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CURRENT STATUS OF THE TEMPERATURE AND HUMIDITY REGIME OF THE TROPOSPHERE IN THE SIBERIAN SECTOR IN DIFFERENT CIRCULATION PERIODS

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Abstract. The paper studies the long-term dynamics of air temperature and relative humidity anomaly indices in the surface layer and at different levels of the troposphere in Siberia and neighboring regions (European and Far Eastern sectors). As the main cause of the observed variations in climatic parameters we considered circulation factors, which were taken into account using the typification of macrocirculation processes proposed by B.L. Dzerdzeevsky. Seasonal differences were revealed in the distribution of anomaly indices and the area occupied by anomalies of different signs of annual and monthly mean temperature and relative air humidity, which are most pronounced during circulation periods of increased duration of meridional northern processes in the Siberian sector and in the Northern Hemisphere as a whole. The highest rates of change in the temperature regime in the Siberian sector over recent decades have been observed at the level of the isobaric surface AT–700 hPa (3 km), which affects the advective-dynamic factors of surface cyclo- and frontogenesis, as well as the processes of cloud formation and precipitation. In general, an increase in the heat content of the lower and middle troposphere and a decrease in the relative moisture content near the tropopause can be accompanied by an increase in the amount of the potential energy and convective instability energy reserves and can lead to an increase in climate risks in the Siberian sector.

Keywords: temperature, relative humidity, climate, circulation epoch, typification, anomalies.

INTRODUCTION

At present there is a great risk of underestimating all factors of the influence of various space and geological processes on the global climate change [Lorenz, 1967; Kotlyakov, 2019]. The main mechanisms behind climate changes in the atmosphere are associated with incoming solar radiation and cosmic ray variations, volcanic activity, greenhouse gases, internal variability of climatic parameters, oceanic activity, geodynamics of the earth's crust, convection of matter in the Earth mantle, etc. Among these mechanisms, solar activity is the main natural factor driving the climate change. The anthropogenic factor is responsible for the greenhouse effect and is generally linked to an increase in the concentration of carbon dioxide and other small gas components in the atmosphere, including water vapor.

Interannual and interdecadal temperature variations are often attributed to natural climate changes as well as to key modes of climatic variability, including quasi-cyclic processes such as El Niño/Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), Antartic Oscillation (AAO), etc. [Mokhov, Smirnov, 2022]. The rate of climate change has been increasing since the early 1970s against the background of a significant increase in the contribution of the North Atlantic Oscillation (NAO), which is associated with increasing zonal transport over much of the territory of Russia up to the Yenisei basin. It is observed that since the mid-1990s, with the shift of the center of the circumpolar depression to the north of the Scandinavian Peninsula, the intensification of Arctic invasions, and the increase in the frequency of atmospheric processes of meridional types, the influence of the Scandinavian anticyclone (Scand) (in the positive phase) has been sharply increasing [Zhang et al., 2008]. The increase in the frequency of Arctic invasions and cold winters in northern Eurasia during this period, known as a hiatus in warming, should be regarded as a consequence of this phenomenon and, possibly, as its indicator [Popova et al., 2018b]. The overall weakening of the zonal transport in the extratropical zone of the Northern Hemisphere can also be facilitated by the redistribution of surface temperature anomalies in the Pacific Ocean, which some studies consider as a decelerator of global warming [Trenberth, Fasullo, 2013]. Krymskaya et al. [2017], when analyzing oceanic parameters and thermodynamic characteristics of the atmosphere, have revealed that the nonstationary processes in the ocean, associated with El Niño and La Niña, affect atmospheric processes over the territory of Kyrgyzstan. From the results it can be inferred that slow cooling has been observed for the last 10–15 years.

A rise in global surface temperature is accompanied by a rapid growth in the number of hydrometeorological anomalies, which increases the risk of extreme regional events, and also points to the possible development of new circulation mechanisms when climate changes reach a certain level [Mokhov, 2022]. According to Roshydromet, 1000 dangerous hydrometeorological phenomena were recorded in Russia alone in 2020, 372 of which with significant damage to the economy and population [Report on Climate Features ..., 2021]. The increase in the number of dangerous hydrometeorological phenomena in Russia is closely correlated with the high rate of warming in Russia on average, which significantly exceeds the global averaged values and amounts to 0.51°C per decade for 1976–2020.

Regional climate changes in Russia unlike global ones are characterized by greater space-time irregularity, atmospheric processes of regional types, manifested against the background of nonuniform relief and long-term dynamics of oceanic and continental atmospheric action centers. In general, at high latitudes the surface air temperature rises faster than at middle ones. However, within the same latitudinal zone, this process occurs differently when moving from west to east. An even more complex structure is noted in the distribution of cloud cover parameters, the amount and intensity of atmospheric precipitation, humidity and wind characteristics.

Circulation regime changes are evident as a rise in surface air temperatures, accompanied by an increase in the absolute moisture content of the troposphere and hence by a change in the amount of precipitation, which affects the long-term regime of river runoff in various regions of Russia [Garmaev et al., 2022]. In some regions, against the global warming in recent decades, there has been a tendency to lower mean air temperatures. According to the empirical model of regional changes in the temperature regime of the lower atmosphere, there is cooling in the surface atmospheric layer in Central Asia, driven primarily by solar activity [Karimov et al., 2020]. In the Republic of Belarus, among the natural factors of current trends in climate change, the manifestation of a quasi-60-year oscillation is considered, which is consistent with the dynamics of the Atlantic Multidecadal Oscillation (AMO). It is suspected that in the following years during the descending phase of AMO (2023–2043) the mean air temperature in the warm season may decrease compared to the previous decade [Loginov, 2022].

Given the multidirectional climatic trends, it is important to examine in more detail the temperature and humidity characteristics of the atmosphere, which contribute to the formation of moisture conditions, cloud and precipitation processes across the globe. Annual and diurnal variations of air temperature and relative humidity, in turn, significantly depend on natural and climatic factors. In particular, during the winter periods in 1966–2019, the greatest positive statistically significant trends in relative air humidity anomalies were observed throughout the European territory of Russia, where linear trend coefficients, significant at a given 5 % level, run to 0.4–0.5 % for 10 years; slightly lower trends were in the Asian territory of Russia, to 0.4 % for 10 years [Kuznetsova, Shvets, 2020]. In spring, relative air humidity decreased over most of the territory of Russia. In summer and fall in regions dominated by tundra and coniferous forests, the relative air humidity increased; and in forest-steppe, steppe, and monsoon regions, it decreased, yet the trends are statistically insignificant in general [Kuznetsova, Shvets, 2020].

Thus, the climate changes observed from the mid-20th century at the extratropical latitudes of the Northern Hemisphere, including the territory of Russia, along with the anthropogenic effect, closely correlate with variations in large-scale atmospheric circulation patterns [Popova et al., 2018a]. Changes in the atmospheric circulation intensity and patterns determine the heat and moisture content of different tropospheric layers, which, in turn, are influenced by the relief; this suggests the relevance and practical significance of the studies into the spatial-temporal dynamics of temperature and humidity characteristics at different levels of Earth’s atmosphere.

The purpose of this work is to statistically analyze space-time irregularities in the distribution of climatic indices such as air temperature and humidity at different levels of the troposphere in the Siberian sector. We have formulated the following objectives: to calculate monthly and annual average indices of anomalies in meteorological temperature and relative humidity fields at different levels of the troposphere from the criterion proposed by Bagrov N.A. [Bagrov, Myakisheva, 1966]; to analyze the current status of the temperature and humidity regime in conjunction with circulation factors. To assess the spatial structure of temperature anomalies, we have taken maps of monthly surface air temperature anomalies $\Delta T_A \geq \pm 6$ °C for 2010–2015 and 2015–2020. To more reliably estimate the contribution of global and regional factors to climate change, we have compared the temperature and humidity characteristics obtained for the Siberian sector and neighboring regions — European and Far Eastern.

1. DATA AND METHODS

At present, the typification of macroscale atmospheric processes developed by Dzerdzeevsky B.L. and supplemented by N.K. Kononova is widely used to assess the circulation factors of climate change in Russia. According to this typification, the elementary circulatory mechanism, acting as a single integral mechanism of macrocirculatory exchange, manifests itself differently in various regions of the Northern Hemisphere [Dzerdzeevsky, Monin, 1954]. This typification through trajectories of moving pressure systems (cyclones and anticyclones) reflects the main ways of heat and moisture transfer, which allows for a more detailed analysis of the causes of regional climate changes. Atmospheric processes of all types over extratropical latitudes of the Northern Hemisphere have been classified into four groups. The first group includes atmospheric circulation of zonal types; the second group, processes with one Arctic invasion; the third, with two or more Arctic invasions; and the fourth group contains processes in which cyclonic activity covers the Arctic. The average duration of the circulation processes of the types considered varies from 3.6 to 5.3 days.

According to Dzerdzeevsky's typification, three circulation epochs have changed over the period from 1899 onward: two meridional (from 1899 to 1915 and from 1957 to the present day) and one zonal (1916–1956). We deal with the epochs of zonal circulation (1948–1956 (I)) and meridional southern circulation. The epoch of the meridional southern circulation includes four time periods (see Figures 1 and 2): a simultaneous increase in the duration of meridional northern and southern processes (1957–1969 (II)); longer duration of zonal processes (1970–1980 (III)); a rapid increase in the duration of meridional southern processes (1981–1998 (IV)); a decrease in the duration of meridional southern processes and an increase in the duration of meridional northern processes (1999–2020 (V)).

For the study, we have chosen the Siberian sector (60°–119° E) in the latitude range from 30° to 90° N. To assess the spatial scale of the identified temperature and humidity anomalies, calculations have also been made for neighboring sectors — European (0°—59° E) and Far Eastern (120°–169° E). The calculations are based on daily average data on air temperature and relative humidity near the Earth surface and at the levels of isobaric surfaces AT-850 hPa (1.5 km), AT-700 hPa (3 km), AT-500 hPa (5 km), AT-300 hPa (9 km) from the National Oceanic and Atmospheric Administration (NOAA) of the United States for the period from 1948 to 2020.

In climatic studies, deviations of meteorological values from long-term averages or their ratio to the mean standard deviation σ are widely used as an index of anomaly [Gruza, Rankova, 2012]. To quantify the anomalies of meteorological air temperature and relative humidity fields in different tropospheric layers, we have taken the criterion proposed by N.A. Bagrov [Bagrov, Myakisheva, 1966]:

$$K = \frac{1}{N}\sum_{n=1}^{N}\frac{A_n}{\sigma_n^2}, \tag{1}$$

where A_n is an anomaly at a point n (n=1, 2, 3, ..., N); σ_n is its standard deviation. It is supposed that points on this territory make up a fairly uniform network, and the anomaly at n has a distribution close to normal.

The K index is a dimensionless normalized mean of the anomaly, which characterizes the intensity of centers of anomalies of different signs in the territory considered. Normalization, i.e. calculation of the ratio of monthly air temperature and relative humidity anomaly A_n to its standard deviation σ_n, makes it possible to exclude the influence of seasonality and geographic latitude on the values under study.

The advantage of this parameter is that, knowing the distribution of the anomaly for a certain month (year), we can set some threshold values K for it, which will be bounds of the degree of anomaly. As a threshold value we can take the average K index for the entire calculation period, equal to 1, when in the territory under study in each node of the network the absolute value of the anomaly is equal to the standard deviation (A_n=σ_n, n=1, 2, 3, ...,N). Thus, for the K index lower than or equal to 1, the air temperature and relative humidity anomalies are within the standard deviation, i.e. natural variability.

To determine the area that anomalies of a particular sign can occupy, the parameter P was introduced [Bagrov, Myakisheva, 1966]:

$$P = \frac{n_+ - n_-}{n_+ + n_-}, \tag{2}$$

where n_+ is the number of points with a positive anomaly; n_- is the number of points with a negative anomaly in the territory of interest.

The P value indicates not only the sign prevailing in the anomalies, but also the relative size of the area occupied by this anomaly (see Table). As a rule, the deeper the center of the anomaly, the larger the area occupied by the anomaly of one sign. In this case, the anomaly K value is large and $P\to1$. If the anomaly is positive, $P\to+1$; if it is negative, $P\to -1$. If there are several centers of different signs, the P index fluctuates around 0. In this case, if K is high, there are high intensity anomaly centers in the territory; if K is low, there is a low intensity (blurred) field of anomalies of different signs. Hereinafter, K and P are referred to as anomaly indices.

2. LONG-TERM DYNAMICS OF ANOMALY INDICES OF AIR TEMPERATURE AND HUMIDITY

Look at the plots of the K and P anomaly indices of annual average air temperatures calculated for 1948–2020 and averaged over different circulation epochs and their periods: 1948–1956 (I), 1957–1969 (II), 1970–1980. (III), 1981–1998. (IV), 1999–2020 (V). Changes in the anomaly indices of annual average surface air temperatures have two pronounced anomalous periods (Figure 1, *a*): the cold period from 1957 to 1969 when most (70–80 %) of the territory of Europe and Siberia was occupied by negative anomalies of mean air temperatures at $K\geq2$, and the abnormally warm period from 1999 onward when positive anomalies of annual average temperatures at $K\geq3$ have been recorded almost throughout Eurasia. At AT–850 hPa (1.5 km), which is close to the upper edge of the boundary layer, the behavior of the K and P indices correlates well with their variations near the Earth surface (r=0.83, R^2=69 %). At AT–700 hPa (3 km), i.e. at the level of the steering flow in the direction of which the pressure systems move near the Earth surface, the circulation period of decreasing duration of meridional southern processes and increasing duration of meridional northern processes (1999–2020) stands out as abnormally warm. Moreover, over recent years, the index $K\geq4$ and its interannual variability have been significantly increasing in the Siberian sector and neighboring regions (Figure 1, *c*). At AT–500 hPa (5 km), which reflects characteristics of the middle troposphere, the temperature anomaly index K exceeded 1 only during the period dominated by zonal

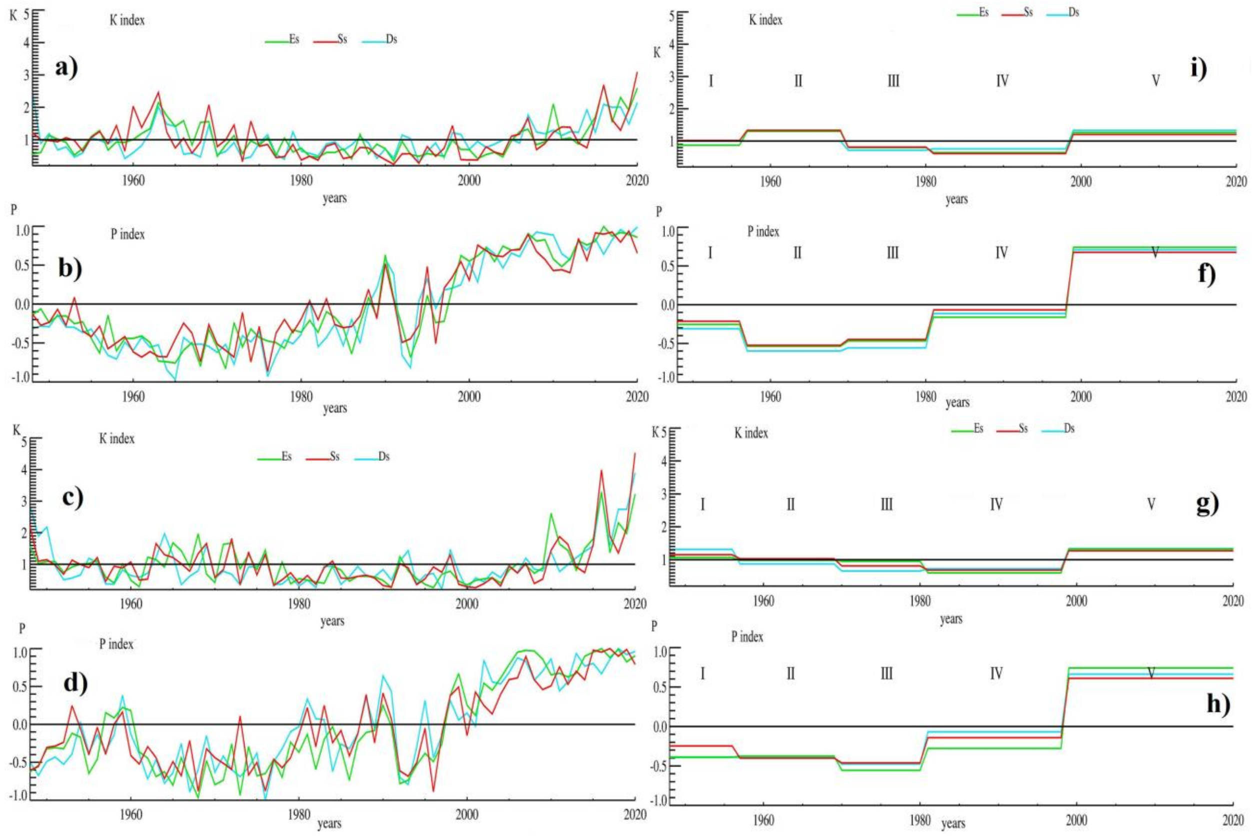

Figure 1. Variations in the anomaly indices *K* and *P* of annual average air temperature near the Earth surface (*a*, *b*) and at a level of 3 km (*c*, *d*) in 1948–2020, as well as their mean values in different circulation periods near the Earth surface (*d*, *f*) and at 3 km (*g*, *h*) in the European (Es, green line), Siberian (Ss, red line), and Far Eastern (Ds, blue line) sectors

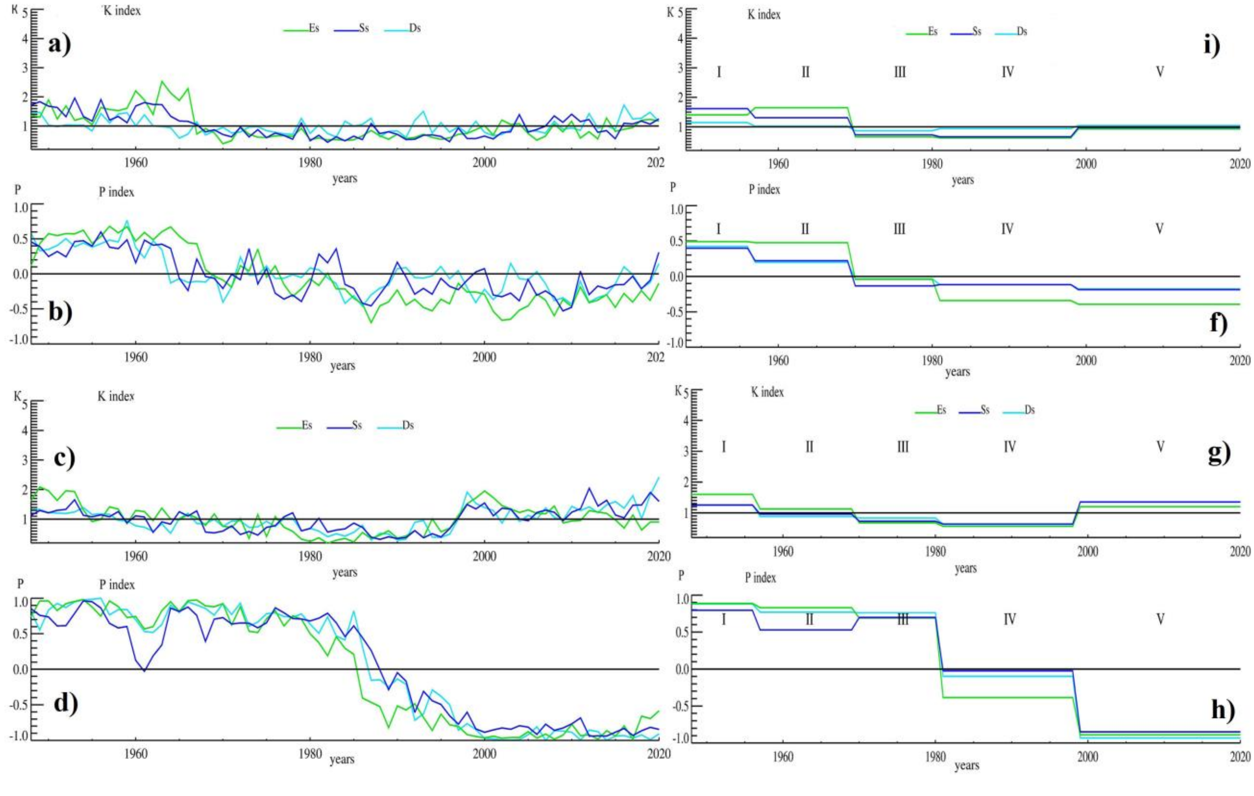

Figure 2. Variations in the anomaly indices *K* and *P* of relative humidity near the Earth surface (*a*, *b*) and at a level of 9 km (*c*, *d*) in 1948–2020, as well as their mean values in different circulation periods near the Earth surface (*d*, *f*) and at 9 km (*g*, *h*) in the European (Es, green line), Siberian (Ss, dark blue line), and Far Eastern (Ds, blue line) sectors

Correlation between the *P* index and the percentage of the total areas of *S* anomalies of opposite signs in the territory of interest [Bagrov, Myakisheva, 1966]

P	1	0.8	0.6	0.4	0.2	0	–0.2	–0.4	–0.6	–0.8	–1
S_+, %	100	90	80	70	60	50	40	30	20	10	0
$S_–$, %	0	10	20	30	40	50	60	70	80	90	100

circulation (1948–1956), when only insignificant areas of the Siberian sector were occupied by positive or negative temperature anomalies. At AT–300 hPa (9 km), the periods of longer duration of zonal processes were abnormal in terms of the distribution of annual average air temperatures: 1948–1956 and 1970–1980. In the last decade, the *K* index was within σ, but there was a trend toward increasing *K* and *P*. We have found that in most of the troposphere the temperature regime changes were most pronounced in 1999–2020 in the Siberian sector, whereas at the level of 9 km the highest anomaly indices were recorded in the European and Far Eastern sectors.

By analyzing the long-term changes in the anomaly indices of the annual average relative humidity near Earth surface and at AT-850 hPa (1.5 km), we have revealed that the periods 1948–1956 and 1957–1969 were abnormally humid. During these years, up to 60 % of the Siberian sector was occupied by positive relative humidity anomalies (Figure 2, *a*). In subsequent years, there was a tendency toward decreasing *K* and *P*, which was mainly reflected in an increase in the area occupied by negative anomalies of annual average relative humidity both in the Siberian sector and in Eurasia as a whole. In the middle troposphere (3–5 km), the period 1948–1956 stands out as abnormally humid. In recent years, the *K* index and the area occupied by negative temperature anomalies have been increasing, especially in the European and Siberian sectors at AT-700 hPa (3 km) and in the Siberian and Far Eastern sectors at AT-500 hPa (5 km). The most rapid changes in the anomaly indices of the annual average relative humidity are observed in the upper troposphere, where, along with the abnormally humid period 1948–1956, there was a well-marked trend toward increasing *K* and decreasing *P* in 1999–2020 (Figure 2, *b*, *f*). This implies an increase in the dryness of air in the upper troposphere (9 km) with a high correlation between adjacent regions. For the *K* index, the pair correlation coefficients r=0.85, R^2=72 % in the Siberian and European sectors, r=0.88, R^2=77 % in the Siberian and Far Eastern sectors.

In the intra-annual distribution of temperature anomalies in the lower 1.5-km layer of the troposphere over the last decade during the cold period of the year from November to January in the Siberian sector, an increase has been recorded in the area occupied by positive temperature anomalies. In February, positive temperature anomalies persist, but the area occupied by them decreases. The anomaly index *K* increases significantly, followed by an increase in the area occupied by negative temperature anomalies in the period from March to October. In the middle troposphere at 3–5 km, an increase in *K* and the area occupied by positive air temperature anomalies occurs in the last decade in the period from November to February, and from March to October there is an increase in *K*, accompanied by an increase in the area occupied by negative temperature anomalies. Near the tropopause level (9 km), an increase in the *K* index and the area occupied by positive air temperature anomalies is observed in the last decade only in the winter months, in the rest of the year there is an increase in the *K* index, followed by an increase in the area occupied by negative temperature anomalies.

To assess the spatial structure of temperature anomalies, we have drawn maps of monthly temperature anomalies $\Delta T_A \geq \pm 6$ °C. The criterion $\Delta T_A \geq \pm 6$ °C is convenient because it is half the amplitude of possible changes in the monthly average temperature in winter in the Northern Hemisphere, recorded over the past 100 years. By applying this criterion, we can look into the spatial and temporal features of the formation of extremely warm and cold calendar seasons [Sazonov, 1991]. In order to assess the current trends in climate change in the Siberian sector and the Northern Hemisphere as a whole in more detail, we have compared the periods 2010–2015 and 2015–2020.

In the winter seasons 2015–2020, compared to 2010–2015, there was an increase in the area of large positive and negative temperature anomalies in the Northern Hemisphere, including the Siberian sector. The largest positive and negative temperature anomalies were recorded in winter near the Barents, Kara, and White Seas (Figure 3). In spring, the area occupied by negative temperature anomalies decreased, and the number of large positive anomalies at high latitudes, including the northern regions of Siberia, increased. In summer, the area and frequency of large negative temperature anomalies over most of the Northern Hemisphere decreased, as did the frequency of large positive anomalies. In the Siberian sector, no changes were detected in the summer temperature regime anomalies during the periods considered. In fall, the area occupied by large negative temperature anomalies, including the Siberian sector, increased; no significant changes were found in the frequency of large positive temperature anomalies.

3. DISCUSSION

In 1948–2020, two circulation periods are distinguished as anomalous in the air temperature distribution in the Siberian sector in the lower troposphere (to 1.5 km): the cold period from 1957 to 1969 when the duration of the meridional northern and southern processes increased, and the abnormally warm period from 1999 to 2020 when the duration of the meridional southern processes decreased, whereas the duration of the meridional northern processes increased. In the middle troposphere, at AT–700 hPa (3 km), where the rate of temperature regime changes is higher than in the other tropospheric layers, the warm period of 1999 to 2020 stands out as anomalous. At AT–500 hPa (5 km), only the warm period dominated by zonal circulation (1948–1956) stands out as anomalous. Near the tropopause at AT–300 hPa (9 km), the periods of longer duration of

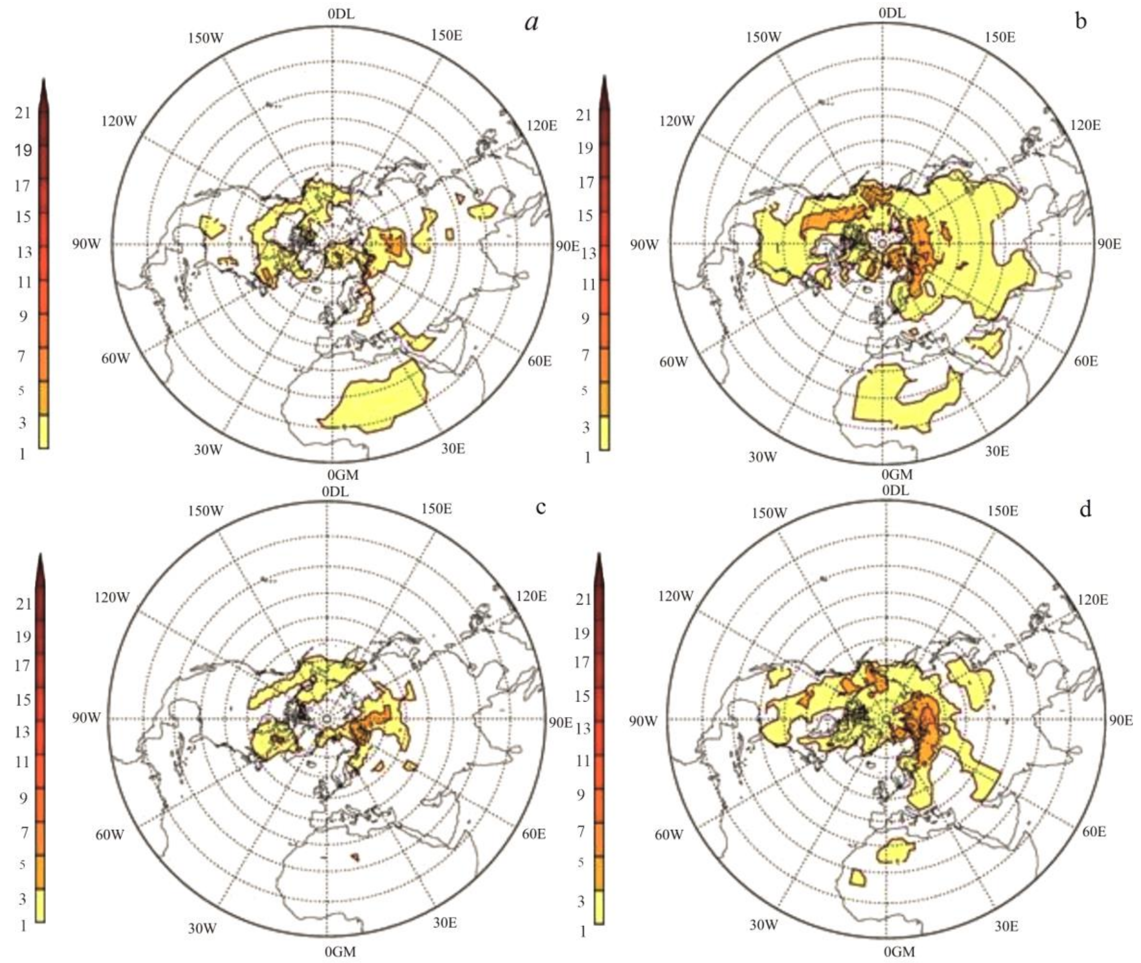

Figure 3. Frequency of large negative surface temperature anomalies ($|\Delta T_A| \geq -6$ °C) in winter in 2010–2015 (*a*) and 2015–2020 (*b*) and large positive surface temperature anomalies ($|\Delta T_A| \geq 6$ °C) in winter in 2010–2015 (*c*) and 2015–2020 (*d*)

zonal processes (1948–1956 and 1970–1980) were anomalous in the distribution of annual average air temperatures; yet, over recent years, there has been a trend to increasing K and P anomaly indices.

In 2015–2020 as compared to 2010–2015, the number of large positive and negative temperature anomalies increased in the Siberian sector in winter; in spring, the number of large positive anomalies increased in the north of the region; in summer, temperature contrasts smoothed out; in fall, the number of large negative temperature anomalies increased. Thus, over recent years, the winter weather contrast has been increasing in the Siberian sector, warming is most pronounced in spring in the north of the region; and cooling, in fall.

The highest rates of temperature regime change in recent decades have been revealed at AT–700 hPa (3 km), which is important for the dynamics of surface pressure systems and the processes of cloud formation and precipitation. An increase in temperatures at this level of the troposphere can occur with both an increase in blocking processes and an increase in reserves of potential energy and energy of convective instability, which can lead to an increase in the number of dangerous weather events, including convective ones. The highest rates of change in relative humidity were detected in the upper troposphere at 300 hPa (9 km).

The observed changes in the temperature and humidity regime in the Siberian sector correlate with the long-term dynamics of the meteorological parameters of interest in the European and Far Eastern sectors, which indicates the large-scale nature of current manifestations of climate change. The increase in the frequency of positive air temperature anomalies and negative relative humidity anomalies during the period of decreasing duration of meridional southern processes and increasing duration of meridional northern processes can be interpreted as natural fluctuations of the climate system caused by the redistribution of atmospheric mass between high and low latitudes or by intensification of heat exchange of the equatorial regions of the Pacific and Atlantic Oceans with middle and high latitudes.

4. MAIN RESULTS

The current trends in climate change in the Siberian sector during the period under study (1948–2020) are manifested in the heterogeneous nature of the distribution of temperature and humidity anomalies in different tropospheric layers, which significantly complicates the search for the underlying factors that contribute to regional climate changes. At the same time, we have revealed that the long-term dynamics of the temperature and relative humidity anomaly indices correlate with circulation factors. In particular, the highest air temperature anomaly indices in the Siberian sector and neighboring regions (European and Far Eastern) fall on the abnormally cold period of 1957 to 1969 and the abnormally warm period from 1999 onward, when the duration of meridional northern processes significantly increased in the Northern Hemisphere. The increase in the duration of the meridional northern processes led to an increase in the area occupied by large positive and negative temperature anomalies in the Siberian sector and most of the Northern Hemisphere in 2015–2020 as compared to 2010–2015. Thus, the research clearly shows that circulation factors, along with anthropogenic ones, have a significant impact on regional climate changes and are responsible for the high level of climate risks in the Siberian sector.

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