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Empirical Statistical Model of Climatic Changes in the Volga Region

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Abstract. Climatic changes in the Volga Federal Region from 1928 to 2017 are examined. CRU data, meteorological stations, and reanalysis ERA-Interim data are used. An estimation of global factors in the variability of air temperature in the region is made. For the first time, for the VFR, an empirical-statistical model is constructed for vertical distributions (up to 64 km) of air temperature, average standard deviation of temperature, linear trend slope coefficient, and low frequency temperature component. The effect of Arctic Oscillation on temperature changes near the Earth's surface and in the layer of 7-3 hPa in the stratosphere are evaluated.

1. Introduction

The climate of the Middle Volga Region has been studied for 200 years already. The history of these studies and their main stages are presented in [7]. In recent decades the interest to regional climatic changes has grown due to the active phase of global warming. The development of modern information and computational technologies, as well as free access to reanalyses and results of ensemble calculations with the CMIP5 program, etc., contribute to the above-mentioned situation.

Let us study the temperature conditions in Kazan region to determine the degree of impact on the regional temperature conditions by different-scale factors and evaluate possible future temperature variations.

2. Data

Monthly air temperature means for the period from 1928 to 2017 available at meteorological stations located in Kazan and in the immediate vicinity of the city were used as a source for the study. These stations were Kazan, University; Kazan, Central Hydrometeorological Station; Vyazovye and Arsk. The Kazan, University station is located in the city centre, and the Kazan, Central Hydrometeorological Station (former Kazan, reference station) is located at a distance of eight km to the south of the centre, currently within the city boundaries. The Vyazovye station is within 40 km to the west of Kazan, and the Arsk station, within 60 km to the northeast.

The annual (January – December), winter (December – February), and summer (June – August) air temperature means were calculated on the basis of monthly means. However, a detailed analysis of temperature time series at the Kazan, Central Hydrometeorological Station showed their significant heterogeneity primarily connected with intensive development of the surrounding areas. This fact does not permit us to correctly use these data for studying regional climatic changes in the presence of the above-mentioned heterogeneities. Therefore, data and findings of the study of changes in the temperature conditions obtained from the remaining three stations (Kazan, University, Vyazovye and Arsk) were analysed hereafter. Furthermore, the time series of near-surface air temperature anomalies provided by the Department of Climatic Research of the University of East Anglia (hereinafter CRU data) were used to identify the key large-scale changes.

Low-frequency digital filtration (LF Potter filter) and the correlation analysis method were applied for studying long-term changes in the temperature conditions.

Long-term temperature variations at the regional stations are practically identical. For all seasons of the year the correlation coefficients exceed 0.95. However, the correlations are stronger in the second half of the studied period, they are related to the modern stage of global warming (the correlation



coefficient is minimum, 0.98). The peculiarities of changes in the thermal regime in Kazan are connected with the specific environment of the large city. Thus, among other factors, the mean temperatures and temperature variability are higher (Table 1).

3. Results

The thermal regime of Kazan region is characterised by a marked annual cycle of temperature. A minimum is observed in January, and a maximum in July. The thermal regime variability is notably large and strongly pronounced in winter. A comparison of the air temperature norms for different observation periods demonstrates a substantial increase of the near-surface air temperature over all seasons. At the same time, the largest temperature increase was registered in the winter period (Table 1).

The time series of temperature anomalies smoothed with respect to the norms for the period between 1961 and 1990 with the help of low-frequency filtration with a band pass exceeding 20 years also revealed a substantial increase of the temperature over the entire Northern Hemisphere and Kazan region, in particular (Figure 1).

Table 1. Long-term means (norm), mean square deviations (MSD), maximum and minimum near-surface air temperatures (°C) in Kazan region averaged for the periods: 1928-2017, 1928-1957, 1958-1987, and 1988-2017.

	Year (I – XII)			Winter (XII – II)			Summer (VI – VIII)		
	Kazan	Vyazovye	Arsk	Kazan	Vyazovye	Arsk	Kazan	Vyazovye	Arsk
	1928-2017								
Norm	4.57	3.77	3.17	-10.41	-11.11	-11.89	19.10	18.20	17.83
MSD	1.19	1.17	1.18	2.76	2.77	2.75	1.40	1.35	1.39
Max	6.91	6.13	5.68	-5.33	-6.20	-6.84	24.03	22.90	22.63
Min	1.42	0.63	0.12	-17.50	-18.17	-18.80	16.30	15.20	14.73
	1928-1957								
Norm	3.85	3.12	2.52	-11.91	-12.43	-13.21	18.99	18.12	17.77
MSD	0.99	0.97	0.96	2.65	2.68	2.62	1.27	1.21	1.26
Max	5.50	4.73	4.03	-6.80	-7.30	-8.23	21.23	20.31	20.13
Min	1.42	0.63	0.12	-17.50	-18.17	-18.80	16.30	15.20	14.73
	1958-1987								
Norm	4.28	3.43	2.80	-10.47	-11.33	-12.07	18.55	17.66	17.27
MSD	1.00	1.03	1.02	2.61	2.67	2.66	1.26	1.31	1.32
Max	6.23	5.48	4.92	-5.33	-6.20	-7.03	22.03	21.43	21.23
Min	1.80	0.93	0.27	-16.77	-17.47	-18.40	16.67	15.50	15.10
	1988-2017								
Norm	5.59	4.77	4.20	-8.87	-9.58	-10.38	19.75	18.81	18.44
MSD	1.12	1.12	1.14	2.51	2.59	2.59	1.46	1.43	1.46
Max	5.00	4.18	3.72	-10.43	-11.27	-11.97	21.43	20.80	20.63
Min	3.96	3.18	2.66	-13.13	-13.97	-14.67	16.67	15.93	15.80

Moreover, the smoothing permitted us to more precisely determine periods of unambiguous sign change in the near-surface air temperature. Thus, during the winters of 1928 – 1957 the temperature in the studied region was increasing with a rate of about 0.6-0.8°C/10 years, and then up to 1970 the temperature was slightly decreasing by a value of about 0.8°C. From the early seventies of the 20th century, active warming of the climate was observed in Kazan region. From the late 20th century it significantly weakened and gave way to a weak cooling, and then, at the end of the first decade of the 21st century, the winter temperature started rising again. As a result, on the curve of the low-frequency

component from 1928 to 2017 the winter temperature mean grew by 4.7°C in Kazan, by 4.2°C in Vyazovye, and by 4.1°C in Arsk.

The summer air temperature mean changed in a different way. From the beginning of the studied period to approximately the second half of the seventies of the XX century the temperature was generally falling with an oscillation period of about 20 years. Within this period the decrease was around 1.3°C outside the city and half the value (around 0,7°C) in Kazan, which was a consequence of the warming influence of the urban conditions. From the middle seventies the temperature began intensively rising in both Kazan region and the whole hemisphere. As a result, the summer temperature mean increased by 1.9°C outside the city and by 2.2°C in the city.

Variations of the annual air temperature mean were smoother. The annual temperature mean started rising in the middle forties of the 20th century. Thus, till 1990 the increase rate in Kazan was 0.17°C/10 years, and 0.11-0.12°C/10 years outside the city. From that time the warming was intensifying at a quicker rate: at that period the increase rate of the annual temperature mean reached 0.6°C/10 years in Kazan, and 0.5°C/10 years in the rural area. As a result, from 1945 to 2017 the annual temperature mean increased by 2.7°C in Kazan, and by 2.1°C at Vyazovye and Arsk stations. Consequently, as already noted above, the increase in the annual temperature mean throughout the entire period of study was predominantly driven by warming of the cold season.

Figure 1 shows that although the temperature variations in Kazan region were sharper, they were quite consistent with the temperature variations observed in the whole hemisphere in both winter and summer. This is especially true for the last stage of warming, which has begun in the middle seventies of the 20th century. The above-mentioned air temperature oscillations result from the action of global, regional, and local factors. To estimate the contribution of the global factors to the temperature variability in Kazan region, the authors calculated the correlation coefficients for temperature anomalies in the region and the entire Northern Hemisphere. The correlation coefficients were calculated for the entire study period and two sub-periods, with the first one being the period preceding the last warming (1928 – 1976), and the second one being actually the period of the most intense warming observed since 1977 to the present day.

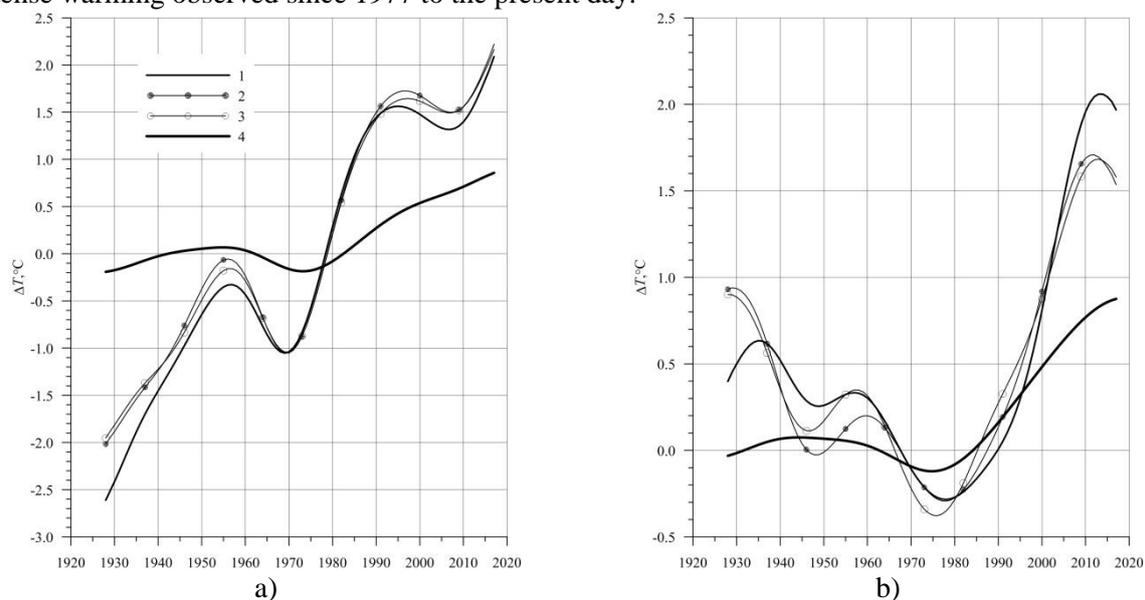


Figure 1. Low-frequency component of near-surface air temperature anomalies (°C) with a period exceeding 20 years in Kazan region and the Northern Hemisphere: a) winter (December – February), b) summer (June – August).

1- Kazan, University, 2 – Vyazovye, 3 – Arsk, 4 – Northern Hemisphere (according to CRU data).

The correlation coefficients during the entire study period were about 0.61 in winter and 0.48 in summer; between 1928 and 1976: 0.52 and 0.40, respectively, and between 1977 and 2017: 0.52 and 0.53, respectively. The coefficient increment in summer during the latter period is connected with a smoother summer temperature increase over this period. Since the squared correlation coefficient describes the contribution of the factorial characteristic to the variability of the resulting characteristic and the temperature variations over the entire Northern Hemisphere depend on the influence of global processes, it is possible to estimate the contribution of the global processes to the temperature variability in Kazan region. This contribution varies during the year. Over the entire study period it was 37% in winter and 23% in summer.

The authors use weather observation data (from databases of RIHMI-WDC (Russian Institute of Hydrometeorological Information – World Data Centre)) from 183 stations, as well as NCEP/NCAR, ERA-Interim reanalyses for studying the climatic processes in the Volga Federal Region (VFR). Paper [2] presents evaluation results for the present-day climatic changes in the VFR against the background of the processes taking place in the temperate zone of the Northern Hemisphere. ERA-Interim reanalysis data for the air temperature were compared with the meteorological network data. The correlation coefficients, r , have turned out to be very high ($r > 0.9$), which permits us to use the reanalysis data in climate studies. Comparison of ERA-Interim and NCEP/NCAR reanalyses data for 1979-2016 (correlation coefficients and differences of monthly temperature means were calculated) brought about good results as well. Thus, the temperature differences in the VFR changed within the following limits: 0.1-1.1°C (January), 0.3-1.2°C (April), 0.1-1.1°C (June), and 0.5-1.1°C (October). The coefficients of correlation between the monthly temperature means of two reanalyses at the considered grid points varied from 0.87 to 0.99 throughout the year. The correlations were especially strong in January and July ($r = 0.95-0.99$). For this reason the distributions of the air temperature mean and linear trend slopes (LTSs) in the VFR were plotted with a spatial resolution of $1.8 \times 1.8^\circ$ for the central months of the seasons for standard levels of 1000, 925, 700, 500, 300, 100, 50, and 10 hPa using NCEP/NCAR data for 1979-2016. Note that in the VFR at the level of 1000 hPa the LTSs were negative in January ($-0.1 \div -0.2$ °C/10 years) and positive in July ($0.15 \div 0.65$ °C/10 years). Over the whole troposphere up to the level of 300 hPa in the entire VFR the LTSs were above zero, which was an evidence of warming, while from the level of 200 hPa the LTSs were negative, and this trend persisted in the lower stratosphere (up to 10 hPa) as well. Thus, in January at the level of 10 hPa the LTSs varied within the range of $-0.15 \div -0.75$ °C/10 years.

Modelling quality assessment was conducted for real temperature variations in the area from 1861 to 2005 using 7 climate models selected from the CMIP5 project (a total of 39 models were considered). Analysis of the results testified that models better simulate the cycle of temperature for the warm season than for the cold season. Statistical errors were identified as a result of testing the climate model ensemble. With the help of the 7 CMIP5 models (BNU-ESM, CMCC-CM, MPI-ESM-LR, MPI-ESM-MR, GISS-E2-H, EC-EARTH, FIO-ESM), rather realistic air temperature trends were obtained for 4 periods within 1896-2005, and LTSs (°C/10 years) were estimated for each month of the year under different scenarios: RCP2.6; RCP4.5, and RCP8.5. Calculation of the monthly air temperature mean distribution in January and July between 2005 and 2098 was presented for various scenarios. Under the “rough” scenario RCP8.5 the monthly temperature mean can rise by 8°C in January and by 6°C in July.

The present article primarily focuses on study of the distribution of the air temperature characteristics up to the layer of 0.1 hPa (64 km), which was conducted for Volga Region for the first time.

ERA-Interim reanalysis data for the air temperature over the Northern Hemisphere within the period from 1979 to 2016 were used as a source material. For the VFR the authors used the monthly air temperature means at 26 levels at 24 points of a geographic grid with a step of 2.5° for reanalysis, which permitted them to obtain time series after averaging. The authors calculated mean values at each level for each season and the whole year, as well as mean square deviations (MSD), linear trends, interlayer and horizontal correlations with temperature values of the temperate zone and the first

natural synoptic region. Correlations between the air temperature variations and the Arctic Oscillation (AO) indexes were evaluated. To single out oscillations with a period exceeding 10 years the time series were subjected to low-frequency filtration at different levels using a Potter filter. Determination coefficients of the linear trend and low-frequency component (LFC) were calculated.

Table 2 presents the vertical distribution of long-term air temperature means A_v ($^{\circ}\text{C}$), MSD, and linear trend slopes A $^{\circ}\text{C}/\text{year}$ on 26 isobaric surfaces. The data averaged for the VFR for both the winter (XII-II), summer (VI-VIII), and whole year (I-XII) demonstrate that the A_v temperature drops with altitude in the troposphere and lower stratosphere (50-30 hPa), rises in the middle and upper stratosphere, and drops again in the mesosphere. A marked annual cycle of the temperature is registered. It is negative in the whole atmospheric mass in winter and above the level of 700 hPa in summer. In winter the MSD reaches a maximum value near the ground (2.26°C), then the measured values of the interannual variability decrease, and increase again beginning from the level of 30 hPa, reaching 6.41°C at the level of 3 hPa. In summer MSDs are significantly lower than in winter at all levels, and only at the level of 0.8 hPa the MSD is equal to 2.22°C .

Table 2. Characteristics of low-frequency variability of temperature means in Volga Federal Region presented on 26 isobaric surfaces based on the data averaging results at 24 points of a geographic grid with a step of 2.5 for ERA-Interim reanalysis (1979–2016).

P, hPa	H, km	Winter					Summer				
		A_v^a $^{\circ}\text{C}$	$R_{ms}^{b\circ}$ C	$A^{\circ}\text{C}/\text{ye}$ ar	R^2L^d %	R^2F^e %	A_v^a $^{\circ}\text{C}$	$R_{ms}^{b\circ}$ C	$A^{\circ}\text{C}/\text{ye}$ ar	R^2L^d %	R^2F^e %
Earth	0.0	-10.84	2.26	0.009	-5	40	17.73	1.28	0.045	11	34
1000	0.1	-9.12	2.12	0.004	-6	37	19.21	1.38	0.054	14	38
925	0.8	-9.42	1.67	0.008	-5	24	14.71	1.38	0.050	11	37
850	1.5	-9.81	1.49	0.016	-4	27	9.57	1.28	0.040	7	37
700	3.0	-15.90	1.32	0.021	-2	33	0.06	1.00	0.035	10	41
600	4.3	-22.47	1.17	0.011	-4	34	-6.78	0.91	0.031	9	40
500	5.7	-31.03	1.01	0.000	-6	31	-15.45	0.95	0.030	7	41
400	7.3	-42.15	0.81	-0.013	-3	30	-27.30	0.96	0.026	4	41
300	9.4	-54.99	0.59	-0.011	-1	52	-42.87	0.82	0.028	9	43
250	10.6	-59.97	1.02	0.003	-5	57	-50.17	0.63	0.021	8	28
200	12.0	-60.85	1.49	0.004	-5	46	-51.50	1.42	-0.020	-3	23
150	13.9	-59.75	1.31	-0.008	-5	38	-50.01	0.92	-0.009	-4	22
100	16.3	-61.73	1.37	-0.018	-3	27	-51.95	0.83	-0.020	2	23
70	18.5	-63.95	1.55	-0.021	-3	21	-52.38	0.77	-0.023	6	36
50	20.5	-65.55	1.75	-0.026	-3	23	-51.40	0.68	-0.029	18	53
30	23.7	-66.29	2.10	-0.018	-5	27	-48.96	0.57	-0.026	21	46
20	26.3	-64.55	2.58	-0.005	-5	32	-45.06	0.45	-0.019	18	42
10	30.9	-56.57	3.92	0.011	-5	33	-36.48	0.41	-0.027	49	69
7	33.3	-48.84	4.90	-0.037	-5	35	-31.13	0.37	0.018	23	60
5	35.6	-40.88	5.75	-0.085	-3	36	-25.38	0.72	0.037	28	83
3	39.3	-31.21	6.41	-0.053	-5	25	-13.11	1.06	-0.074	57	89
2	42.3	-25.96	6.37	-0.005	-6	21	-5.51	1.24	-0.071	36	86
1	47.5	-18.37	4.34	0.045	-4	30	-1.36	2.02	0.079	14	84
0.8	49.3	-16.30	3.82	0.057	-3	37	-1.97	2.22	0.104	22	86

0.51	52.7	-14.27	3.41	0.061	-2	46	-7.88	1.97	0.092	22	88
0.29	56.9	-18.17	3.55	0.037	-4	37	-22.53	1.48	0.033	1	79
0.1	64.4	-30.21	3.79	-0.041	-4	29	-51.50	2.01	-0.099	25	66

^a A_v – temperature mean, °C.

^b R_{ms} – mean square deviation, °C.

^c A – temperature LTS, °C/year.

^d R^2L – adjusted coefficient of linear trend determination showing the variance percent of the raw data explained by the trend. It is determined as a squared correlation of the raw data and linear trend whose parameters are calculated using the least square method, corrected by the number of smoothing function parameters, which takes into account the variance reduction explained by the trend. Small (and especially negative) values of R^2L show inapplicability of the linear trend model for the given time series.

^e R^2F – determination coefficient of the low-frequency component (LFC) showing the variance percent of the raw data explained by the LFC. It is determined as a squared correlation of the raw data and smoothed series.

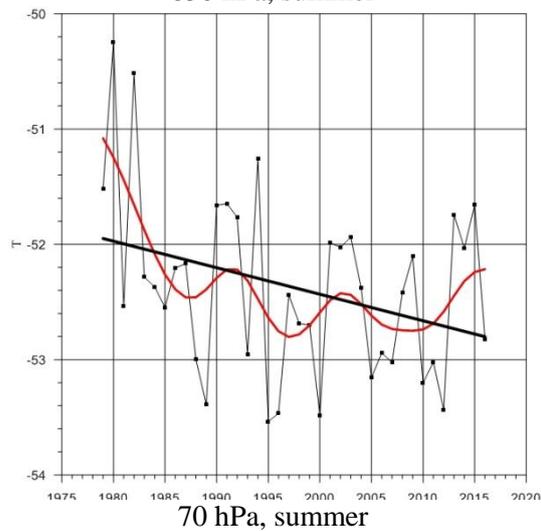
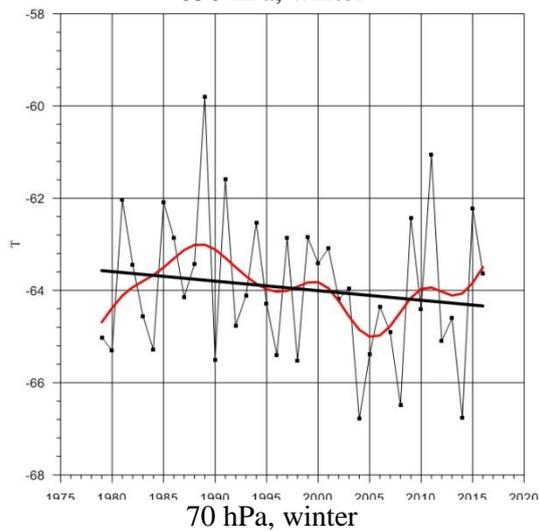
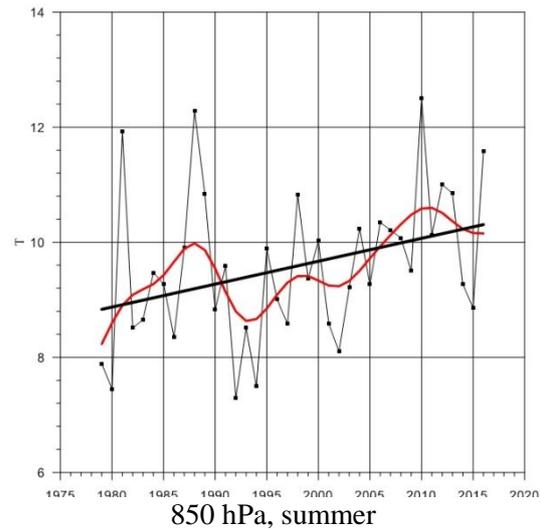
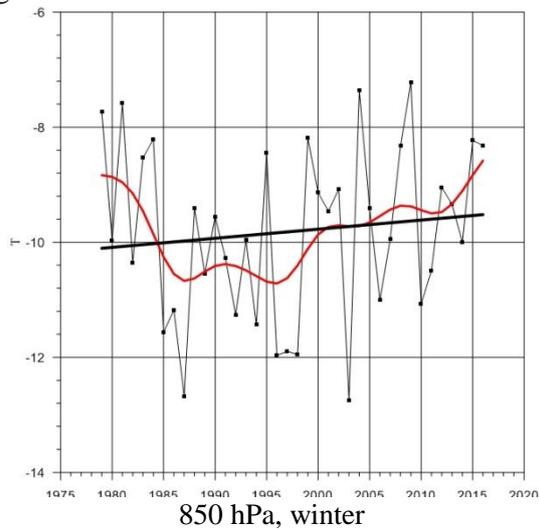
The process of air temperature variation is vertically heterogeneous in time. In the troposphere in winter and summer the LTSs were positive, which gave evidence of a tendency towards its warming that was more intensive in summer than in winter from 1979 to 2016. In the stratosphere, cooling was registered ($A < 0$), especially noticeable in the layer of 150-20 hPa. In the layer of 1-0.29 hPa warming took place again, while at the uppermost level (0.1 hPa) the temperature decreased. At the same time, in the case of annual averaging the model was simpler: in the layer of 1000 – 200 hPa $A > 0$, in the stratospheric layer of 150-2 hPa $A < 0$, and then in the layer of 1-0.29 hPa $A > 0$. In the lower mesosphere (0.1 hPa) intensive cooling took place, especially in summer. Layers with different tendencies alternated.

Figure 2 presents long-term variations of the temperature means in the VFR, which reflect the nature of the temperature variation at the selected levels over the last 38 years. It is obvious that the trends plotted on the basis of the annual values evidence warming in the troposphere, cooling in the lower and middle stratosphere, a temperature rise in the upper stratosphere and its fall in the lower mesosphere. Low-frequency component marks out levels of 5, 1 and 0,5 hPa in the upper stratosphere, where the most intensive temperature oscillations are observed.

One can judge about the correlations between the processes taking place in different atmospheric layers by the behaviour pattern of the correlation coefficient calculated between the levels in the air temperature field. Analysis of the findings shows that in the winter and summer troposphere in the layer of 1000 – 400 hPa the correlations are strong ($r \sim 1.0$), then in the layer of 400-250 hPa in winter and in the layer of 300-200 hPa in summer the correlations dramatically weaken, which is explained by the tropopause impact. In the winter stratosphere the correlations are closer, in summer in the upper stratosphere and in the layer of 0.29-0.1 hPa they drastically weaken, which is the evidence of atmosphere stratification. The levels of 10 and 7 hPa ($r = -0.04$), 5 and 3 hPa ($r = -0.07$) are weakly correlated. During this time the ozone screen is essential for the thermal regime, while the dynamic mixing is not as intense (weakening of the vertical wave interaction). The correlation weakening effect was earlier reported in our paper [8], in the course of analysis of the processes taking place in the polar zone of the Northern Hemisphere.

To identify the correlation between the air temperature oscillations in the VFR and Arctic Oscillation (AO), the correlation coefficients were calculated for 26 levels in winter, summer, and during the whole year. According to the contemporary conception, the AO is the result of interaction between the troposphere and stratosphere, to a large extent [1]. The positive phase of the AO is associated with the positive anomaly of the circumpolar vortex intensity and strengthening of the mean zonal flow, while the negative phase of the AO is observed during weakening of the circumpolar vortex and mean zonal flow. According to [4], since the seventies of the previous century the positive phase of the AO has been trending to prevail. As shown in Figure 1, in winter in the lower troposphere the correlations between the temperature and AO are rather strong ($r = 0.60$ at the level of 1000 hPa), which is the indication of warming in the VFR due to the circulation factor. The correlation

strengthening in the upper troposphere (in the layer of 300-200 hPa) and middle and upper stratosphere (7-3 hPa) are reported as well. In the stratosphere the correlation is negative, in contrast to the troposphere ($r=-0.43$ at 7 hPa). It is possibly connected with the Rossby planetary wave propagation from the troposphere to the stratosphere and the winter stratospheric warming phenomena leading to circumpolar cyclone breakdown. In this case the zonal flow weakens and the temperature starts rising, which results in a negative correlation between them. This requires special studies. As the AO manifests itself mainly in winter, the summer correlation coefficients turned out to be non-significant.



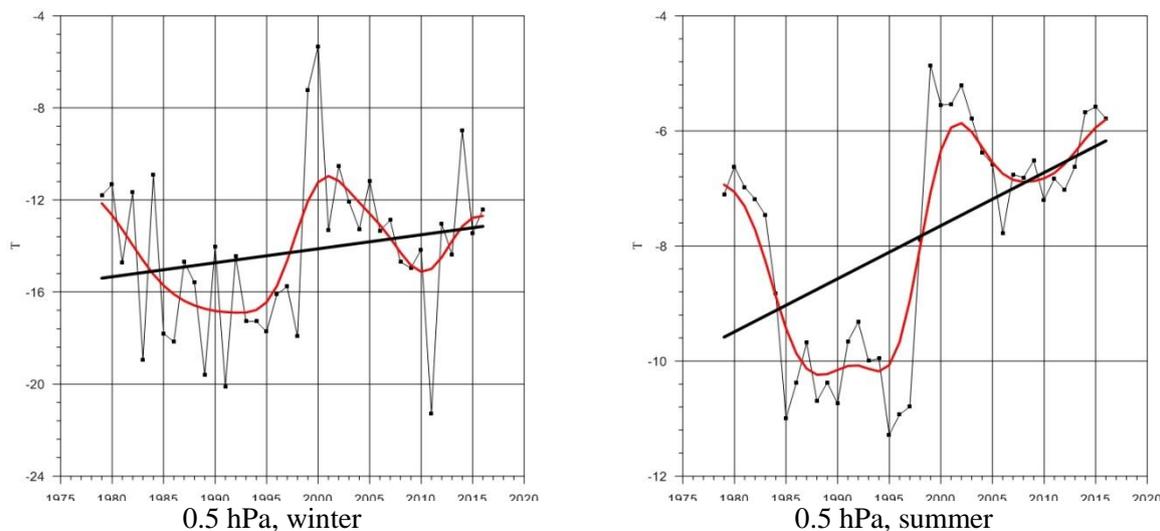


Figure 2. Multiyear curve of the air temperature means in Volga Federal Region: winter (December – February) and summer (June – August); raw data, linear trend and low-frequency component with a period exceeding 10 years, 1979 – 2016.

Assessment of the horizontal correlations between the temperature variations in Volga Federal Region and the temperate zone of the Northern Hemisphere demonstrated that the winter correlations were less close than the summer correlations in the atmospheric mass. While in summer the correlation coefficients are significant and have large numerical values ($r > 0.6$ in the troposphere and $r > 0.7$ in the stratosphere), except for the layer between 200 and 150 hPa, in winter the situation is more complicated: only in the lower tropospheric layer $r > 0.6$; then the correlation ratio increases in the upper stratosphere ($r > 0.6$).

At the same time, it should be emphasized that the correlation between the winter air temperature in the VFR and the temperature of the Euro-Atlantic sector is rather strong ($r = 0.88$ on the surface). The correlations weaken in the layer of 500-400 hPa only, and they are persistently strong in the stratosphere-mesosphere, which is the evidence of the process homogeneity. Except for the layer of 200-150 hPa, especially in the stratosphere and lower mesosphere, the correlation coefficients reach high values in summer. Peculiar features of the barometric circulation regime in the temperate latitudes of the Northern Hemisphere are described in [5, 6].

Calculation of the vertical correlation coefficients in the air temperature field between the fixed levels and all the rest overlying levels shows that in the troposphere the correlations rapidly weaken with altitude in winter (r decreases from 1 to -0.36 at the level of 10 km), the lower layers are weakly correlated with the higher stratospheric layers ($r < 0$). In summer the correlations between the levels are strong in the troposphere ($r \sim 0.9-1.0$), however, in the upper troposphere they dramatically weaken and turn negative ($r = -0.65$) beginning from the lower stratosphere. The authors plotted vertical correlations between the stratospheric layers. In winter they smoothly weaken with altitude, while in summer the situation is less consistent. Notable is a chaotic form of the autocorrelation curves, which is coherent with data presented in [3].

Analysis of the height-time sections of the first-order LFC differences of the air temperature ($^{\circ}\text{C}/\text{year}$) with a period exceeding 10 years revealed the following: since 1988 positive differences have been prevailing in the troposphere in winter, that is, the temperature has been rising with time. In the stratosphere up to an altitude of 30 km the falling (cooling) tendency is more pronounced. Far more contrasting phenomena are observed in the layer of 30-64 km, where centres with large temperature differences appear. The period between 1996 and 2004 is distinguished by warming, and the periods from 1986 to 1990 and from 2004 to 2010 are notable for strong cooling. In summer the picture is serene, without big contrasts. The warming tendency prevails in the troposphere, while in the

stratosphere the cooling tendency dominates. As a whole, the annual section (Figure 3) correlates with the winter conditions, to a greater extent. Here centres with strongly marked cooling and warming periods alternate in the layer of 30-64 km.

To get a cumulative result for the air temperature (AT) variations throughout the entire studied period, the authors calculated the vertical profiles for the sums of the first-order differences of the raw data and LFC with a period exceeding 10 years for the AT registered in the troposphere and stratosphere in the VFR. The profiles of the above-mentioned characteristics plotted for winter and summer display altitudes with extreme temperature rise or fall. Thus, in winter in direct proximity to the earth surface and at the level of 12-13 km considerable warming is registered; then intense cooling observed at 35 km gives place to warming with altitude in the lower mesosphere. In summer the positive AT sum decreases with altitude in the troposphere; in the lower stratosphere (12.5 km), in contrast to the winter value, the AT sum becomes negative, close by the level of 43 km intense cooling is observed ($\Sigma = -3.5 \div -4.2^\circ\text{C}$), and in the lower mesosphere (50-55 km) warming is registered. Thus, considerable seasonal differences in the plotted profiles and atmosphere stratification by thermal state are observed. In particular, it is important to mention the layer in the lower stratosphere (12-30 km), where the AT sum is positive in winter and negative in summer. At the same time, vertical variations of this value are not as substantial in summer.

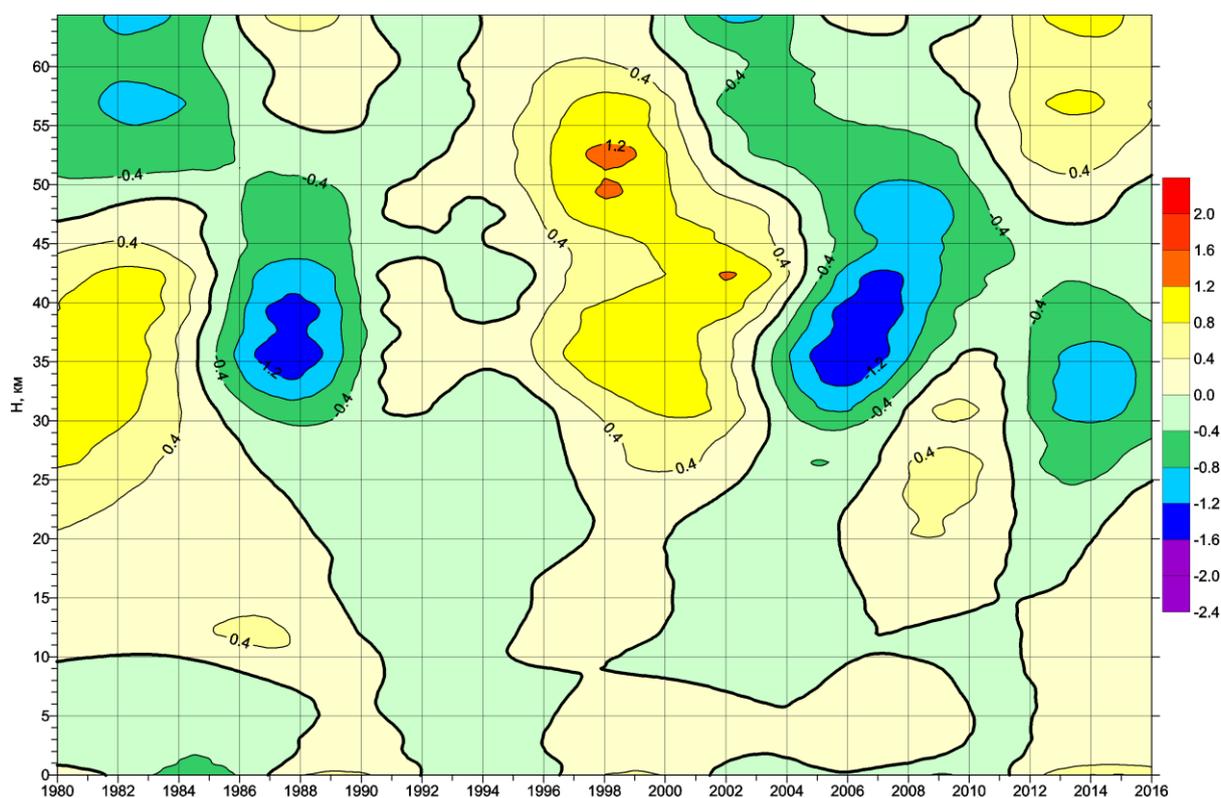


Figure 3. Time variation of the vertical profile of the first-order LFC differences with a period exceeding 10 years for the winter air temperature mean in the VFR, $^\circ\text{C}/\text{year}$.

Conclusions

1. The contribution of global process to the air temperature variability in Kazan region is 37% in winter and 23% in summer. The temperature increase is greater in winter than in summer (4.7 and 2.7°C , respectively, for Kazan from 1928 to 2017).

2. A considerable difference between the winter and summer for vertical air temperature distributions has been discovered, for example, in winter, at the level of 12-13 km, maximum warming

is registered, while in summer significant cooling is observed. The greatest air cooling takes place in the stratosphere, in the layer of 35-40 km in winter and in the layer of 35-45 km in summer.

3. The following nature of the vertical correlations in the temperature field has been discovered: the correlations between the layers dramatically weaken in the tropopause area in both winter and summer. In summer the correlations between the troposphere and lower stratosphere are negative, which evidences the antiphase nature of temperature variation.

4. According to the correlation analysis, in winter the Arctic Oscillation has the strongest impact on the surface layer of the troposphere (the temperature increases) and the stratospheric layer of 7-3 hPa, where the temperature decreases.

5. According to the analysis of the first-order differences of LFC with a period exceeding 10 years, centres of temperature increase or decrease with a cyclicity of 8-10 years are observed in the upper stratosphere and the lower mesosphere in winter.

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