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Original article

Formation of Large Anomalies in the Thermal Conditions of Waters on the Western and Eastern Shelf of the Sakhalin Island

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Abstract
Purpose. The study is aimed at identifying the mechanisms forming large anomalies in the water thermal conditions on the western and eastern shelf of Sakhalin Island being impacted by the atmospheric processes in spring-summer periods.
Methods and results. The data of coastal observation stations performed by the Hydrometeorological Centre of Russia in 1980–2021 permitted to study and assess the multi-year variability of water thermal regime in the fishery regions on the western and eastern Sakhalin shelf from May to August. The extreme fluctuations of monthly average thermal conditions of the water areas were revealed. The years known for formation of large negative and positive anomalies in the water thermal conditions were determined using the criterion analysis method. The fact that frequency of arising of large negative anomalies exceeds that of large positive ones was found. It was established that the mechanisms forming large anomalies were conditioned by the regional features of atmosphere circulation, i.e. by the abnormal changes in development and spreading of the atmosphere action centers (summer Far East depression, Okhotsk anticyclone and Hawaiian maximum). The cause-effect relations were determined.
Conclusions. In Sakhalin Island coastal regions, formation of large anomalies in the water thermal regime is conditioned by the abnormal changes of the baric fields structures in the regional atmosphere action centers, as well as by the changes in their local impact.

Keywords: Sakhalin Island shelf, large temperature anomalies, thermal regime, water dynamics, Sea of Japan, Sea of Okhotsk, atmosphere action centers

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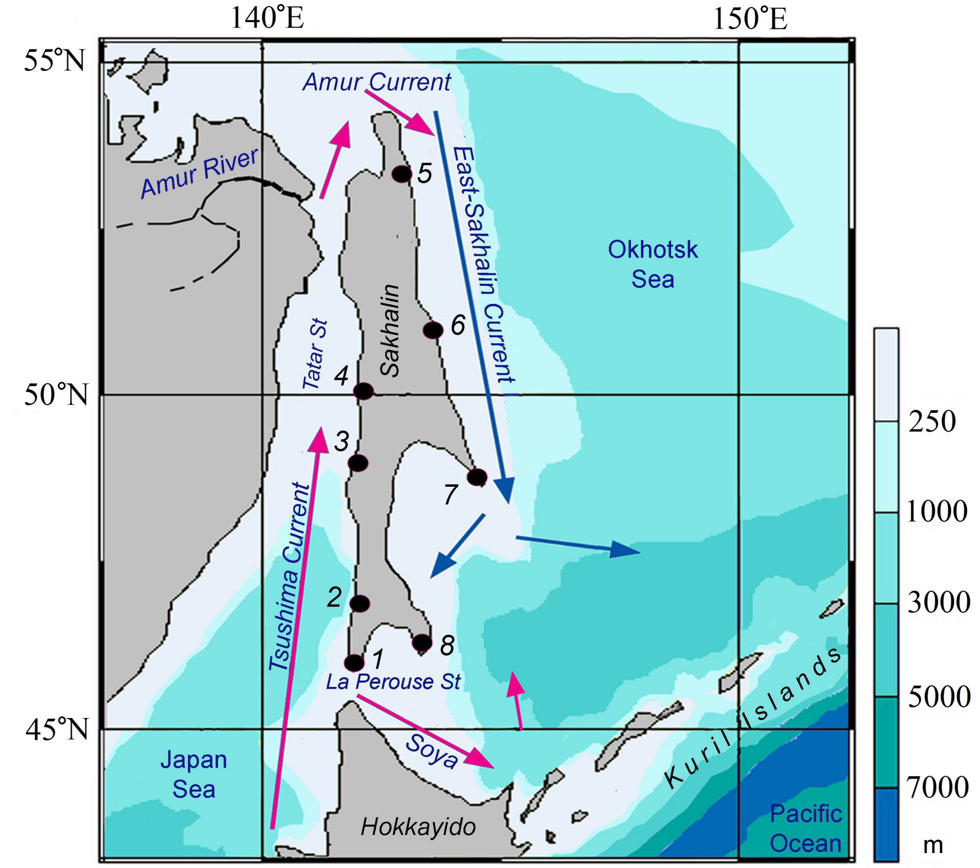
Introduction

Currently, due to the increasing frequency of large anomalies of hydrometeorological phenomena in the backdrop of global warming, much attention is paid to the analysis of these anomalies [1–4].

The subject of this work is to study the features of large anomalies formation in the water thermal conditions on the western and eastern coasts of Sakhalin Island in summer. Water areas under consideration (Fig. 1) are characterized by complex hydrological conditions due to significant length of the island from the south to the north (about 1000 km between 46°N and 55°N). A set of factors that determine features of the area hydrological regime includes the presence of waters of various origins washing the western and eastern coasts of the island (warm Tsushima Current waters of the Sea of Japan and cold East-Sakhalin Current waters of the Sea of Okhotsk, respectively), redistribution of these waters by the system of coastal currents under conditions of indented coastline, as well as the monsoon nature of atmospheric processes with seasonal variations in wind direction [5].



F i g. 1. Region under study. Location of the hydrometeorological stations (HMS): *1* – Cape Krilyon, *2* – Kholmsk, *3* – Uglegorsk, *4* – Pilvo, *5* – Odoptu, *6* – Komrvo, *7* – Cape Terpeniya, *8* – Novikovo

At the same time, the Sakhalin Island waters are important fishery regions in the Far East seas with numerous catch. These are areas of high biological productivity, areas of reproduction of pink salmon which forms the basis of the Asian salmon catch. Its life cycle is largely determined by such an important factor as thermal conditions. However, abnormally low temperatures at the river mouths during the fry migration (May–June) can lead to its death, and extremely high temperatures near the coast affect migration and spawning (July–August) negatively. The formation of abnormally cold or warm thermal conditions in some years leads to the displacement of catch regions which causes difficulties in fishery forecasting [6, 7]. In this regard, the study of cause-effect relations and factors affecting the formation of anomalous thermal conditions in these waters is of particular importance.

In recent decades, the relationship between thermal regime variability during the summer fishing period and the development intensity of regional atmosphere action centers (AAC) has been assessed and their relationship has been identified in a number of areas in the Sea of Japan and the Sea of Okhotsk. The differences in the variability of baric fields in the years with thermal regime anomalies are shown [8, 9]. The approaches for identifying previous baric structures that affect the formation of anomalous conditions of water thermal regimes [10] were proposed.

At the same time, in the areas of the Sakhalin Island shelves of the Sea of Japan and the Sea of Okhotsk the causes for formation of anomalous thermal conditions in certain years are not clear enough. Questions about the formation mechanisms of large cold and warm thermal anomalies in these waters remain open. Identification of these mechanisms and assessment of cause-effect relations constituted the purpose of this study.

The following tasks were resolved under this study:

– research and assessment of interannual variability of the water thermal regime for the period from May to August on the western Sakhalin shelf – the zone affected by the waters of the warm Tsushima Current (HMS Kholmsk, HMS Uglegorsk, HMS Pilvo) and its branch in the Sea of Japan, the Soya Current (HMS Cape Crilyon), as well as on the eastern Sakhalin shelf (HMS Odoptu, HMS Komrvo, HMS Cape Terpeniya, HMS Novikovo) – the zone affected by cold waters of the East-Sakhalin Current (Fig. 1);

– identification of years with large anomalies of thermal conditions from May to August at each HMS;

– assessment of AAC role in the mechanisms forming large anomalies in the water thermal regimes taking into account the features of hydrological conditions in each region.

Data and methods

To study the long-term variability of thermal regime in the region coastal waters, water temperature observations from ESIMO electronic database (available at: http://portal.esimo.ru/portal/), RIHMI-WDC (available at: http://meteo.ru) at the HMS of the Hydrometeorological Centre of Russia for 1980–2021 were used.

To analyze thermal conditions, we used the data on the sea surface temperature in the nodes of 0.25 × 0.25° regular grid for 1980–2021 from the archives of the Japan Meteorological Agency (JMA) (http://ds.data.jma.go.jp/gmd/goos/data/rrtdb/jma-pro/cobe_sst_glb_M.html).

The long-term variability of atmospheric circulation of the second natural synoptic region (2 n.s.r.) was analyzed. We used the reanalysis archive data (NCEP/NCAR Reanalysis Monthly Means and Other Derived Variables) of surface atmospheric pressure (P_0) and geopotential (H_{500}) in the nodes of 2.5 × 2.5° regular grid for 1980–2021. We also used the surface pressure (P_0) and H_{500} geopotential maps for 2000–2021 compiled by JMA to analyze baric fields.

Anomalies (deviations from long-term average values) of surface pressure P_0 and geopotential H_{500} were applied when assessing the interannual variability of AAC development intensity. To assess the variability of thermal conditions, water temperature anomalies (deviations of monthly averages from long-term averages) were used. World Meteorological Organization recommends calculating climatological standard norms as average data for the closest 30-year reference period to the current time ending with the year with the last digit 0 [11]. Monthly average anomalies of all parameters applied in the work were calculated concerning the climate norm for the period 1991–2020.

For calculating large water temperature anomalies, we used the method outlined in [12]. The criterion for the occurrence of such an anomaly (T_w) is the temperature deviation from an average value by 1.2σ, where σ is standard deviation. Five groups of anomalies were distinguished according to their magnitude: extremely low ($T_w \leq -1.2\ \sigma$); low ($-1.2\ \sigma < T_w < -0.4\ \sigma$); average ($-0.4\ \sigma \leq T_w \leq 0.4\ \sigma$); high ($0.4\ \sigma < T_w < 1.2\ \sigma$); extremely high ($T_w \geq 1.2\ \sigma$). Calculations were carried out for all water temperature intervals. The paper presents the results of calculating large anomalies at each HMS for May, June, July, August in 1980–2012.

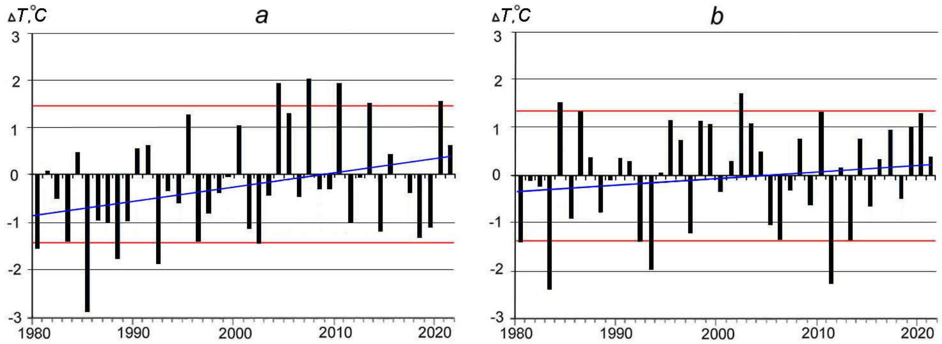
The frequency (*f*) of exceeding the value of 1.2 σ was also calculated as the ratio of the number of large water temperature anomalies to the series length. This frequency is a probabilistic-statistical assessment of a time series [13]. We were interested in the probability of exceeding the value of 1.2 σ. In probability theory, such a value is also called the tail of distribution. The frequency of 1.2 σ level excess can be considered as an empirical assessment of the tail of distribution.

During the analysis of regional time series of climate parameters, when large fluctuations for local areas are revealed, it is necessary to refine the trend assessments. We assessed trend significance by the relation *a*/*s*, where a is linear trend coefficient of the time series of water temperature variability, *s* is residual variability (residual variance square root [1]). The relation *a*/*s* characterizes statistical significance of the results at a fixed series length with a specified critical value corresponding to the accepted significance level. Applying the Student's t-test, this relation makes it possible to determine the probability with which the hypothesis of linear trend coefficient equality to zero is accepted (or not accepted) [14]. The coefficient critical value is 0.04 for a 95% significance level with a series duration of 30 years. The statistical assessments we used are featured by a more accurate indication of the residual variability *s* which is not affected by inaccuracies in determining the linear trend coefficient a [15].

[1] Borovkov, A.A., 1984. *Mathematical Statistics. Additional Chapters.* Moscow: Nauka, 144 p. (in Russian).

Variability of the water thermal regime

Assessments of interannual variability of water temperature anomalies carried out for all HMS (except for HMS Komrvo due to an incomplete data series) show that a predominant upward trend indicates no significant trends in anomalies during the period under study. This is explained by high values of residual variability (fluctuations) both on the western and eastern shelves (Fig. 2, Table 1).



F i g. 2. Interannual variability of water temperature anomalies in the western, HMS Kholmsk (*a*), and eastern, HMS Cape Terpeniya (*b*), areas of the Sakhalin shelf (blue lines denote the linear trends, red ones – the criteria of large anomalies)

Table 1

Assessments of variability of water temperature anomalies at HMS in 1980–2021

HMS	Significance of the trend *a*/*s*				Residual variability *s*			
	May	June	July	August	May	June	July	August
Krilyon	0.03	0.03	0.02	0.03	0.90	0.96	1.06	1.07
Kholmsk	0.03	0.03	0.03	0.03	1.01	1.07	**1.52**	1.41
Uglegorsk	0	0	0	0.01	0.94	1.07	1.42	1.44
Pilvo	0.02	0	0.01	0.03	0.82	1.22	1.09	1.22
Odoptu	0.02	0	0.01	0	0.82	1.47	1.18	**1.59**
Terpeniya	0.02	0.01	0.01	0	1.04	1.02	1.20	1.14
Novikovo	0.01	0.01	0.02	0.02	1.26	**1.59**	1.35	**1.50**

According to these assessments, the greatest fluctuations are observed on the western shelf of the island affected by the warm Tsushima Current at HMS Kholmsk in July. In some years, the northern branch of the current reaches the northern Tatar Strait part –up to HMS Uglegorsk and further to HMS Pilvo [9, 16, 17]. Year-to-year variation in the distribution of the Tsushima Current waters determines changes in the thermal conditions of the water area off the west coast.

On the eastern shelf, at HMS Odoptu the greatest variability is observed in August, at HMS Novikovo – in June and August. HMS Odoptu is located in the north of the eastern shelf. Long-term variations of water thermal regime here are determined by the interaction of waters of different origins – warm waters of the Amur Current and cold waters of the East-Sakhalin Current (Fig. 1) [18].

In July – August, southerly winds weaken the East-Sakhalin Current during the summer monsoon development, but upwelling which often occurs under effect of prevailing southeasterly winds off the east coast (HMS Komrvo area) largely determines the cold thermal regime of the waters here. The upwelling zone is often observed in July–August in the eastern shelf central zone northwards of Cape Terpeniya (HMS Cape Terpeniya); it also determines significant fluctuations here. At the southeastern shelf of the island (HMS Novikovo),water thermal regime is determined by the variability of the anticyclonic circulation component flows in the southern part of the Sea of Okhotsk including cold waters of the East-Sakhalin Current and the intrusions of transformed warm water jets of the Soya Current [19, 20]. The wind effect directions and water dynamics in the area of the Sakhalin eastern coast are important factors determining variations in the water area temperature regime and the formation of significant anomalies.

To identify years in which large water temperature anomalies were observed, criterion values were calculated for each HMS (Table 2).

T a b l e 2

Criterion of water temperature large anomaly (°C) at HMS in 1980–2021

Station	May	June	July	August
Krilyon	±1.18	±1.27	±1.35	±1.42
Kholmsk	±1.31	±1.38	±1.94	±1.82
Uglegorsk	±1.15	±1.30	±1.72	±1.76
Pilvo	±1.03	±1.49	±1.36	±1.56
Odoptu	±1.05	±1.80	±1.47	±1.96
Komrvo	–	±0.98	–	–
Terpeniya	±1.29	±1.27	±1.49	±1.40
Novikovo	±1.57	±1.96	±1.71	±1.91

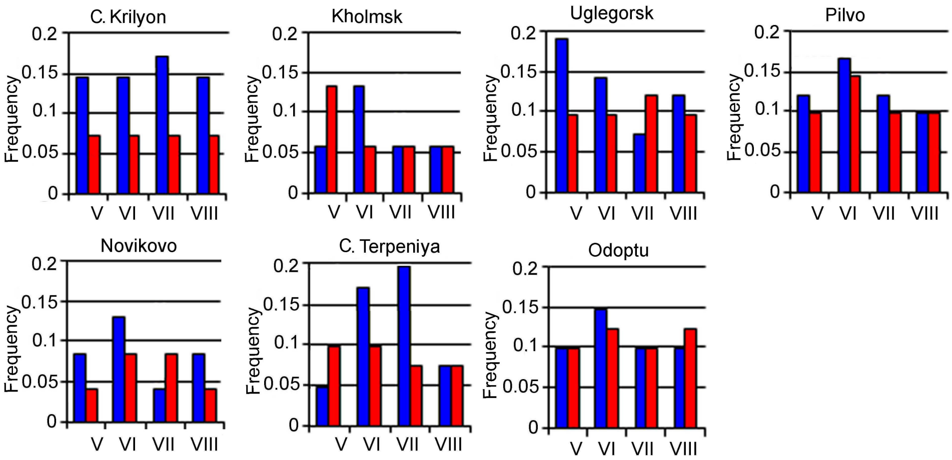
The calculations demonstrate that the values of the large anomaly criterion are different for each station. The highest values are observed in July and August which is consistent with an increase in residual variability (Table 1).

Taking into account the assessments, we identified the years in which negative and positive large water temperature anomalies exceeding the criterion values were formed. Also, the frequency of arising of large anomalies in each month was determined (Fig. 3).

According to the calculation results presented in Fig. 3, the frequency of arising of large negative anomalies in water temperature prevails at most stations of Sakhalin Island in May – August 1980–2021. It should be noted that the risk of severe cold snaps is especially important in May–June, when the salmon fry migrate to coastal areas.

In May, the highest frequency of arising of negative anomalies is observed at the western shelf HMS while its peak is noted at HMS Uglegorsk. However, the frequency of occurrence of positive water temperature anomalies exceeds the one of negative anomalies at HMS Kholmsk in May.

In June, the frequency of arising of negative water temperature anomalies exceeds the one of positive anomalies both at the western and eastern coasts. At the same time, the greatest frequency increase of positive anomalies is noted at HMS Pilvo (western shelf) and HMS Odoptu (northeastern shelf).



F i g. 3. Frequency of arising of strong negative (blue color) and positive (red color) anomalies of water temperature at HMS in May – August 1980–2021

In July, the highest frequency of arising of negative anomalies is observed at the stations located on capes – HMS Cape Crilyon and HMS Cape Terpeniya. The frequency of arising of positive anomalies is the highest at HMS Uglegorsk. It exceeds the frequency of arising of negative anomalies at this station. An excess of the frequency of arising of positive anomalies over the one of negative anomalies also takes place at HMS Novikovo.

In August, high frequency of negative anomalies remains at HMS Cape Crilyon. The highest frequency of arising of positive anomalies is observed at HMS Odoptu where it exceeds the one of negative anomalies.

The analysis shows that thermal regime characterized by arising of large water temperature anomalies in May – August is observed at the HMS of both western and eastern shelves.

As noted above, variability of the water area temperature regime in spring-summer period and formation of significant positive or negative anomalies are determined by the features of hydrological conditions in the west and east of the island. However, in some years, thermal regimes characterized by the formation of large anomalies of only one sign are observed in a number of HMS of both regions.

Thus, the thermal regime characterized by negative water temperature anomalies was observed on the western and eastern shelves of the island during the period under study in May 1980, 2005, June 1983, 2011, July 1988, 1997, August 1981, 1992, 2002; positive anomalies – in May 1995, 2002, 2019, June 2010, July 1990, 2013, 2021, August 1995, 2000, 2006.

Formation of thermal conditions with large anomalies of the same sign on both coasts of the island in some years is, apparently, the result of impact of one factor – the atmospheric effect. In this regard, it is very important to determine the mechanisms of this effect.

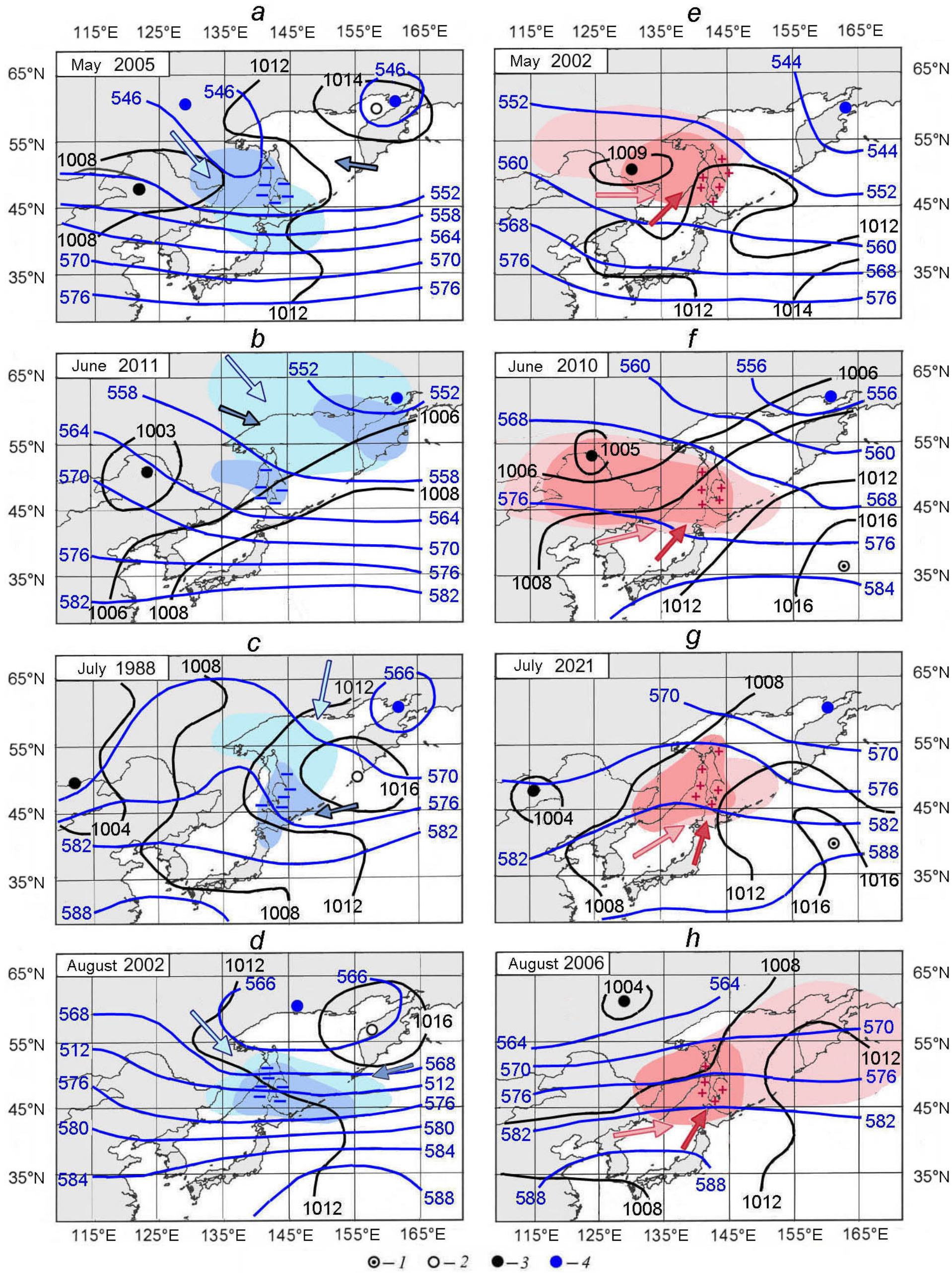
Mechanisms of large anomalies formation

As provided at this stage, the atmospheric circulation and transport of air masses over the region under study during the summer monsoon (with characteristic southerly winds) are determined by the seasonal AAC – the Okhotsk High (OH) formed over the Sea of Okhotsk in the surface field and the cold Troposphere Low in the middle troposphere, as well as the Summer Far East Low (SFEL) as a part of the extensive Asiatic Low directed towards the Amur region. On the ocean side, atmospheric circulation is associated with the North Pacific high-pressure zone development – the Hawaiian High (HH). At the same time, the development intensity of regional AAC varies year after year. In addition, a variability in the position of these atmospheric baric formations and a corresponding change in their local impact are observed [8, 9].

Fig. 4 shows the examples of specific monthly average baric fields in May – August during the years of formation of thermal regimes characterized by large cold (Fig. 4, *a – d*) and warm (Fig. 4, *e – h*) thermal water anomalies in the studied coastal areas of Sakhalin Island.

The analysis of atmospheric fields structure shows that extreme cooling in the island coastal waters is observed in such baric situations when the Troposphere Low marked on the AT_{500} absolute topography maps is directed towards the southwest of the Sea of Okhotsk in high-altitude fields. The formation of centers with extremely low values of geopotential anomalies H_{500} is observed in the depression delta above the study area. In these centers, cold air accumulates at the downward flows near the ground and negative water temperature anomalies are formed. In turn, the OH localization in the northeast and east of the Sea of Okhotsk and the SFEL displacement to the west (Fig. 4, *a*, *c*, *d*) contribute to the influx of cold air masses from the northeast in the surface field.

In case of OH absence (Fig. 4, *b*) during significant SFEL development from the area of which cyclones move towards the Sea of Okhotsk along the southern trajectories, cold air masses are also transported to the island area in the rear part of the cyclones from the northwest. This transport supports the cold waters flow of the East-Sakhalin Current [21] and upwelling on the eastern shelf [22, 23] but prevents the development of the warm Tsushima Current and its branch, the Soya Current, in the southwest of the Sea of Okhotsk [9, 17] which determines the arising of negative water temperature anomalies along the entire coast in combination with the center of cold air masses forming here.



F i g. 4. Typical structures of the surface baric fields P_0 (black isobars, hPa) and geopotential H_{500} (blue isohypses, hPa) in the yeas of formation of large negative (*a* – *d*) and positive (*e* – *h*) water temperature anomalies. *1* – Hawaiian High, *2*– Okhotsk High, *3* – Summer Far East Low, *4* – Troposphere Low. Light blue and pink arrows denote the direction of basic motion of the cold and warm air masses in the mid troposphere, blue and red ones – the motion direction in the near land layer; signs "–" and "+" show the negative and positive anomalies of water temperature; light blue color marks the centers of negative anomalies of geopotential H_{500} and pink color – the centers of positive anomalies of geopotential H_{500}; blue and red colors show the centers of abnormally low and high air temperature, respectively

The formation of extremely warm regimes is due to the development of the HH western branch. In years when as early as May (Fig. 4, *e*) the study area is affected by the tropospheric ridge, localization of an extreme center of H_{500} geopotential positive values is observed above Sakhalin Island. We indicate an extreme center of positive air temperature anomalies in the surface field and positive water temperature anomalies in the water area. With the strengthening of the HH ridge and its propagation to the Seas of Japan and Okhotsk (Fig. 4, *f*, *g*), the area with extreme values of geopotential H_{500} is located above the Primorye coast, the Tatar Strait, and Sakhalin Island. An intense influx of warm air masses takes place along the western periphery of the HH. Intensification of southerly winds occurs as well. In the case when the SFEL displaced towards the north (Fig. 4, *h*), its interaction with the HH front part ensures the intrusion of warm air masses from the south which also contributes to the formation of positive anomalies in the island water areas. At southern and southwestern transport in the atmosphere, the intensity of the warm Tsushima Current increases. According to instrumental observations, the propagation of current to the Tatar Strait northern zone [16, 17] is noted. Active development of its branch – the Soya Current [19, 20] – and weakening of the cold East-Sakhalin Current [21] which ensures the formation of large positive anomalies in water temperature in combination with the thermal atmospheric impact are also observed.

Thus, when analyzing baric situations during the years when large cold or warm water temperature anomalies are formed on the Sakhalin Island shelf, differences in the structure of atmospheric fields were identified. As a result of different local thermal atmospheric impact on the underlying surface, differences in the mechanisms forming cold and warm thermal conditions were identified. At the same time, a dynamic atmospheric effect takes place contributing to changes in the near-island water circulation which together determines the formation of large temperature anomalies in the water area.

Conclusion

Assessment of interannual variability of the water thermal regime condition for the period from May to August 1980–2021 revealed no significant upward trend in the water temperature time series at a predominant growth tendency in the water area of the Sakhalin Island western and eastern shelves during the warm period. This is explained by high values of residual variability (fluctuations) on both western and eastern shelves.

The greatest fluctuations in water temperature anomalies are observed in July and August. The frequency of arising of large negative anomalies in the thermal regime condition exceeds the frequency of arising of positive ones both on the western and eastern shelves of the island.

Considering the calculated criteria for temperature anomalies, years with large negative and positive anomalies in the water thermal regime condition were identified. It was revealed that in some years we observed the occurrence of large anomalies of the same sign at a number of stations in both regions under different hydrological conditions on the western and eastern shelves of the island. Formative cause-effect relations are identified. The mechanisms forming large water temperature anomalies in the region associated with the position variability and intensity development of seasonal regional AAC were established. It is shown that anomalously cold thermal conditions are formed when a center of decrease of geopotential H_{500} and area of abnormally low surface air temperature are observed over Sakhalin Island. Such extreme zones are caused by the OH intensification or the passage of cyclones along the southern trajectories during the SFEL development. In the years known for large positive anomalies in water temperature, we observe the opposite pattern when a hotspot of extremely elevated H_{500} geopotential values and an area of abnormally high surface air temperatures above Sakhalin Island are located. Such conditions are associated with an increase in the HH warming effect and a corresponding change in the air masses transport. Anomalous variations in the baric structure of atmospheric fields causing the accumulation of abnormally cold or warm air masses in individual centers over the entire study area determine the formation of large temperature anomalies in the waters of the Sakhalin Island western and eastern shelves.

The results of the performed studies can be used for assessing extremeness of thermal environmental conditions during the catch, as well as in predictive models.

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