	–
$R/WPSH$	0.62	0.65	–0.64	–0.49	0.61	0.71	0.67
$R/NINO.W$	0.86	0.85	–0.67	–0.49	0.81	0.88	0.90
$R/NPGO$	–0.51	–0.53	0.57	0.48	–0.48	–0.58	–0.54

Note. SAT and SST are the annual average values of the surface air and sea surface temperatures based on the reanalysis data; statistically significant (95%) estimates are highlighted in bold.

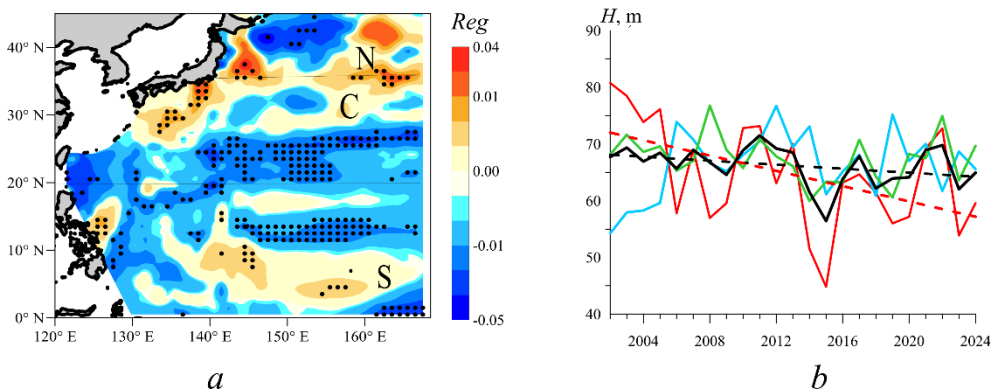


Fig. 6. Spatial distribution of regression coefficients between the I_{mean} and MLD annual values, crosses mark grid nodes with statistically significant (95%) estimates of the linear trend (*a*); interannual variability of the averaged over regions MLD depths (*b*). Solid lines are the MLD values, dashed ones – the linear trends for 2002–2024; red lines correspond to the northern region, blue lines – to the central region, green lines – to the southern region, and black ones – to the entire water area as a whole

Strong correlation relationships between MHW characteristics and the $NINO.W$ index reveal that SST anomalies in the western equatorial Pacific are a key factor in extreme warming events in the region. This leads to heat accumulation in the surface layer, increased intensity, and increased duration of MHWs (Table 2). Thus, the identified relationships reflect the local impact of large-scale processes

on the structure of pressure and wind fields, thermal conditions, and MHW characteristics in the region.

Since the 1990s, intensification of the subarctic cyclonic gyre in the North Pacific, described by the *NPGO* index [40], has affected the Kuroshio-Oyashio current system and altered SST gradients. The dynamics of the gyre are determined by several key factors: the variability of position and expression of atmospheric action centers, fluctuations in surface pressure in the North Pacific, and associated changes in the wind regime. This causes anomalous warming in the northwestern sector due to advection of warm waters and vertical mixing weakening, which contributes to the formation of marine heat waves primarily in the northern and central regions. Long-term changes in *PDO* and *IPO* have a significant impact on heat transport between equatorial and temperate latitudes through oceanic and atmospheric teleconnections. In their negative phases, these indices enhance anticyclonic conditions over the northwestern Pacific, creating an environment favorable for the formation of heat waves [39, 40].

Conclusion

The characteristics and trends of interannual variability of SST and marine heat wave parameters were determined in three selected regions located in different latitudinal zones in the northwestern Pacific Ocean. An analysis of the causal relationships between MHW characteristics and large-scale as well as regional processes in the ocean and atmosphere over the past two decades was carried out. The following results were obtained.

1. The study area as a whole is characterized by stable positive linear trends in interannual sea surface temperature changes, statistically significant throughout the territory. The average trend value of annual SST across the region is ~ 0.5 °C/10 years, while it increases from south to north – from 0.3 °C/10 years in the southern part to 2 °C/10 years in the western part of the northern sector. Interannual SST fluctuations in the selected regions occur with a periodicity of 2–5 years and are associated with changes in the *NINO.W* climate index.

2. Against the background of interannual and seasonal changes in the temperature regime, short periods of extreme positive SST anomalies, classified as marine heat waves, began to appear annually in the study area since the early 1980s, gradually occupying an increasing area of the selected regions. By 2020, these events covered the entire area of the region.

3. Average annual frequency of MHW manifestations at grid nodes across the entire study area was ~ 3 events/year, with an observed increase of 1.8 events per decade.

4. Average duration of individual MHW events across the entire region was ~ 14 days, varying in the northern, central, and southern regions in the interannual course from ~ 12 to 18 days, with an average trend for the entire area of 5.9 days/10 years.

5. The largest spatially averaged values of all three intensity metrics (mean, maximum, and cumulative), as well as the corresponding trends, are typical for the northern region, which is consistent with data from other studies. It was here, off the eastern Pacific coast of Japan, that in 2021 the most powerful, prolonged,

and extensive MHW and harmful algal bloom events occurred, leading to catastrophic consequences for marine ecosystems and key sectors of the region economy.

6. The maximum frequency of MHW manifestations (up to 5 events/year) is observed in the area off the eastern coast of Honshu Island. The duration of individual anomalies varies within 8–45 days, with the highest values recorded in the northern sector of the area.

7. Mean and average maximum intensity of MHWs in the region are 1.4 and 2.8 °C, respectively, and their maximum values of 3.6 and 4.7 °C are also noted in the northern region and are especially pronounced in the marine zone located northeast of Japan.

8. The highest values of the composite intensity index were noted in the northern region and in waters northeast of Japan, which is consistent with the spatial distribution of the cumulative index. Both indicators serve as key ones of the potential MHW impact on marine ecosystems and reached absolute maxima in the period 2020–2024. The growth of these parameters likely contributed to the increased frequency of massive harmful algal blooms off the Pacific coast of Honshu and Hokkaido islands, where temperature anomalies manifested most intensely during the considered period.

Correlation relationships between MHW parameters and the leading modes of large-scale processes in the ocean and atmosphere – such as the Pacific Decadal Oscillation, the North Pacific Oscillation of the Subarctic Gyre, the Interdecadal Pacific Oscillation, the Western Pacific Subtropical High, and *ENSO (NINO.W)* climate index – are well expressed throughout the region. Correlation analysis also indicates a close ($R > 0.7$) relationship between most MHW characteristics and changes in surface air temperature and SST in the region.

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About the authors:

Igor D. Rostov, Leading Researcher, Laboratory of Informatics and Ocean Monitoring, V. I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch of Russian Academy of Sciences (43 Baltiyskaya Str., Vladivostok, 690041, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0001-5081-7279**, **SCOPUS Author ID: 6603588318**, **SPIN-code: 2329-0391**, **ResearcherID: AAG-5614-2021**, rostov@poi.dvo.ru

Elena V. Dmitrieva, Senior Researcher, Laboratory of Informatics and Ocean Monitoring, V. I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch of Russian Academy of Sciences (43 Baltiyskaya Str., Vladivostok, 690041, Russian Federation), CSc. (Tech.), **ORCID ID: 0000-0002-0094-5296**, **Scopus Author ID: 36788322900**, **SPIN-code: 6818-1898**, e_dmitrieva@poi.dvo.ru

Contribution of the co-authors:

Igor D. Rostov – research management, results analysis, manuscript writing

Elena V. Dmitrieva – data processing, data analysis, figure design, text editing

The authors have read and approved the final manuscript.

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