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Long-period Variations in Extreme Temperature Statistics in Russia as Linked to the Changes in Large-scale Atmospheric Circulation and Global Warming

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Abstract—Some aspects of long-term variability of temperature extremes on the territory of Russia are considered using average daily surface air temperature data from 367 weather stations over the period of 1960–2016. The number of days with extremely high summer temperature has increased monotonously (with strong peaks in some years) in the European part of Russia since the 1980s; in the Asian part of Russia this growth stopped in the early 2000s. The number of cold extremes has decreased. Changes in winter mainly agree with the general warming, but in the Asian part of Russia the warming trend is superimposed by about 40-year oscillations resembling variations in the leading atmospheric circulation modes: the North Atlantic Oscillation (NAO) and the Scandinavian pattern. The statistics of indices of extremes in the opposite phases of the modes revealed a strong response in winter, which explains qualitatively the features of long-term variations in temperature extremes. A difference in composites between the positive and negative NAO phases is mostly negative for cold extremes and positive for warm ones. The response to the Scandinavian mode is opposite. In summer, the response is generally weak, but in the west of the European part of Russia the heat wave duration is strongly linked to variations in the Scandinavian pattern.

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1. INTRODUCTION

It is known that climate changes exert both negative and positive effects on different aspects of the human society and natural systems [7, 22]. However, the negative effects caused by hazardous climate changes attract the most significant attention. Changes in the frequency, duration, and intensity of especially large (extreme) weather and climate anomalies that accompany even relatively small variations in average climatic parameters are caused, in particular, by deviations in the atmospheric stability and statistics of circulation patterns. These changes can complicate adaptation and timely response to such phenomena. A vivid example is devastating floods, forest and peat fires of the recent past, etc. Therefore, the special investigation of extreme phenomena statistics both due to the anthropogenic climate change and due to the natural climatic variability on different timescales is very important.

Changes in temperature extremes were studied for many countries. The indices of extremes from the list recommended by the WMO Expert Team on Climate Change Detection and Indices (ETCCDI) are commonly used. Most indices are suitable for the description of climatic extremes on the global scale (see http://etccdi.pacificclimate.org/list_27_indices.shtml).

The global analysis presented in [18, 24] and the analysis for the Northern Hemisphere [11] revealed an increase in the frequency of warm nights, a decrease in the annual temperature range and in the number of frost days in many regions of the globe in the second half of the 20th century.

On the other hand, some papers noted deviations from the general trend. The statistically significant decrease in the number of warm nights is observed in Japan and locally in the Balkan Peninsula [11]. The increase in the number of frost days was registered in the Balkans, in the north of the European part of Russia (EPR), in Japan and North America along the southeastern coast of the USA and the Labrador Peninsula; this trend is insignificant.

On the global scale, the duration of the continuous period (not less than 3 days) with maximum and minimum temperature above the 90th percentile increases in summer and over the year in 1950–2011 [27].

The estimates of trends for Asia were obtained using the set of temperature indices of extremes for 1958–2012. The trends which agree with the global warming are observed for all indices. For the majority of indices, the most noticeable warming is detected in the high latitudes [23].

Recently variations have been studied in the number, intensity, and duration of cold waves (the number of days with temperature below the 5th percentile of minimum daily temperature distribution) on the territory of Russia in winter (December–February) for different 10-, 20, and 30-year periods during 1951–2010. The results revealed a decrease in the number of cold waves and an increase in minimum temperature in winter in most of Russia since the 1990s. However, these trends weaken in the early 2010s, and the vast zone with an increase in the number of cold waves and with a decrease in minimum temperature is formed in the south of Western and Eastern Siberia [6]. The number of days with abnormally high temperature (above the value of the 95th percentile of maximum daily temperature distribution) has grown since the 1990s. The most significant growth has been registered in the EPR and the Far East [5].

Seemingly, very few studies by Russian scientists analyze trends in the indices of extremes proposed by ETCCDI; so, it is hard to compare trends in the extreme changes for Russia with the conclusions made for the other regions.

The present paper is mainly a diagnostic study of the long-period variability of temperature statistics at the tails of the temperature distribution function for large Russian regions. It considers two types of extreme weather and climate events which characterize temperature extremes:

—the values of temperature at the points of routine observations (at weather stations) which significantly deviate from the normal: the anomalies exceeding certain thresholds (extreme heat or extreme cold); for this group, the most reliable statistics can be obtained using observational data;

—long episodes during which temperature goes beyond the prescribed level known as heat and cold waves (it should be remembered that the levels are not necessarily extreme in this case). Such episodes, which are often associated with long-lived atmospheric circulation patterns [1, 14], can cause the most significant negative consequences: the vast durable droughts, the winterkill of crops and fruit trees, high mortality in risk groups, etc.

To provide the uniformity of threshold setting within large regions, including those stretched from north to south, the thresholds used in the present study are not fixed temperature values (which are used in meteorology to determine severe weather events, for example, extreme heat) but the values of percentiles at the ends of the empirical distribution function: for example, the 5th or 95th percentiles. This is a convenient approach to the diagnostic study of long-term variability [3, 11]. At the same time, the use of fixed thresholds is essential in the problems of climate services.

2. DATA AND METHODS

The well-known archive of station data on daily maximum, minimum, and average temperature and on total precipitation for 600 stations of the Russian Federation developed and maintained (with a significant delay though) by All-Russian Research Institute of Hydrometeorological Information [28], was used as the main historical dataset on daily air temperature. The series since 1960 from 367 stations containing the minimum number of gaps (including those with not more than two gaps in winter and summer after 1975 for calculating trends in intraseasonal statistical characteristics) were selected from the above dataset based on data completeness criteria to prepare the second assessment report [3]. For the further processing convenience, data were transformed into the synoptic archive, i.e., into the 367-dimension time series supplied with a group of attributes (year, month, day). For the present study, the series of average daily temperature after 2011 were complemented with the values computed using the controlled SYNOP data from the MAKT database (the Hydrometcenter of Russia).

The following circulation indices are utilized in the present study: the Hurrell's version of the North Atlantic Oscillation (NAO) [25] and the Barnston–Livezey version of the Scandinavian pattern (SCA) [19].

Here, several indices of temperature extremes are considered which are similar to those proposed for describing extremes by ETCCDI (27 indices of extremes). These are indices based on the number of days per season during which temperature exceeds extreme quantiles of the sample distribution function for average daily temperature of the calendar day *d*: P_5^d, P_{95}^d, as well as moderate extremes P_{10}^d, P_{95}^d. This is just the number of days with $T < P_5^d$, $T > P_{95}^d$ (let us denote them as ND05, ND95) as well as the number of days per season with heat and cold waves, i.e., the continuous episodes with the duration of not less than 5 days during which temperature exceeded thresholds of moderate extremes. These indices are called NCW10 (cold waves) and NHW90 (heat waves). Earlier the variations in some of these indices were analyzed for the territory of Russia in [3, 15, 20].

The modified algorithm for the estimation of daily air temperature quantiles was used for calculations in the present paper. The approach recommended by ETCCDI suggests increasing the sample volume for each day *d* of the calendar year ($d = 1,\ldots, 365$) by five times by including two previous days ($d - 2$, $d - 1$) and two next days ($d + 1$, $d + 2$). However using this approach directly is not so correct for the stations located in the zone of continental climate with the annual temperature amplitude of several tens of degrees: the difference between the average values of temperature $eT(d - 2)$ and $eT(d + 2)$ can reach $4\ (T_{\max} - T_{\min})/365$ (if the annual course is assumed sinusoidal), namely, up to 2 C for Yakutia: this is proved by direct estimates for separate stations.

Another circumstance is that the resulting curve of annual variations in percentiles calculated in such way is quite non-smooth, has teeth with a width of about 10 days and a significant amplitude: for example, it is equal to P_{95}^d about 1 C in summer and 2–4 C in winter for Vize Island station (20069) (the values for P_5^d are slightly smaller). This is the result of the purely sample effect and 5-day smoothing which will negatively be manifested during the computation of the index statistics, especially for heat and cold waves. It will induce false waves and will break real waves in case of using such toothed curve for the threshold values. To take these into account, the following algorithm was constructed.

1. The calculation of annual variations in the mean values for each station

$$eT(d) \quad (\ {}_{y \quad 1961,\ldots,\,2016}\ {}^*(y,\, d)(T(y,\, d)))/(\ {}_{y \quad 1961,\ldots,\,2016}\ {}^*(y,\, d))$$

where $\ {}^*(y, d)$ is the indicator of data absence: 0 if data for the day (y, d) are absent ($T(y, d)$ = the absence attribute) and 1 if data are available.

2. Its smoothing by the low-pass filter with the cut point of 90 days (to avoid edge effects at the beginning and end of the year, three waves were smoothed and the second smoothed wave was chosen): $F_{90}eT(d)$.

3. The calculation of anomalies relative to the smoothed annual course:

$$vT(y,\, d) \quad T(y,\, d) \quad F_{90}eT(d).$$

4. The computation of quantiles P^d of anomalies based on the fivefold sample $\{vT(y, d \quad 2)$, $vT(y, d \quad 1), vT(y, d), vT(y, d \quad 1), vT(y, d \quad 2)\}$, $y = 1961,\ldots, 2016$.

5. The smoothing of annual variations in quantiles with the low-pass filter and the transition to the natural values by adding annual variations in the mean values.

It should be noted that all statistical characteristics were computed rather for the full period than for the base period in order to avoid displacement when passing from the base period to the other parts of the sample [29].

The composites of seasonal (winter, summer) indices of extremes (ND05, ND95, ND10, ND90, NCW10, NHW90) were calculated, i.e., the mean values for the sample of seasons, when the certain circulation index (NAO or SCA) was in the upper quartile (the samples NAO+, SCA+) and in the lower quartile (NAO–, SCA–); each sample included 14 seasons for the period of 1961–2016. The maps of the difference in composites and separate composites presented as deviations from the means over the whole period were analyzed for revealing a possible asymmetry in the response (these maps are not presented but the cases of the clear asymmetry are noted in the text). The significance of differences was assessed using the bootstrapping. For the index NX and the mode M with the composite difference $D(\mathrm{NX}, \mathrm{M}; i)$ ($i = 1,\ldots, 367$ is the station number), two random samples of vectors (NX_i and NX_i) were constructed, each including

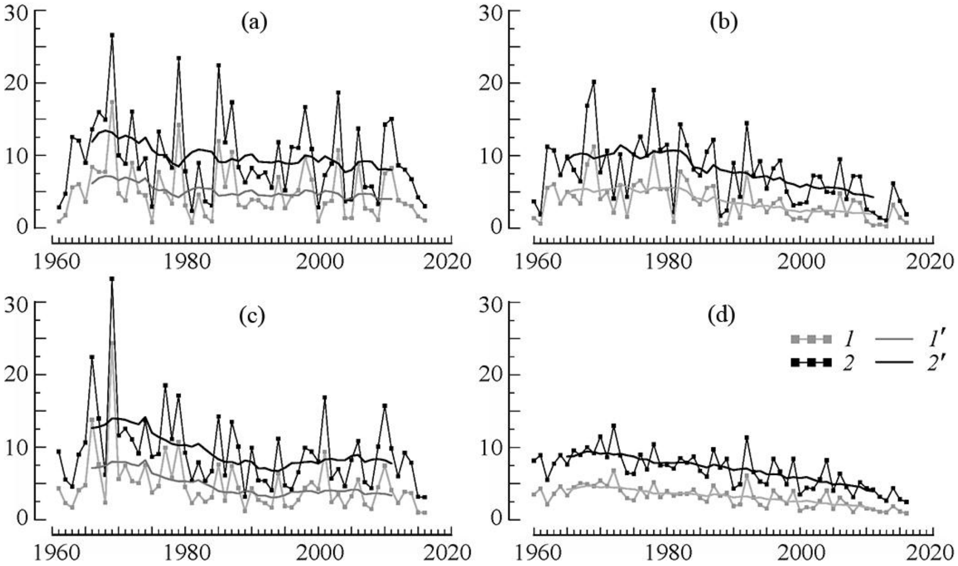

Fig. 1. The variations in (*1*) ND05 and (*2*) ND10 averaged over the regions of (a, b) the EPR and (c, d) APR for (a, c) winter and (b, d) summer. (*1* , *2*) smoothed curves obtained through the 11-year moving average.

14 elements from the full sample which is considered as a model of population (the total possible number of subsamples is $K = C_{57}^{14}$; it is easy to show that lg$K$ > 12.8 that is quite acceptable for this problem). If the absolute value of the difference in the mean values $\left|e\mathrm{NX}_i \quad e\mathrm{NX}_i\right|$ equals or is above the absolute value $|D(i)|$, the counter $C(i)$ initially equal to zero increases by 1. The procedure was repeated L times for a rather large L; the value of $C(i)L^{-1}$ is the bootstrapped estimate of probability of the fact that the difference in the means between two random samples from the population will exceed (in absolute value) the difference in composites: thus, the criterion is two-tailed. The value of $L = 10^5$ was accepted (if $L = 3 \quad 10^5$, the estimates did not almost change); the utilized Fishman's generator of random numbers [12] has a period of $>2 \quad 10^9$, which is more than enough for the analyzed problem solution.

3. VARIATIONS IN EXTREME TEMPERATURE CHARACTERISTICS

The seasonal number of cold extremes and moderate extremes in the recent decades has basically decreased, in accordance with a general warming trend. However, the regional and seasonal features should be noted. In summer, the decrease in the number of extremes begins after 1980 in the EPR (this is consistent with data on the variations in average temperature resulting from the climate monitoring in the Russian Federation [10]). In the Asian part of Russia (APR), the decrease in the number of extremes starts since 1970, although summertime air temperature on most of this territory starts rising later, since the 1980s.

In winter, the number of cold days in the EPR after the middle of the 1970s has decreased very poorly, and the number of extremely cold days has remained almost constant. In the APR, ND10 and ND05 (Fig. 1) rapidly decrease to the middle of the 1990s and slightly increase till 2010: this agrees with the general pattern of average wintertime temperature variations in the APR.

Extreme winters with the maximum number of days with extremely low temperature are distinguished. The average number of days with temperature below the 5th percentile was almost 25 in the APR in the winter of 1970 and 17 in the EPR in 1969. However, in general, the number of extreme winters when the number of days with the 5% extremes exceeds the expected value of 4.5 by two and more times, is much greater in the EPR than in the APR: 7 versus 4. No such extreme summer seasons were observed in the APR, and two such seasons were registered in the EPR: evidently, such difference between summer and winter is explained by much more intensive atmospheric circulation in winter. It is also likely that the difference in this aspect between the EPR and APR is associated with the direct influence of principal circulation systems of the Atlantic sector on the European territory.

In summer, there is an increase in the number of hot days (ND90, ND95) (Fig. 2) after 1980 both over the EPR (~3 days per decade for ND90, >1.5 for ND95) and the APR; however, for the APR on average, the

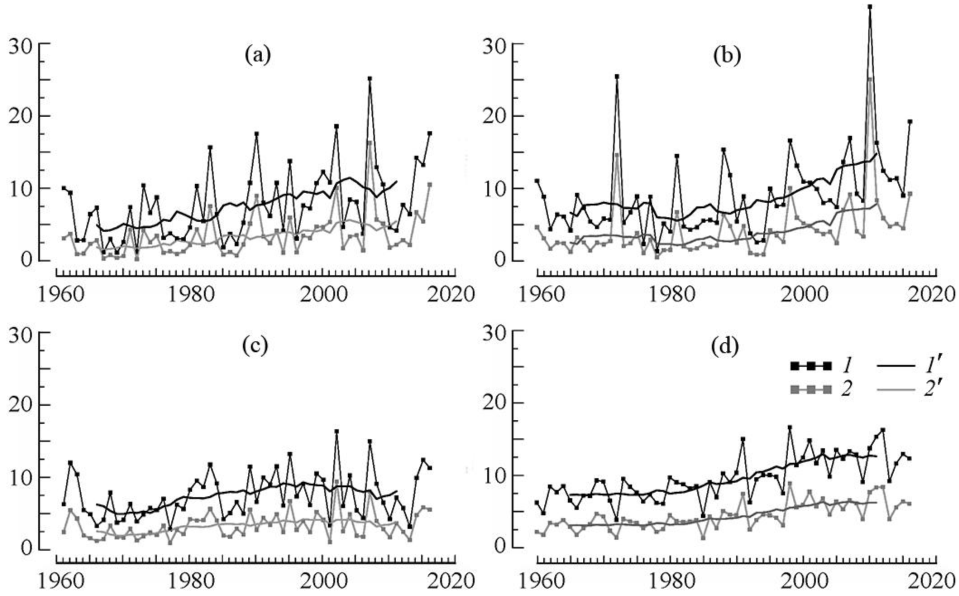

Fig. 2. The same as in Fig. 1 for (*1*, *1*) ND90 and (*2*, *2*) ND95.

growth of ND90 was not observed after 2000, its value remained at the level of 12–13 days per season as compared with ~8 in 1970; the ND90 trend for 1980–2002 is >2 days per decade. It should be remembered that all these concern average variations over the very large territory of the APR, however, for its smaller regions and for its different parts summertime warm indices change with different rates. It is noteworthy that the beginning of the growth for heat extremes coincides with that for the mean values. There is a certain asymmetry in the variations in heat and cold extremes over the APR in summer. Over the EPR, the growth of ND90 and ND95 is accompanied by very significant interannual variations. An increase in the number of warm days being constant after the 1960s (~1.5 days per decade) occurred in winter over the EPR; however, four years in a row (2010–2013) should be noted with the small number of warm days, about the mean level of the early 1970s (especially significant for extremely warm days (ND95)). In the APR, the increase was observed only till the middle of the 1990s, after that the number of warm winter days dropped till the early 2010s.

It should be noted that the number of extremely warm winters (in the above sense) was 3 in the EPR and 1 in the APR. The number of extremely warm summers is 4 in the EPR, while no such seasons were registered in the APR. The years 1972 and especially 2010 stand out: 15 and 25 extremely hot days in the EPR on average, and their number in 2010 was larger by 5 (20%) even taking the trend into account. It is interesting to compare the ranking of years based on average seasonal temperature (the anomaly vT_s) and on ND95 for the EPR. The year 2010 was the warmest ($vT_s = 3.25$ C) and the most extreme one, whereas the year 1982 was the third in the value of vT_s (2.44 C) after the year 2016 ($vT_s = 2.47$ C) which was only the fourth in terms of ND95 equal to 9. The third extreme year, 1998 (ND95 = 10), was only the ninth in the series of vT_s (1.43 C). Thus, a warm summer will not necessarily be more extreme at the same time. An important problem is to reveal the factors (in particular, circulation ones) causing such differences.

It should be noted that there is a very high degree of similarity between variations in the number of cold (ND05 and ND10) and warm (ND90 and ND95) extremes and moderate extremes in both seasons; this is true both for long-period and interannual variations (all correlation coefficents are >0.97).

4. THE CONNECTION BETWEEN THE VARIATIONS IN INDICES OF EXTREMES AND PRINCIPAL MODES OF CLIMATIC VARIABILITY

As noted above, the variations in the indices of extremes and moderate extremes of temperature qualitatively agree with the variations in average seasonal temperature in the region. A vivid feature has been observed for average wintertime temperature in Russia in the recent decades: its long-period variations represent a trend superimposed by the oscillation with the period of ~40 years: the rapid warming was observed on the whole territory of Russia till the middle of the 1990s, and cooling was registered almost everywhere

The differences in the mean duration of cold and heat waves (*E*) for the opposite phases of the NAO and SCA for the regions of Russia (sectors) and for winter and summer obtained from the samples of seasons corresponding to 15% of the highest and lowest values of the circulation indices

(a) Cold extremes

Region	NAO				SCA			
	ND10		NCW10		ND10		NCW10	
	E	STD	*E*	STD	*E*	STD	*E*	STD
Winter								
EPR	**–7.64**	**5.88**	**–4.17**	**4.24**	3.82	5.79	2.67	4.08
APR	**–7.21**	**6.41**	**–4.61**	**4.92**	**6.89**	**3.53**	**4.48**	**4.94**
Western Siberia	**–8.82**	**8.19**	**–5.67**	**6.48**	**10.56**	**8.21**	**6.66**	**6.54**
Eastern APR	**–6.65**	**6.08**	**–4.24**	**4.58**	**5.61**	**5.50**	**3.72**	**4.52**
Chukotka	–0.13	4.46	0.44	3.02	–1.72	4.33	–0.69	3.10
Summer								
EPR	1.78	5.07	1.07	2.78	–1.53	4.67	–0.22	2.72
APR	*1.37*	*2.34*	0.41	1.00	–0.47	2.63	–0.17	1.09
Western Siberia	–0.03	4.02	–0.40	1.95	0.43	4.52	–0.27	2.25
Eastern APR	*1.86*	*2.35*	*0.69*	*0.91*	–0.78	2.70	–0.14	1.05
Chukotka	1.78	3.52	*0.79*	*1.30*	**–4.07**	**4.02**	*–1.32*	*1.86*

(b) Warm extremes

Region	NAO				SCA			
	ND90		NW90		ND90		NW90	
	E	STD	*E*	STD	*E*	STD	*E*	STD
Winter								
EPR	**5.30**	**4.37**	**2.12**	**2.31**	*–4.50*	*5.66*	*–2.58*	*4.10*
APR	**2.63**	**2.97**	*0.91*	*1.35*	*–5.05*	*5.96*	**–2.14**	**1.93**
Western Siberia	**5.41**	**4.73**	**2.00**	**2.12**	**–6.99**	**5.65**	**–2.98**	**3.59**
Eastern APR	1.66	2.67	0.54	1.29	**–4.37**	**3.06**	**–1.84**	**1.50**
Chukotka	–1.54	4.22	–1.57	2.89	–0.83	3.80	–0.47	2.51
Summer								
EPR	–1.48	4.18	*–1.57*	*2.68*	*3.21*	*5.03*	*2.50*	*3.90*
APR	*–1.81*	*2.67*	*–1.07*	*1.62*	0.30	3.02	0.06	1.92
Western Siberia	–1.67	3.81	–1.40	2.63	–0.25	3.60	–0.22	2.73
Eastern APR	*–1.86*	*2.86*	*–0.96*	*1.65*	0.49	3.29	0.15	1.91
Chukotka	–0.11	3.84	–0.21	2.62	0.68	2.94	0.05	1.94

Note: The standard deviation STD was obtained for the united sample. The differences being significant at the 1% and 5% levels are bolded and italicized, respectively. The boundaries of the sectors: EPR is west of 60 E; APR is east of 60 E; Western Siberia is 60 –90 E; eastern APR is east of 90 E; Chukotka is the Chukotka and Koryak autonomous districts.

after that (till 2010). The "excessive" warming in North Eurasia attracted attention already in the 1990s. It was attributed to the effect of NAO, whose variations exhibited an upward trend for the positive phase since the 1960s [21, 25]. Later, the oscillatory pattern of the NAO and temperature variations in North Eurasia was detected as well as the behavior of another Atlantic circulation mode, SCA, which agrees with these changes [19]. A number of empirical-statistical models were constructed which connect temperature varia-

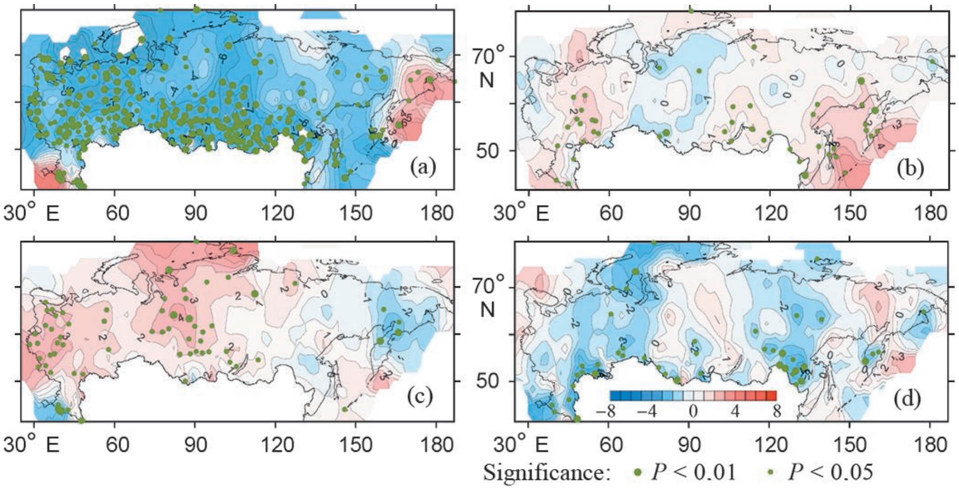

Fig. 3. The difference in the mean values of seasonal total duration of (a, b) cold and (c, d) heat waves for the positive and negative phases of the North Atlantic Oscillation for (a, c) winter and (b, d) summer (the color scale) as well as their significance (the circles).

tions in North Eurasia with these modes [16, 17] and additionally take into account the global warming [2, 4]. As a result, it was found that variations against the trend background are basically explained by the pattern of variations in these modes; expectedly, it is also true for changes in extreme characteristics.

However, as it was mentioned above, there is no direct correspondence between variations in average temperature and indices of extremes. Therefore, it makes sense to estimate directly the response of indices of extremes to changes in large-scale circulation conditions. Earlier, such analysis was conducted for the limited area (the Black Sea region) and for the NAO only [13].

The analysis revealed that the geographic pattern of the response in extremes of the same sign (i.e., ND05, ND10, NCW10 and ND95, ND90, NHW90) is very similar, although it certainly differs in magnitudes (a general idea about these differences is given by data presented in the table). Therefore, let us present only the maps of the difference in the mean values of indices for the opposite phases of the modes (Figs. 3 and 4). The noticeable differences between the phases will be commented in the text in terms of composite deviations from the mean over the whole period designated as *v*ND05 etc.

For both circulation modes, the response to their variations is stronger in winter, and this stronger winter response is observed for the cold extremes, whereas the responses of cold and warm extremes in summer are generally comparable. Let us consider the geographic features of the response.

4.1. North Atlantic Oscillation

Cold indices (ND05, ND10, NCW10). Winter. The significant response of cold indices to the NAO phase change (Fig. 3a) is observed almost on the whole territory of Russia and is significant at the 1% level in the south (except for the North Caucasus) and to the northwest of 120° E. Almost everywhere the number of cold days is smaller during the positive NAO phase; the exception is the North Caucasus, Kamchatka, and Chukotka. The mean regional differences in cold indices are significant at the 1% level for all analyzed regions (see the table).

There are differences in the geographic distribution of the response intensity between opposite NAO phases. During the negative phase, the response is generally stronger as compared to the NAO+; for example, the increase in the number of cold days is especially significant (vND10 > 6) in the EPR, except for the North Caucasus and the southern regions of Siberia. During the NAO+, a considerable decrease in the number of cold days (vND10 < –3) is basically observed in the northeastern EPR, in the north of Yakutia, and in Transbaikalia.

Warm indices (ND95, ND90, NHW90). Winter. The response is mainly concentrated in the western half of Russia up to 100 E and is positive, i.e., warm days are registered more often during the strong NAO phase (Fig. 3c). The significant (but only at the 5% level) differences in the mean values during the opposite NAO phases are observed in the EPR and in the northern half of Western Siberia (here, the response is

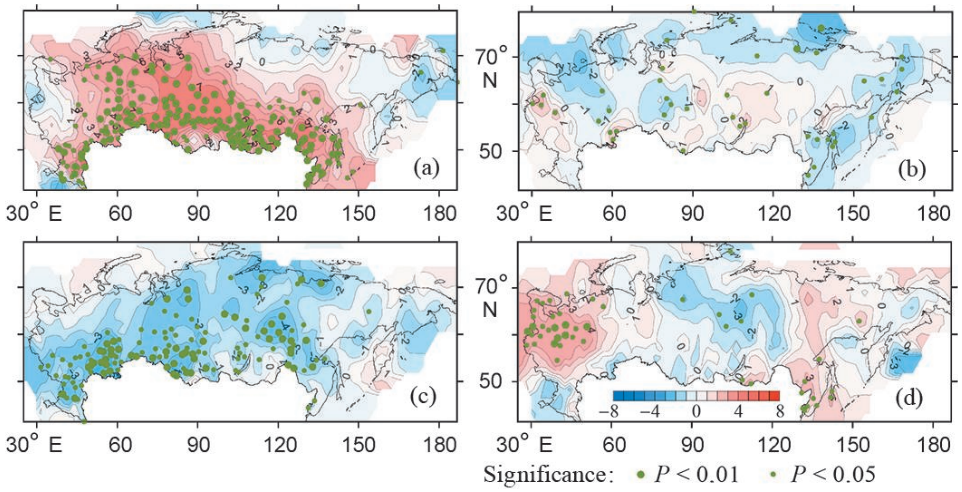

Fig. 4. The same as in Fig. 3 for the positive and negative phase of the Scandinavian pattern.

significant at the 1% level at some stations). The response of the total number of warm days (ND90) is much more intense during the negative NAO phase: the mean anomaly of the number of warm days is negative almost everywhere (except for the extreme northeast of Russia and for the Caucasus region) and reached –5 days in the western EPR. During the positive NAO phase, the high value of ND90 is also observed in the EPR, Western Siberia, and in the north of Central Siberia (the anomaly does not exceed 3 days). The regional differences in ND90 are significant at the 1% level (except for the eastern APR: at the 5% level) and the differences in the heat wave duration are significant at the 1% level in the EPR and Western Siberia, at the 5% level in the APR and are insignificant in the east.

Summer. The effects that the NAO makes on the indices of temperature extremes of both signs on the territory of Russia are much weaker in summer. The response patterns are almost symmetrical and represent alternating sectors with a response of the same sign: for warm indices (Fig. 3d), the negative response prevails and is observed in the eastern EPR, the Urals, and western part of Western Siberia as well as in the northwest and south of the Far Eastern Federal District; a roughly opposite pattern is observed for cold indices (Fig. 3b). The significant response is mainly observed in the southern part of the country. An interesting feature of the average values of warm indices is that the anomalies in the central and western EPR are negative for both NAO phases and differ in the value only (however, they have different signs in the Volga Region and in the southern EPR).

4.2. Scandinavian Pattern

Cold indices (ND05, ND10, NCW10). Winter. The response of cold extremes to the SCA phase change (Fig. 4a) is slightly more compact than for the NAO: it is almost equal to zero in the western half of the EPR to 40 E and in the northern APR east of the Taymyr Peninsula. On the rest of the territory, it is positive: the number of cold days (cold wave days) during the positive SCA phase is much greater than during the negative phase, and the significance is at the 1% level almost everywhere. The region-averaged response is significant everywhere including the EPR (however, at the 5% level only) due to the significant response in the eastern part and in the south. The mean response over the Western Siberian region exceeds 1.5 STD.

Warm indices (ND95, ND90, NHW90). Winter. In the most of the Russian Federation, the response of warm indices (Fig. 4c) to the SCA variations is negative, i.e., they are smaller during the positive phase. The significant response is observed in the southern half of the EPR (everywhere in the Volga Federal District at the 1% level), in Western Siberia, and the Irkutsk oblast. In general, the response of warm indices is weaker than that of cold indices and differs structurally: the response of cold indices is significant along the whole southern border of Russia, and the response of warm indices in the south is observed to 90 E only (the south of Western Siberia); no significant response is observed in the Urals.

Summer. The most significant response is observed in the warm indices (Fig. 4d) in the EPR, except for the south. It is positive and is evidently associated with the intensification of anticyclone activity in this region during the positive SCA phase. The warm indices also grow in the Far East and drop in Siberia during the positive phase. The cold indices (Fig. 4b) demonstrate a predominantly negative response to the SCA phase being maximum along the coasts of the Pacific and Arctic oceans. A noticeable positive response is observed in a rather small area in the western EPR.

5. DISCUSSION AND CONCLUSIONS

The results of the present study characterizing trends in temperature extremes for the large regions of Russia generally agree with the results of studies for many regions of the globe generalized in the IPCC report [26]. The change in the number of hot and cold days in Russia is generally consistent with the modern trend towards the warming since the middle of the 1970s (it should be noted that the dating of the beginning of these changes presented in [5, 6] (the 1990s) is evidently false: this is associated with the technique which does not analyze the series of indices but compares the statistical characteristics for the 10–30-year periods starting from the first year in a decade). However, the trend in the average seasonal values of temperature in winter is superimposed by the strong oscillation with the periods of growth till the middle of the 1990s and after the 2010. It was caused by the changes in the large-scale atmospheric circulation in the Atlantic-European sector [4] which is also manifested in the variations in indices of extremes. The number of cold days and the cold wave duration are larger during the negative NAO phase and during the positive SCA phase, and the response for the SCA is much stronger in the APR; the response is opposite for heat waves and for the number of hot days. In combination with the long-period variations in the NAO (a growth occurred till the middle of the 1990s and after 2010 as well as a decline occurred between them) and SCA (almost opposite changes), this explains the features of variations in wintertime extreme temperature indices including their pronounced pattern for the APR. This pair of atmospheric circulation modes also explains the extreme (in terms of significantly outstanding values of the number of cold or hot days) nature of some seasons in the EPR. For example, in the winter of 1968/1969 the EPR-averaged number of extremely cold days ND05 was almost 4 times above the mean (4.5 days). Then the high negative values of the NAO index (that corresponds to the weakening of the zonal transport in the Atlantic European sector and to the cyclone activity in the EPR) and the high positive values of the SCA accompanied by the intensification of anticyclonic circulation were observed in all winter months. The combination of the strong negative NAO phase and the positive SCA phase also accompanied other phases with the greater number of extremely cold days (1979 and 1985), while the NAO effect is generally more significant. As to the winters with the great number of extremely warm days (1990, 2002, and 2007), the negative SCA phase, i.e., low anticyclone activity, is more important. However, during the most outstanding winter of 2006/2007 (http://climatechange.igce.ru/index.php?option=com_docman&task=doc_download&gid=43&lang=ru), the extreme nature of December 2006 is defined by the high positive value of the NAO, and January was characterized by the negative value of the SCA (–2.33); remember that the indices are standardized. It should be noted that, in terms of the average seasonal value of temperature, that winter was not extremely warm due to cold February: it was only the eighth in the series from 1936 till 2018.

In summer, the response of characteristics of extreme temperature statistics to the NAO and SCA is much weaker; therefore, there are no such pronounced features in their long-period changes, they agree with the global warming trend: the indices of cold extremes drop, and the indices of warm extremes increase. However, the monotonous growth in the number of hot days in the EPR is accompanied by the strong peaks in some years with the maxima in 1972 and 2010. The indices of extreme heat in the EPR are characterized by the high values of the SCA (Fig. 4). The peak in 1972 was accompanied by the high values of the SCA in all summer months (1.75, 2.13, and 1.32). However, in the most outstanding summer of 2010, the SCA was positive in July only and was not too high (0.79); in June and August, it was negative although it had a small value: most likely, the explanations should be sought in another circulation pattern. It is well known that strong summer heat is basically formed in the area of the blocking anticyclone [14]; most of summer temperature extremes in the EPR are connected with the blocking in the east of the region (see [1] that gives some quantitative estimates). Thus, the factor of formation of abnormally hot summers should be sought among the circulation patterns affecting the blocking statistics for the EPR. One of such patterns is the East Atlantic/West Russia circulation pattern (EA/WR) defined by the dipole of the geopotential height anomaly with the centers in the area of the British Islands and over the EPR, where high pressure corresponds to the negative phase of this mode. Preliminary results demonstrate that the frequency of blocking over the EPR with the maximum between 55 and 60 N and between 45 and 55 E (the Ural maximum [1]) increases dramatically (more than twice) during the strong negative phase of the EA/WR (the index is <–1.5). The number of blockings also grows during the positive SCA phase, not so strongly though; the maximum is localized in the northwestern EPR (65 –70 N, 25 –35 E: the Karelian maximum

[1]). Thus, the great number of hot days in the EPR can be explained by the intensification of westerlies blocking under different combinations of phases of these two modes.

The seasonal generalizations of ETCCDI extreme temperature indices together with the atmospheric circulation indices can be a useful tool for the diagnosis of both long-period changes in climate extremes and separate extreme seasons. It should be remembered that the standard technique for the percentile calculation recommended by WMO can lead to the displacement of estimates (see the section "Data and Methods" of the present paper); therefore, its modification excluding these displacements should be applied: one method is proposed in the present paper. It should also be noted that the real climate monitoring requires considering not only such large and inhomogeneous (in terms of long-period variations and formation conditions of large anomalies) region as the APR, but also generalizations for its more homogeneous parts: for example, the geographic regions used in the regular climate monitoring in Russia (see [9]).

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