of various origins and redistribution of oceanological characteristics in the water area by a system of insular currents – that is a variety of factors that determine the features of the region hydrological regime as a whole and in individual subregions of the ridge [1, 2].

F i g. 1. Region under study and scheme of the hydrometerological stations location (HMS): *1* – Oktyabrskaya, *2* – Ozernoy, *3* – Severo-Kurilsk, *4* – Kurilsk, *5* – Yuzno-Kurilsk

At the same time, the insular water area of the ridge is an economically significant zone of the Pacific-Okhotsk region, rich in biological resources. This is a zone of active fishing for saury, squid and salmon. However, formation of extreme cold or warm thermal conditions in the area under study in some years negatively affects the functioning and productivity of ecosystems, the distribution of commercial objects, leads to a shift in fishing areas, and causes additional difficulties for commercial forecasting [3, 4]. In this regard, it is very important to study the interrelations of factors and causes that determine formation of anomalous thermal conditions in the water area.

One of the significant factors determining the features of the formation of the region hydrological regime is variability of synoptic-climatic conditions. During the summer fishing period, atmospheric processes here are determined by the interaction of regional atmospheric action centers (AAC). Estimates of the relationship between the thermal regime variability in a number of areas of the Sea of Japan and the Sea of Okhotsk, in the area of the Kuril archipelago, and the intensity of AAC development, carried out in the last decade, showed their pronounced relationship. It was assumed that significant differences in the processes of formation of baric fields in years anomalous in terms of thermal conditions, a qualitative scheme was proposed for the influence of the structure of baric fields on the thermal regime of water areas [5, 6]. Studies on the application of the mathematical method of interval recognition to identify the previous baric structures that determine the extreme states of the thermal regime of waters that affect fishing conditions [7] were carried out.

At the same time, the problem of low forecast accuracy is still relevant and is often associated with anomalous thermal conditions [3, 4]. The purpose of this study is to reveal the mechanisms of formation of the thermal regime extreme states under effect of atmospheric processes, taking into account the peculiarities of hydrological conditions in the Kuril Ridge specific areas.

Data and methods

As part of the work, the following tasks were solved:

– study of the features of thermal regime interannual variability in July–August in *the southern subarea*, which includes the Yuzno-Kuril region, the zone of the Soya current and the East-Sakhalin current effect (Yuzno-Kurilsk HMS, Kurilsk HMS), and in *the northern subarea*, covering the northern part of the ridge and the southern Kamchatka water area, the zone of the Kuril-Kamchatka current effect (Severo-Kurilsk HMS, Ozernoy HMS, Oktyabrskaya HMS) (Fig. 1);

– study of the interannual variability in the severity (variability of pressure) and the position of seasonal AAC;

– determination of the role of seasonal AAC in the formation mechanisms of extreme thermal regimes of the water area in each subarea.

The studies of the thermal regime long-term variability in the coastal waters of the region were carried out using observational data on the water temperature of the ESIMO electronic database (http://portal.esimo.ru/portal/), VNIIGMI-WDC (http://meteo.ru) at Roshydromet HMS for the forty-year period of 1977–2019. To assess the variability of thermal conditions, some anomalies (deviations of temperature values from the average) were used. The analysis of waters' thermal regime variability was carried out on the basis of methods for constructing graphs and tables for areas identified taking into account the water circulation effect. Cluster analysis was applied to identify years with the extreme states of thermal regime.

To analyze the thermal conditions in the water area under study, the data on the water temperature on the sea surface at the nodes of a regular grid $0.25 \times 0.25°$ from the archive of the Japan Meteorological Agency JMA (http://ds.data.jma.go.jp /gmd/goos/data/cobe_sst_glb_M.html) for the period of 1977–2019.

The atmospheric circulation analysis was carried out over the central second natural synoptic region (2 n.s.r.) on the basis of reanalysis archives (NCEP/ NCAR Reanalysis Monthly Means and Other Derived Variables) of surface atmospheric pressure (P_o) and geopotential H_{500} at the nodes of a regular grid $2.5 \times 2.5°$ for the period of 1977–2019. Anomalies (deviations of pressure values from average values) were used to assess variability of the intensity of AAC development. To analyze baric fields, maps of surface pressure and H_{500} geopotential for 2000–2019, compiled by JMA, were used.

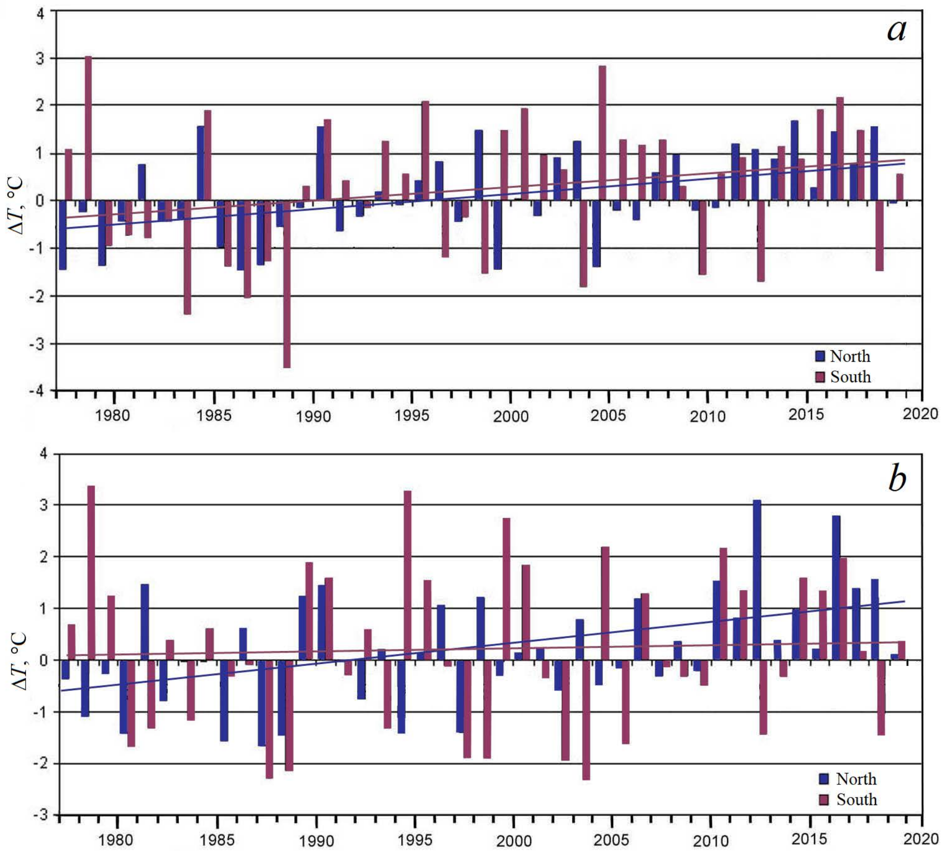
The mean long-term values and anomalies of all parameters used in the work were calculated for the 1981–2010 base period.

Formation and variability of thermal regime of waters

Northern subregion. The interannual variability of the thermal regime of the water area of the ridge northern subregion was estimated from observations at the Severo-Kurilsk, Ozernoy and Oktyabrskaya HMS on the southern coast of the Kamchatka Peninsula. The Severo-Kurilsk HMS is located in the north of Paramushir Island of the Kuril Islands northern group. With the shallow water of the North Kuril straits (less than 200 m in depth), only the Fourth Kuril Strait has a depth of about 600 m. An active sea-ocean water exchange occurs through this strait. On the Pacific side of the ridge, the strait is subject to the effect of the Kuril-Kamchatka current waters propagating from the north. The strait is characterized by a two-way water circulation scheme: in the southern part – the outflow of the Sea of Okhotsk waters, in the northern part – the inflow of the Pacific Ocean [1]. The Pacific waters, entering the strait, turn further to the north and propagate to the southwestern coast of the Kamchatka Peninsula – to the Ozernoy and Oktyabrskaya HMS. That is, the temperature characteristics of the water area of the region are formed under effect of waters of various origins – the Sea of Okhotsk proper and partially the waters of the Kuril-Kamchatka current. Water dynamics in the North Kuril subregion is an important factor determining the temperature regime here.

Southern subregion. In the southern Kuril subregion, the long-term variability of thermal conditions was estimated from observations at the coastal Yuzno-Kurilsk and Kurilsk HMS. The Yuzno-Kurilsk HMS is located on the Pacific coast of Kunashir Island. The Kurilsk HMS is located on the Sea of Okhotsk side of Iturup Island. The temperature characteristics of the water area, as in the northern subregion, are determined by the effect of waters of various origins. From the southern part of the Sea of Okhotsk, warm waters of the Soya current and cold waters from the northern part the Sea of Okhotsk, the eastern branch of the East-Sakhalin current, enter the Kurile zone. Their effect on the formation of thermal conditions here is very strong [6, 8, 9]. The amplitudes of interannual fluctuations in water temperature values near the HMS of the South Kuril region are higher than in the coastal waters of the northern region. This is due to the fact that in some years the thermal regime of waters is determined by the effect of the Soya current warm waters (temperature increase), in others, by the effect of the East-Sakhalin current cold waters (temperature decrease). According to observations of the trajectories of Argo drifters, the effect of the cold East-Sakhalin current can cover the entire southern and central parts of the Sea of Okhotsk [10]. In addition, through the straits bathing the islands, due to the multidirectional water circulation [1], even with the predominant outflow from the Sea of Okhotsk, there is an inflow of cold Pacific waters brought by the Oyashio current. The variability of the components of the system of currents is largely associated with the heat and cold redistribution, which determines the long-term variability of temperature background in the southern subregion.

The formation of the water area thermal regime in each of the subregions is determined by regional features of hydrological conditions. At the same time, the results of the analysis of the temperature regime variability in July–August (the main fishing period) from 1977 to 2019 demonstrate the consistency of interannual fluctuations within the northern (the Severo-Kurilsk, Ozernoy, Oktyabrskaya HMS) and southern (the Yuzno-Kurilsk and Kurilsk HMS) subregions. The long-term variability of water area thermal conditions of each subregion is quite well reflected in the dynamics of the averaged values of water temperature anomalies. The variation of long-term changes in the thermal regime of waters in both subregions (Fig. 2) indicates a warming trend in the area of the Kuril Ridge over the past forty decades, which confirms the studies of previous years [11]. At the same time, significant fluctuations in the variability of temperature conditions are observed in each subregion, which makes it possible to identify years with extreme states of the thermal regime.



F i g. 2. Interannual variability of the water temperature anomalies in the northern and southern areas of the Kuril ridge in July (*a*) and August (*b*), and the corresponding linear trends

Based on the assessment of the interannual variability of thermal conditions in each subregion in July–August over a forty-year period (1977–2019), carried out using cluster analysis using the K-means method, lists of years grouped by anomalies of the thermal regime (close to normal with anomalies in absolute value of less than 1.0 °C; cold and warm with anomalies of 1.0–1.5 °C; and extremely cold and warm with anomalies in absolute value of more than 1.5 °C) were formed. Years with extreme states of thermal regime are presented in Table 1.

Table 1

Years of the abnormal thermal regimes in the Kuril ridge region in 1977–2019

Subregion	Cold	Warm
	July	
Northern	1977, 1979, 1986, 1987	1984, 1990, 1998, 2003, 2011, 2014, 2018
Southern	1983, 1985, 1986, 1987, 1988, 1998, 2003, 2009, 2012, 2018	1978, 1984, 1990, 1995, 1999, 2000, 2004, 2013, 2016
	August	
Northern	1978, 1980, 1985, 1987, 1988, 1994, 1997	1981, 1989, 1990, 1998, 2010, 2012, 2016, 2018
Southern	1980, 1987, 1988, 1997, 1998, 2002, 2003, 2005, 2012, 2018	1978, 1989, 1990, 1994, 1995, 1999, 2000, 2004, 2010, 2016

According to the assessment results, it was revealed that the thermal regime anomalies in some years coincide in sign in the northern and southern subregions, and in some years thermal anomalies of opposite signs are observed for a month or more (Table 2).

Table 2

Years of the opposite and the same abnormal thermal regimes in the Kuril ridge region in 1977–2019

Cold North and South	Cold North, warm South	Warm North, cold South	Warm North and South
	July		
1985, 1986, 1987, 1988	1999, 2004	1998, 2003, 2012, 2018	1984, 1990, 2016
	August		
1980, 1987, 1988, 1997	1978, 1994	1998, 2012, 2018	1989, 1990, 2010, 2016

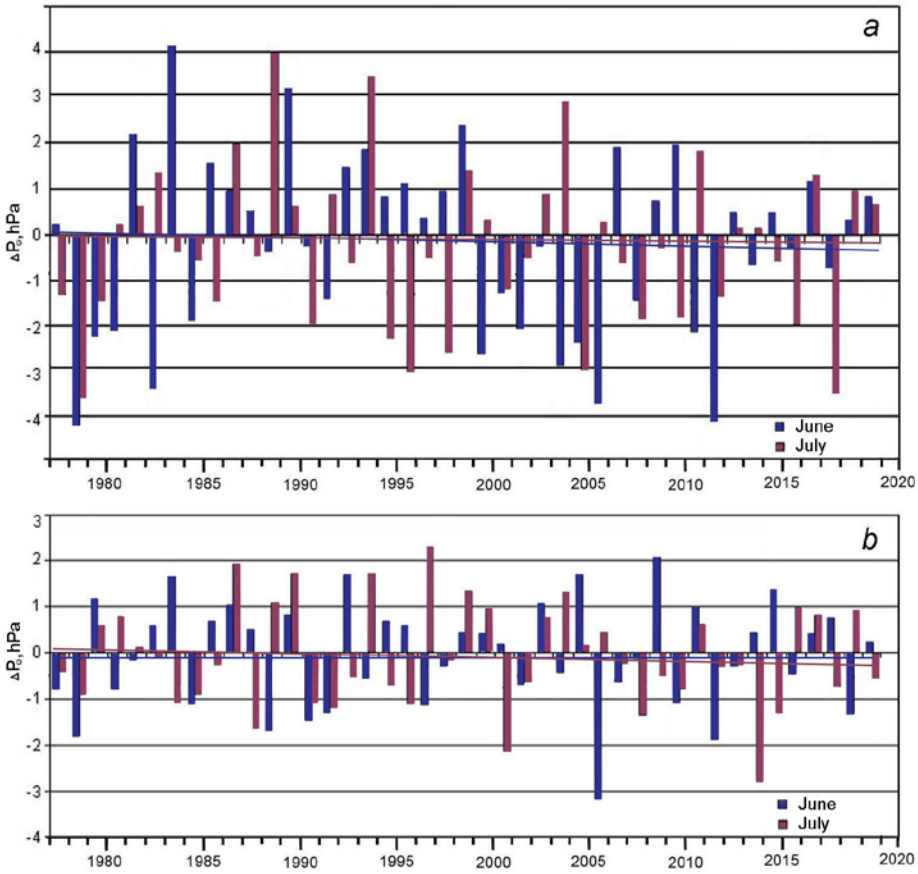
Meanwhile, it is known that the thermal state and hydrodynamics of the sea surface are largely determined by surface wind conditions, the direction and intensity of air mass transfer, which, in turn, are determined by the atmospheric circulation variability [12].

To identify the causes for the formation of significant anomalies in the thermal regime in the study area during the fishing period in certain years, an analysis of the variability of the region's atmospheric processes and their impact on the underlying water area was carried out.

Variability of regional atmospheric processes

The characteristic features of the summer atmospheric processes in the region are associated with the summer Far Eastern monsoon. In summer, a low-pressure zone forms over the mainland – the Asian depression and, as part of it (over Mongolia, northeast China, and the Amur region), the Summer Far East Low

(SFEL) [1]. A high-pressure area is activated over the ocean – the North Pacific or Hawaiian anticyclone (HA). During the first cold stage of the summer monsoon (May – early July), a localized high-pressure area, not associated with HA, is often observed in the surface field over the Sea of Okhotsk – the Okhotsk High (OH). At the same time, in high-altitude fields in the middle troposphere, a cold trough is observed; in its rear part, cold air masses of Arctic origin come out onto the Sea of Okhotsk. They are observed on synoptic maps as small anticyclones that support a high-pressure area over the sea [2]. In addition, the developed OH prevents the exit of cyclones from the Amur region to the Sea of Okhotsk, as a result of which SFEL has a quasi-permanent character and occupies a more southerly position. In this case, the cyclones moving through its trough bring cold air masses to the sea in the rear part, contributing to the formation of a low temperature background.



F i g. 3. Interannual variability of the anomalies of surface pressure ΔP_0 in the Okhotsk High (*a*) and the Summer Far East Low (*b*) areas, and the corresponding linear trends

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[1] Ilyinsky, O.K., 1960. [Summer Far Eastern Low]. In: FERHRI, 1960. *FERHRI Issues*. Leningrad: Hydrometeorological Publ. Iss. 11, pp. 3-53 (in Russian).

[2] Ilyinsky, O.K., 1959. [The Okhotsk High]. In: FERHRI, 1959. *FERHRI Issues*. Moscow: Hydrometeorological Publ. Iss. 7, pp. 10-32 (in Russian).

In some years, the OH effect on thermal conditions, leading to the occurrence of a negative water temperature anomaly, is observed until the end of July, and the transition to the second stage of the monsoon, characterized by the OH destruction, an increase in the HA effect, and the onset of an intensive outflow of warm air to the Sea of Okhotsk, shifts and occurs only in August [2].

In this regard, the change in atmospheric pressure over the sea area in June and July, indicating the intensity of OH development, is especially important. According to the interannual variability of the surface pressure anomalies in the OH and SFEL areas, there are significant fluctuations, which make it possible to distinguish the years of the extreme state of these regional AAC (Fig. 3).

The years of OH active development (pressure anomalies > 2 hPa) are in June 1981, 1983, 1985, 1989, 1998, 2009 and in July 1986, 1988, 1993, 2003. The least development or absence of OH (pressure anomalies < −2 hPa) is in June 1978, 1982, 1984, 1999, 2003, 2004, 2005, 2010, 2011 and in July 1978, 1990, 1994, 1995, 2004, 2017. The years of significant deepening of SFEL (pressure anomalies < −1.5 hPa) are in June 1978, 1984, 1990, 1991, 2005, 2011, 2018 and in July 2000, 2013, 2014. A significant weakening of SFEL (pressure anomalies > 1.5 hPa) is in June 1983, 1992, 2004, 2008, 2014 and in July 1986, 1989, 1993, 1996, 1998, 2003.

A joint analysis of the interannual variability of pressure anomalies in the AAC under consideration and the time course of the interannual variability of water temperature showed that in the study area during the years of the OH active development (in June–July), anomalously cold thermal conditions can form in July–August, and in the years of anticyclone weakening or its absence and SFEL deepening, anomalously warm conditions can form. This confirms the previously identified causal relationships during the formation of extreme thermal anomalies in summer in the South Kuril region [6]. Meanwhile, in some years, this relationship is ambiguous, as evidenced by the interannual variation of anomalies in temperature conditions specifically in each of the subregions under consideration (see Fig. 2). Along with the intensity of the OH and SFEL development, an important role in the thermal regime formation is played by the structure of high-altitude fields and the variability in the position of these atmospheric baric formations.

Mechanisms of formation of extreme thermal conditions

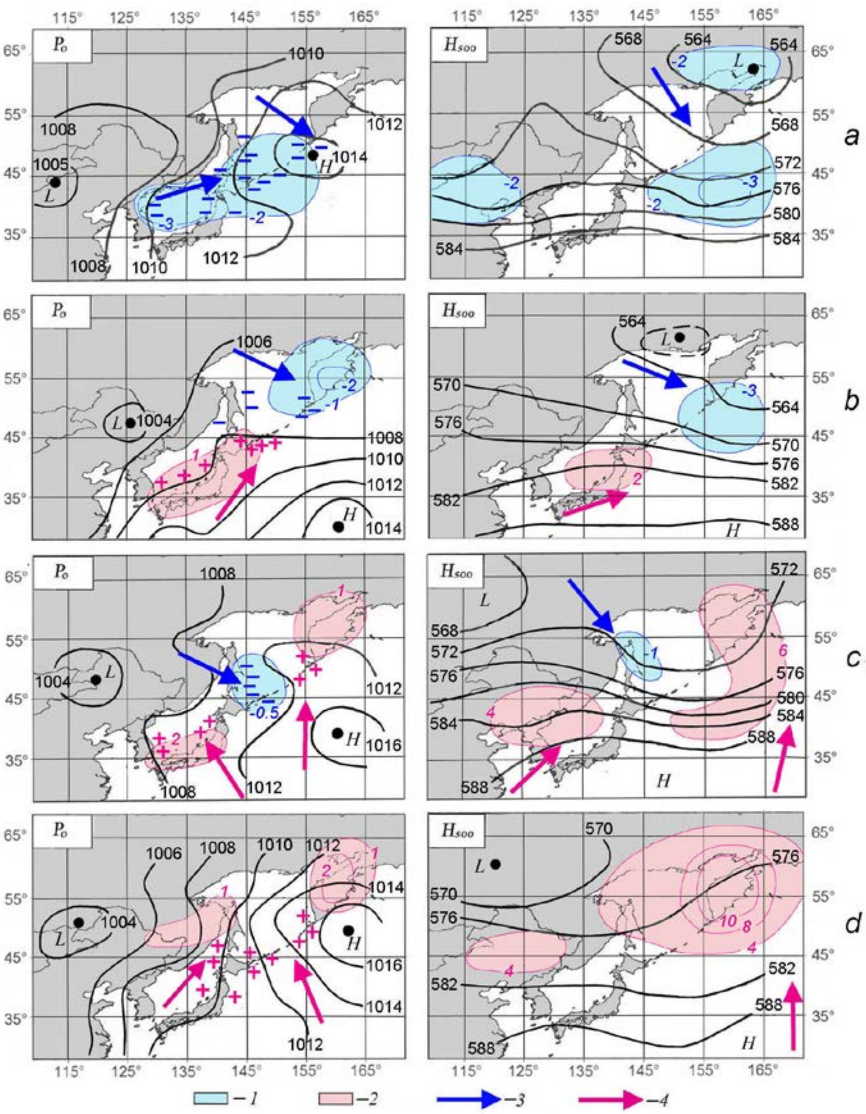
An analysis of baric situations showed differences in surface and high-altitude fields during the years of anomalous cold or warm thermal conditions in the studied areas of the Kuril ridge. In this case, a different local atmospheric effect on the water area takes place, which results here in differences in the mechanisms of formation of abnormal thermal regimes.

The mechanism of formation of extremely cold states of a thermal regime in the water area of both subregions is associated with the developed OH. The high-altitude fields in these years are characterized by the presence of a cold trough marked on the maps of the absolute topography 500mb (AT_{500}), in the area of which the centers of an extreme decrease in the geopotential H_{500} (Fig. 4, *a*) are observed. In these centers, at the descending fluxes cold air accumulates near the ground, and extremely cold thermal conditions are formed. The trough is located above the Kamchatka Peninsula and is directed towards the eastern part of the Sea of Okhotsk and the Kuril Islands, which indicates the propagation of cold air masses in the study area. In the surface field, the OH is localized in the northeastern part of the sea. The SFEL center is located southward of the long-term mean position (the long-term mean position of the center is 45° N, 115° E). Due to the blocking effect of the OH, the depression is directed to the southeastern part of the Sea of Okhotsk. The cyclones moving along the depression, carry cold air masses in the rear part to the near-island water area. With such a structure of atmospheric fields, the carry-over of cold air masses from the north and northwest occurs over the entire Kuril ridge. There is a decrease in the temperature background of the underlying surface and the formation of abnormally cold thermal conditions in the water area of the entire ridge, which was observed in July–August 1985–1988 and in August 1997 (Fig. 2, Table 2).

A dynamic effect also takes place. According to the instrumental data, in the Oyashio current zone, which is "fed" by the Sea of Okhotsk waters entering through the southern Kuril straits, a significant decrease in temperature was observed in 1988 [13, 14], which indicates a decrease in the warm water inflow with the Soya current into the southern part of the Sea of Okhotsk and to the southern straits. The data of instrumental measurements in the extremely cold thermal regime of 1986 also indicate a weakening of the inflow of warm waters into the Sea of Okhotsk southern part and an increase in the outflow of cold Sea of Okhotsk waters with the East-Sakhalin current [6]. In 1997, an intensification of the Kuril–Kamchatka current, along with an increase in the inflow of cold Pacific waters into the North Kuril region was observed in the northern part of the ridge [15].

The mechanisms of formation of thermal regime extreme states opposite in sign in the northern and southern subregions are of particular interest.

The analysis of baric situations over the studied water area during the years of formation of cold thermal conditions in the north of the ridge and warm conditions in the south indicates the following features of the atmospheric fields' structure in the southern part of the region (Fig. 4, *b*). The North Kuriles are located in the area of the tropospheric trough effect, located above the northern part of the Sea of Okhotsk (H_{500} anomalies drop to − 3, − 2 dam), the southern region is under effect of the HA ridge (H_{500} anomalies reach 2 dam). SFEL is shifted to the northeast; the cyclones passing along its trough carry warm air masses to the south of the Sea of Okhotsk in the front part. From the Pacific side to the region of the southern Kuril Islands along the HA periphery, at the top of which the centers of an increase in H_{500} geopotential are observed, the subtropical warm air is carried out. As a result of such a local atmospheric effect, the centers of extremely low and high air temperature anomalies near the ground are formed in the studied subregions of the ridge: temperature anomalies in the north are about −2°C, anomalies in the south – up to 1°C. At the same time, the corresponding anomalies of the temperature regime are formed in the water areas, which were observed in July 1999 and 2004, August 1978 and 1994 (Fig. 2, Table 2). According to the instrumental observations, with this combination of thermal anomalies, the development of both the system of the Kuril-Kamchatka and Oyashio (1999, 2004) [15–18] currents and the Soya current (2004) [8] took place, which is consistent with the contrasts of temperature conditions of the northern and southern water areas near the ridge (the difference in anomalies was 2–2.5°C).



F i g. 4. Typical structures of the surface pressure field P_0 and geopotential H_{500} in the years characterized by the abnormal thermal regimes: *a* – cold over the whole water area, *b* – cold in the north and warm in the south, *c* – warm in the north and cold in the south, *d* – warm over the whole water area (blue numbers denote the centers of negative anomalies of the air temperature and geopotential H_{500}, red numbers – the centers of positive anomalies of the air temperature and geopotential H_{500}; arrows show the air mass motion, and the signs “minus” and ”plus” – the water temperature negative and positive anomalies)

The mechanisms of formation of the opposite ratio of thermal anomalies – warm north and cold south – differ significantly from those described above by the features of the structure of baric fields (Fig. 4, *c*). In field H_{500}, the northern part of the Kuriles is under the warming effect of the HA. The heat ridges are directed to Kamchatka and the Sea of Japan. The tropospheric trough is shifted to the west and has a cooling effect on the coastal waters near Sakhalin Island. There is no OH in the surface field, the SFEL position is eastwards of the long-term mean. The depression is directed towards the Sea of Okhotsk. At the same time, the cyclones moving to the east in their rear part carry cold air masses to the southern Kuril straits. Meanwhile, with the development of a high-altitude ridge over the Sea of Japan, the wind field, facilitating the Soya current flux into the Sea of Okhotsk, at the same time leads to the current deviation to the northeast, corresponding to the orientation of the ridge. As a result, the current does not reach the southern Kuril straits. The similar situations were observed earlier [8]. A thermal regime cold anomaly is formed in the southern part of the ridge. Above the northern water area of the ridge, in addition to the warming effect of the HA ridge, southeasterly and easterly winds contribute to the weakening of the Kuril-Kamchatka current. At the same time, easterly and northeasterly winds create the conditions for the penetration of individual branches of the Alaska current warmer continuation from the east [19]. Positive anomalies of thermal conditions are formed in the northern part of the ridge. Such a ratio of anomalous thermal conditions of the northern and southern water areas of the Kuril ridge was observed in July – August 1998, 2012, 2018. The temperature anomaly contrasts were up to 2–3°C.

The formation mechanism of extremely warm states of the thermal regime throughout the water area near the Kuril ridge (July 1984, August 1989 and 2010, July–August 1990 and 2016) is due to the absence of cold depressions over the Sea of Okhotsk. With regard to the characteristic structure of baric fields, the zonality of isohypses in H_{500} field, which reflects the western transport of air masses (Fig. 4, *d*) should be noted. The entire region of the Kuril ridge is under effect of the HA ridge, at the top of which there are the source areas of an increase in H_{500} potential with pressure anomalies of more than 4 dam (up to 8–10 dam in 2016) and surface air temperature (anomalies of more than 2°C), which contributes to the formation of water temperature positive anomalies (up to 2.5–3°C). In the surface field, the SFEL center is displaced eastward of the long-term mean. The depression is directed to the northeast and has almost no effect on the water area near the Kuril ridge. Such a structure of atmospheric fields with westerly and southwesterly winds contributes to the weakening of the cold Kuril-Kamchatka current and development of the warm Soya current. Thus, according to the expeditionary data, in the extremely warm by thermal conditions 1990, a significant penetration of the Soya current into the Kuril ridge was noted – its waters were observed up to the Frieze Strait [1]. Meanwhile, according to instrumental observations, the transport of cold Kuril–Kamchatka current near the Pacific coast of Kamchatka in 1990 was only 2 Sv, with an average transport of about 10 Sv [20].

Thus, the identified mechanisms for the formation of anomalous thermal conditions in the studied water areas of the ridge are associated with regional features of atmospheric circulation – anomalous changes in the development and position of regional AAC, changes in their local thermal and dynamic effects.

Conclusion

The features of the formation mechanisms of the thermal regime anomalous conditions in an important fishing area – the Kuril ridge zone are revealed, the qualitative cause and effect relationships are determined.

It was found that anomalous thermal conditions in certain areas of the ridge are formed by the local effect of anomalous atmospheric circulation – extreme fluctuations in the intensity of development and position of regional atmospheric action centers. The extreme anomalies that coincide and are opposite in sign in the northern and southern regions of the ridge are due to anomalous changes in the development of the Okhotsk High, formation of a tropospheric trough in the altitudinal field, shift from the long-term average position of the SFEL, changes in the distribution of the North Pacific High (HA) and the corresponding direction of atmospheric circulation.

The differences in baric fields in years with abnormal thermal conditions are demonstrated. The baric fields of the middle troposphere with different positions of troughs and ridges over the eastern coast of Asia are an indicator of atmospheric circulation variability. In these baric fields, local fluxes contribute to the accumulation in separate pockets of cold or warm air masses above the water area, where anomalous thermal conditions are formed. Besides, the dynamic atmospheric action contributes to the changes in the characteristics of individual links in the system of Kuril currents. The redistribution of heat and cold fluxes over the water area takes place, and this ultimately determines the nature of local formation of extremely warm and cold thermal conditions.

The materials of this study can be applied in commercial oceanography, used to verify the results of regional prognostic models of the interaction between the atmosphere and the ocean.

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