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Changes in Air Temperature in Moscow in the Era of Instrumental Measurements

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Abstract—The total series of monthly and annual mean air temperatures *T* in Moscow for the entire period of regular instrumental measurements since 1779 has been studied. On average, over the past 243 years, the temperature in Moscow has been increasing by 0.012 C/year. The warming at the end of the Little Ice Age (at the end of the 18th century–the beginning of the 19th century) gave way to a slight cooling in the middle and end of the 19th century and, then, a current new warming since the beginning of the 20th century and its slight deceleration in recent decades. The strong warming in winter and spring is statistically significant, while in summer and early autumn, centennial changes in temperature are insignificant. The distribution functions of *T* are close to normal in summer and have negative skewness in winter. At the end of the 18th century, extremely low minimum air temperatures reaching –37…–39 C were registered in Moscow. Over 1780–2022, the annual mean air temperature has increased on average by 2.8 C on the Moscow periphery and at least by 1.6 C in the rural zone of the Moscow region. A degree of the Moscow climate continentality has generally been decreasing since the 1780s.

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Keywords: Climate change, air temperature, Moscow, urban heat island, rural zone, seasonal changes, climate continentality, significance of trends

1. INTRODUCTION

The modern rapid increase in air temperature *T* in the middle and high latitudes requires more accurate analysis of changes in regional based on all available data. In view of this, the value of the earliest instrumental observations carried out at the end of the Little Ice Age has increased. The present paper is a continuation of the paper [9], which considered in detail the history of meteorological observations in Moscow and determined a possible error in measurements of *T* at the end of the 18th century and the beginning of the 19th century: (0.3–0.4) C. A high correlation between the average annual values of *T* at different urban stations for Moscow was also shown in [9]. This makes it possible to consider the summary series of data obtained at different time in different parts of the city. The location of the stations is presented in Fig. 1, and their names and observation periods are presented below in the caption to Fig. 1.

The objective of the present paper is to analyze the changes in air temperature both in Moscow and in the surrounding rural zone over the entire period of instrumental observations since 1779. Preliminary results were briefly presented in [6, 7, 21], more detail can be found in [8].

2. CENTENNIAL CHANGES IN THE AVERAGE ANNUAL TEMPERATURE IN MOSCOW

Figure 2 generalizes all the known data on the average annual temperature in Moscow over the period from 1780 to 2022. The average annual values for different time were presented in [2, 5, 14–16]. The value for 1783 was calculated by the authors of [9] based on the data of [17] for all months except June, for which the value from [5] was used; the values of 1810–1812 are based on the information from the Moskovskie Vedomosti newspaper; the values for 1816 and 1817 are based on the data from [12]. The values of condi-

Fig. 1. The location of the first weather stations in Moscow: the shaded area *1* is the possible location of the Mannheim station, the measurement period is 1779–1797; (*2*) Imperial Moscow University, 1808–1812; 1820–1830; 1892–1895; (*3*) the latitude of the I. Lange station, 1816–1817; (*4*) Astronomic Laboratory of the University on Presnya district, 1830–1853; 1895–1941; (*5*) Surveying Institute, 1853–1932; (*6*) Petrovsko-Razumovskoe (TSKhA, Mikhelson Observatory), since 1879; (*7*) Lomo- nosov Moscow State University Meteorological Observatory (MSU MO), since 1954. The double line shows the city borders in 1992–2012.

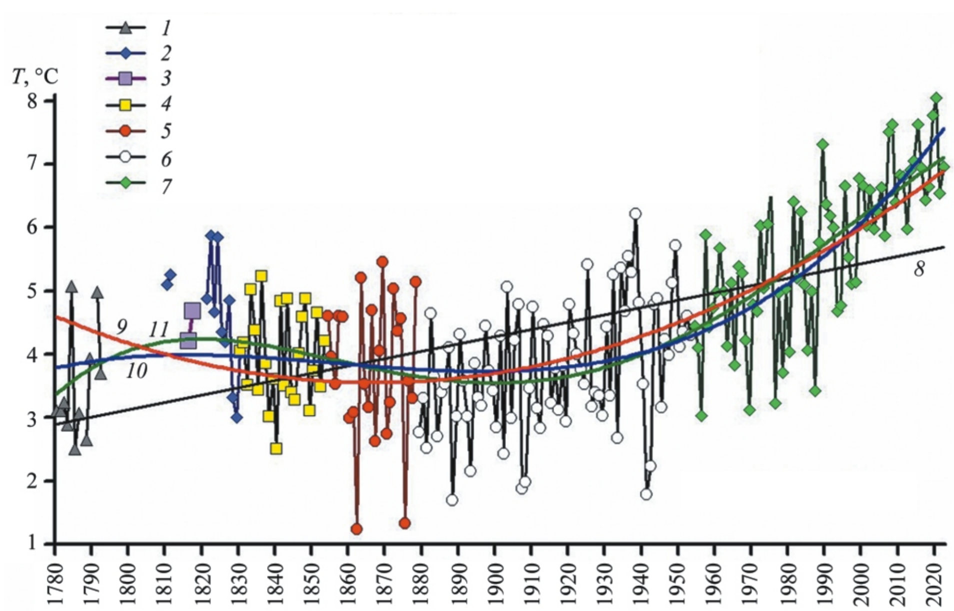

Fig. 2. (*1–7*) The centennial variations in the average annual air temperature in Moscow over the entire period of instrumental observations 1780–2022; (*8*) linear trend ($y = 0.01x + 2.89$); (*9*) parabolic trend; (*10*) cubic trend; (*11*) fourth-degree trend. Measurements: (*1*) the Mannheim station, 1780–1892, (*2*) Imperial Moscow University, 1810–1811, 1821–1830, (*3*) I. Lange station, 1816–1817, (*4*) Astronomic Observatory on Presnya, 1830–1853, (*5*) Surveying Institute, 1854–1878, (*6*) Mikhelson Observatory, 1879–1953, (*7*) Lomonosov Moscow State University Meteorological Observatory, since 1954.

tional average annual temperature for 1784 and 1785 (5.1 and 2.5 C, respectively) obtained by reducing the values for five months by the difference method for the Saint Petersburg station have been also added to the series. All the data until 1820 (for the Mannheim station, until 1791) have been reduced to the modern calendar and, except the data of I. Lange, to real average daily temperature. Thus, the data on air temperature before November 1779 are either absent or unknown for 1787, 1790, from 1793 to 1809, from September

1812 to 1815, from 1818 to May 1820, also for 1859. The series of the data until 2005 was presented in [21], and the one until 2016 was given in [7].

As clear from Fig. 2, air temperature in Moscow in the modern age has generally been increasing with time: the linear regression coefficient k in the linear trend equation is 0.0115 C/year, which means a warming in the past 243 years on average by 2.8 C. It should be noted that $k = 0.008$ C/year for 1752–2007 in Saint Petersburg [4], and the value of k for Moscow for the period 1780–2007 is very close and equal to 0.009 C/year. However, the temperature changes were nonmonotonic. The parabolic trend (line *9* in Fig. 2) indicates the clearest change in the general tendency: the warming that started at the end of the 19th century after a slight cooling and has continued until now. The cubic trend (line *10*) shows already two changes in a sign of the first derivative: the warming at the end of the Little Ice Age (at the end of the 18th century–the beginning of the 19th century) gave way to a cooling in the mid-19th century and, then, to a new warming. The fourth-degree trend (curve *11*) has one degree of freedom more and reflects the third most significant change in the general trend: the slowdown of warming in recent decades, which is evidenced by the negative second derivative of this trend (on the right edge of the series, it is convex). It should be noted that until the 2000s, the warming slowdown was more strongly pronounced [21], but the subsequent very warm years weakened this effect. The standard indicator of the trend significance R^2, which is equal to the squared correlation coefficient, with increasing a degree in the trend equation asymptotically approaches its upper limit: it is equal to 0.31 for the linear trend, 0.50 for the parabolic trend, 0.54 for the cubic trend, and 0.56 for the fourth-degree trend. The fifth- and sixth-degree trends (not presented) additionally indicate the amplification of warming in the 2010s. They almost coincide, and the values of R^2 for them are identical to hundredths (0.57). This means that there were only four basic changes in the general trend, and further complication of the trend does not lead to an increase in its significance.

It should be noted that the estimates of the trend at the beginning of the observation series are less significant due to gaps in the data from 1793 to 1809 and in the 1810s. When uniting different stations in a single series, testing of its uniformity is required. As shown in [9], when comparing the data from different stations in the periods of simultaneous measurements, pair relationships of average annual values of T are very close: the correlation coefficient R in both examples of comparisons is equal to 0.99, and the linear regression coefficient k turns out to be close to 1 in one of the comparisons and equal to 1 in the other one. This confirms the possibility of "gluing" the data from different stations in a total series and the reliability of its analysis. The series of the data from the Mikhelson Observatory (TSKhA) is not completely uniform, since the measurement site was moved in 1898 [1, 13]. However, a separate recalculation of the linear trend in the centennial course using more uniform data of the Surveying Institute until 1931 (before its closing) and the TSKhA data from 1932 to 1953 has showed the same value of k to thousandths: 0.011 C/year.

The spectral analysis of an almost continuous series of monthly mean values of T from June 1820 to November 2017 (in total, 2358) using the Fourier transform has demonstrated only one pronounced maximum in the values of spectral density associated with annual variations. For all other possible periods of more than 12 months, these values are close to 0, so that no steady long-term cyclicity in the centennial variations in the air temperature in Moscow can be seen. The absence of the data for 1859 cannot significantly distort the results.

3. SEASONAL FEATURES OF CLIMATE CHANGE IN MOSCOW

In different seasons, climate change occurs at different rate, sometimes even in different directions. These differences are clear from the comparison of the distribution functions (histograms) of the frequencies of summer and winter temperatures in Fig. 3. The histograms have been constructed from the data of all the measurements in the evening at 22:00 on the example of six years at the end of the 18th century (the results of single readings at the Mannheim station, in total, 529 in summer and 453 in winter) and seven years at the beginning of the 21st century (the data of the MSU MO station thermograph: 644 in summer and 631 in winter). As clear from Figs. 3a and 3c, the summer distributions are qualitatively similar. The modal intervals coincide (in both cases, from 16 to 18 C), the limiting values are also close (the entire range is from 5.0 to 27.3 C in 1785–1792 and from 4.4 to 27.8 C in 2001–2007). Both distributions are normal in accordance with the classic Pearson's test: at a significance level of 1% for the Mannheim station data and 5% for the MSU MO data. The closeness to the normal distribution is also evidenced by very small values of skewness and kurtosis in both cases, and the coincidence to tenths of a degree of the expected value and the median: both values are equal to 16.2 C according to the data for the 18th century and 17.4 C according to the data for the 21st century.

In winter, the distributions have strong negative skewness, which is equal to –0.7 in both cases. An evident reason for that is the snow cover with its high albedo, strictly limiting the upper bound of values of the

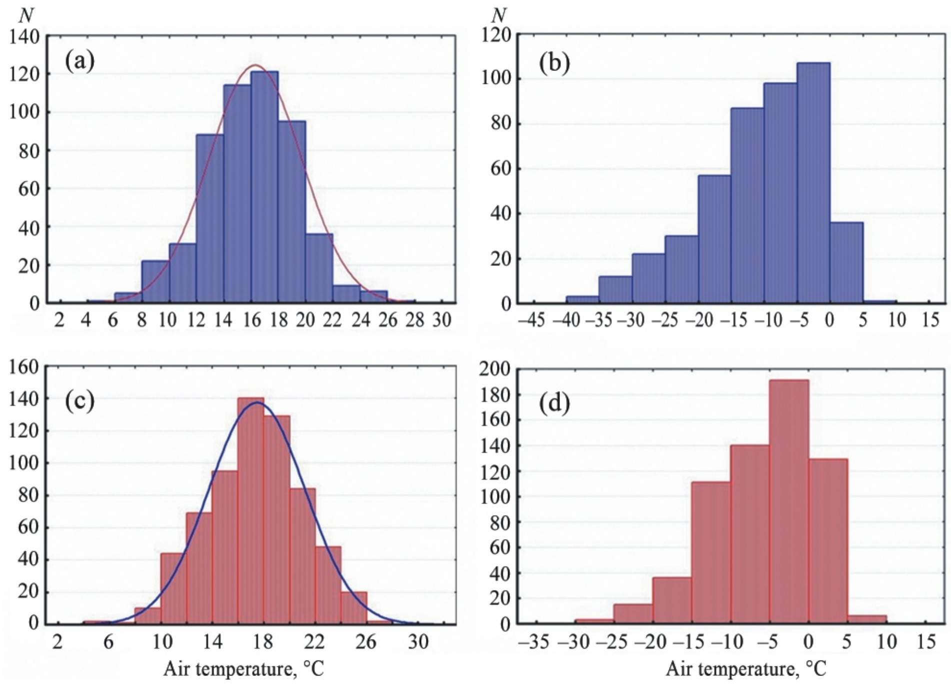

Fig. 3. The distribution histograms of all the values of temperature at 22:00 in Moscow in (a, c) summer and (b, d) winter in different epochs: (a, b) 1785–1792 and (c, d) 2001–2007. The lines are the normal distribution functions; *N* is the number of cases.

radiation and heat budget. Obviously, the ranges of values are different. The highest temperature in the evening is close for both epochs (6.0 C in 1785–1792 and 7.6 C in 2001–2007), while the lowest temperature differs by 9 C (–37.3 and –28.3 C, respectively). This is clearly observed in Figs. 3b and 3d in the more extensive left wing of the distribution in the 18th century, which spreads further towards lower values.

Actually, the end of the Little Ice Age in Moscow was characterized by very low minimum temperature that was equal to (in terms of the modern scale and the new style) –37.3 C on January 24, 1783 and in the evening on January 6, 1786 and even –38.8 C in the morning on December 17, 1788 [17]. Since minimal thermometers were not used at the Mannheim network, the values of real minimum temperature were obviously still smaller. Based on the combined data of two networks of stations (the Mannheim Palatine Society and the Royal Medical Society of France), as well as individual private stations, the author of [18] constructed synoptic surface analysis charts for the territory of Europe for every day during 1781–1785. According to the data collected by J.A. Kington, on January 22 and 23 in 1783, Moscow was situated on the eastern periphery of an anticyclone with a center over Finland. On the last day in 1785, Moscow was also located on the eastern periphery of an anticyclone with a center over the Norwegian Sea. Obviously, in both cases, the newly arrived Arctic air determined severe frosts on next days. For comparison, the minimum minimorum of T in Moscow over the whole history of instrumental observations is –42.1 C and was recorded on January 17, 1940 [15]. On December 31, 1978, it was the last time when air temperature approached such low values here: its minimum according to the MSU MO data was equal to –38.4 C. Thus, the distributions of single temperature values in the 18th and 21st centuries are qualitatively similar in summer, but in winter they are different.

The annual variations in the linear regression coefficient k of linear trends in separate months give the most complete idea of seasonal variations. As clear from Fig. 4c, until 2005, the warming during 226 years occurred on average in 10 of 12 months, most quickly in January [6, 21]. In July and August, despite the general trend, a slight cooling was observed. This is also clear from Fig. 4a when comparing the annual temperature variations in Moscow according to the Mannheim station in 1779–1792 and MSU MO in 1961–1990: in July and August, the mean values in the 18th century were higher than in the second half of the 20th century. However, in next 15 years, the values of the linear trend (k) changed: the trend was already positive in all months, but it was very small from June to September (<0.005 C/year) and even close to 0 in July and August. The absence of statistically significant centennial changes in T in summer and early autumn is also confirmed by the t-test:

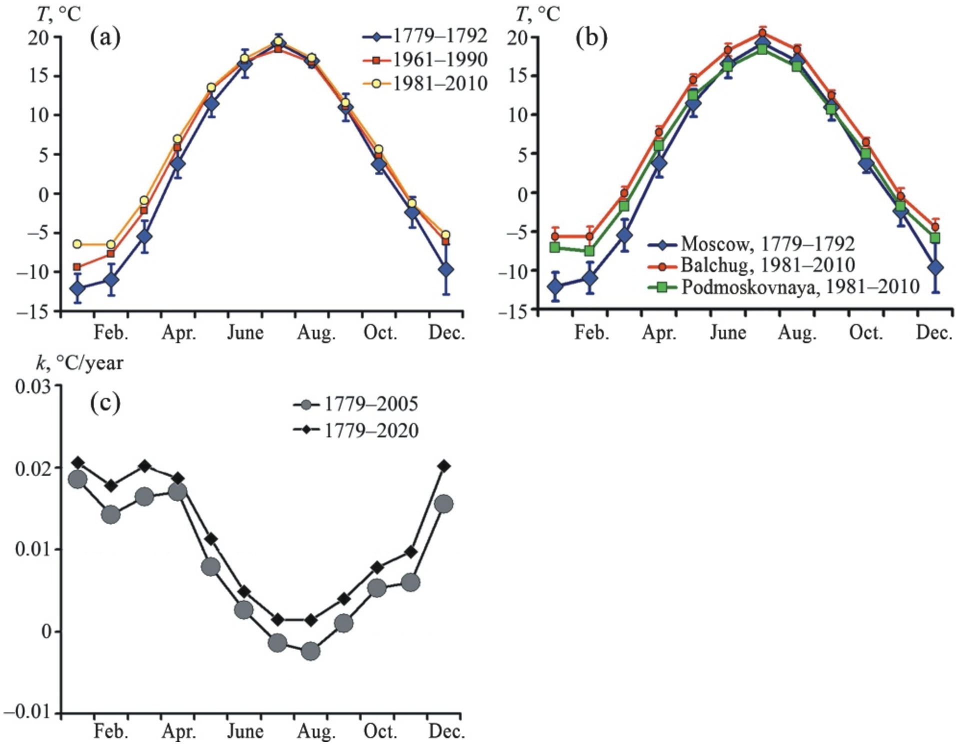

Fig. 4. The annual variations in (a) the air temperature in Moscow in different epochs, (b) air temperature in Moscow and the Moscow region, and (c) linear regression coefficient (the value of linear trends) of T. The confidence intervals have been calculated with a confidence probability of 0.95.

$$Z \quad \frac{\overline{X} \quad \overline{Y}}{\sqrt{\ {}^2(X)/n \quad {}^2(Y)/m}}$$

where $\overline{X}$ and $\overline{Y}$ are the sample expected values; ${}^2(X)$ and ${}^2(Y)$ are the sample variances; n and m are the sizes of both samples. The estimation of the validity of differences in $\overline{X}$ and $\overline{Y}$ using the t-test is also applicable for analyzing the significance of climate change. As shown in Fig. 3, the distribution functions of temperature are close to normal, especially in summer, which makes it possible to use this parametric test. The comparison of the partial samples of the first and last 30 monthly mean values on both edges of the series (over the periods 1780–1833 and 1988–2017) for all the months from June to September revealed that the differences between the sample means turned out to be insignificant even with a rarely used confidence probability of 0.90. For example, in August, the value of Z was equal only to –0.80 with the sample size $n = m = 30$. There are differences that are significant with a confidence probability of only 0.95 in November, 0.99 in May and December, and 0.999 in the other months (actually, at an arbitrarily small significance level, since the absolute values of Z are very high: from –4 to –6). This result shows, on the one hand, absolute validity of long-term climate warming in Moscow in the winter and spring months and, on the other hand, similarity of climatic conditions in summer and early autumn in different ages. This conclusion is also confirmed by Fig. 4a, in which the monthly mean values of T for all the months from December to May at MSU MO in accordance with the normals for both 1961–1990 and 1981–2010 go beyond the upper limits of the confidence probability of 0.95 of the mean values in the 18th century. From June to September, the values of both normals are within the confidence intervals: hence, the differences with this confidence probability are insignificant. A more rapid increase in T in Moscow in winter and spring is also clearly seen from its mean values in separate seasons for different ages presented in Table 1. It should be noted that in Saint Petersburg on average for 1752–2007, the warming also turned out to be strongest in winter and spring (k was equal to 0.014 and 0.010 C/year, respectively), while the smallest changes in T were registered in summer ($k = 0.002$ C/year) [4].

It is noteworthy that linear trends are very sensitive to extreme points of the series, and this limits the capabilities of their use. For example, the secondary minimum of k in February for 1779–2020 in Fig. 4c is explained not by centennial climate changes but only by very cold weather in February in 2006, 2007,

Table 1. The mean air temperature (C) in Moscow in different epochs

Data source	Winter	Spring	Summer	Autumn	Annual mean
All the stations in Moscow, 1779–2022	–8.6	4.3	17.4	4.6	4.4
Moscow University, Lange station, Presnya, Surveying Institute, Petrovsko-Razumovskoe (TSKhA), 1810–1900	–9.6	3.3	17.2	4.2	3.8
TSKhA and MSU MO, 1901–2000	–8.2	4.6	17.1	4.5	4.5
MSU MO, 1961–1990	–7.8	5.6	17.3	4.9	5.0
MSU MO, 1981–2010	–6.1	6.5	18.0	5.3	5.9
MSU MO, 1991–2020	–5.4	6.9	18.4	5.9	6.4

2011, and 2012 with the monthly mean air temperature below –10 C due to the weakening of the Icelandic Low in these months [11]. If excluding these four values, k in February turns out to be the same as in January (0.020 C/year), and the secondary minimum disappears. Similarly, without taking into account only two abnormal hot Julies in 2010 and 2011, the linear trend in July over the entire period is equal to 0 with accuracy to 10^{-5}.

One more effect of seasonal differences in climate change is the long-term changes in the Moscow climate continentality. The Gorchniskii index K_G and the Khromov index K_K have been calculated to evaluate it. More rapid warming in Moscow in the cold season leads to a decrease in the annual amplitude of air temperature and hence in climate continentality. The value of K_G on average for the whole period was decreasing by –0.04/year, and it has thus been reduced from 48 at the beginning of instrumental observations to 39 in the recent years, while K_K has decreased from 0.86 to 0.84, respectively. However, in the early 2010s, the return of rather cold winters was registered due to the negative phase of the North Atlantic Oscillation (NAO), and several abnormal hot summer months were also observed. Due to this, the climate continentality in these years slightly increased [11] despite the centennial trend toward its reduction previously noted in [6].

4. EFFECTS OF THE URBAN HEAT ISLAND

Several papers dealt with studying the Moscow heat island [3, 16, 19, 20]. The effect of this phenomenon on the value of the centennial trend in air temperature in Moscow for 1780–2022 will be discussed below. The resulting estimate (k = 0.012 C/year) indicates primarily the conditions for the nearest or middle periphery of the city, for which most of the values of T_m of the summary series in Fig. 2 have been obtained. Actually, such measurements in the city center were carried out only from 1810 to 1812 and from 1820 to 1829, as well as, perhaps, in 1779–1792 and 1816–1817. On the other hand, at the start of the functioning of the Mikhelson Observatory, Petrovsko-Razumovskoe was a near suburb of Moscow, and it was included in the city limits only at the beginning of the 20th century. However, these short-term measurements outside the city did not affect the value of the linear trend: as noted above, as a result of recalculating the series with including the data of the Surveying Institute until 1931, the estimates of k almost coincided. All other values of T_m were obtained on the eastern, western, northern, and southwestern periphery of the city (see Fig. 1). It is obvious that the resulting trend cannot be a correct estimate of background climate change, since it partially reflects the effect of the Moscow heat island, which was generally increasing with time [19].

For evaluating this effect on the value of the trend, the data from the Balchug station, which is located in dense residential building in the city center, and from the Podmoskovnaya station located 24 km west of Moscow can be used. Unlike many other stations in small cities, which create their heat islands (weak ones though), the Podmoskovnaya station has indicated the conditions of an almost ideal background zone until recent years. When substituting the values of T_m at the Balchug station to the centennial series starting from 1951, the value of the linear trend k increases up to 0.0168 C/year. On the contrary, when including the values of T_m from the Podmoskovnaya station since 1946 (instead of the TSKhA and MSU MO data), k decreases to 0.0066 C/year. Thus, for the city center, the rate of warming has increased over the entire period as compared to the city periphery approximately by a half and has decreases almost by two times for the rural zone of the Moscow region. In other words, over the recent 243 years, the temperature has increased on average by 4.1 C in the conventional city center, by 2.8 C on the conventional city periphery, and by 1.6 C in the rural zone. It should be noted that the conditions in most of the city in the 18th century were similar to rural ones due to a sparse residential building (except the narrow zone around the Kremlin) and prevalence of natural surfaces: meadows and forests. A correct estimation of the Moscow heat island intensity is possible only from the late 1870s, when there were already two stations, and this estimate is about 1 C [19]; a century earlier, the heat island intensity not obviously exceeded several tenths of a degree. Thus, the background climate warming in the Moscow region not distorted by the impact of the heat islands of both Moscow and the small cities in its outskirts is at least 1.6 C and, probably, not more than 2.0 C over the whole period of routine measurements since 1780.

A comparison of the climate conditions of Moscow in the 18th century with those of the current city center (the Balchug station) and the rural zone (Podmoskovnaya station) in 1981–2010 are presented in Fig. 4b. It is clear that the changes in T from June to September for two recent centuries have been statistically insignificant with a confidence probability of 0.95 when the Mannheim station data are compared with the conditions not only for the city periphery (MSO MO) but even for the city center. It is noteworthy that the temperature in the rural zone of the Moscow region in all summer months is currently even slightly lower than according to the Mannheim station, although these differences are insignificant. On the other hand, from December to April, the values of temperature in the rural zone are currently much higher than in Moscow in the 18th century (and even more so than they were in the rural zone). Consequently, the warming in the winter and spring months indicates real and statistically significant background changes in the regional climate, which are not associated with the effects of urban heat islands. It should be noted that the difference in the monthly mean values of T according to the Balchug and Podmoskovnaya stations, approximately indicating intensity of the Moscow heat island, is maximal in summer (>2.0 C) and minimal in autumn and winter (<1.5 C). The average annual difference is ~1.8 C, which is close to the estimation of the Moscow heat island intensity obtained from the data of all the stations in the region in the 1990s (1.6 C) [19].

In addition to the analysis of air temperature, it should be noted that the average annual water vapor pressure in Moscow has not significantly changed since 1870, while relative humidity noticeably has decreased, largely due to the air temperature rise. Thus, the climate of Moscow has become not only warmer but also drier [19]. The decrease in annual precipitation until the mid-19th century was then followed by its steady increase, which was observed during the 20th century and has slowed down in recent decades [10]. Due to the precipitation increase, the snow depth still remains without significant changes, despite the warming in the winter months.

5. BASIC CONCLUSIONS

During the entire period of instrumental observations of 1780–2022, the air temperature in Moscow was increasing on average by 0.012 C/year. The basic changes in the Moscow climate in this period were characterized by the warming at the end of the 18th century and at the beginning of the 19th century, the cooling in the middle and end of the 19th century, the ongoing warming since the early 20th century, and its slight slowdown in the last decades.

The distribution functions of temperature in summer are close to normal, and the high negative skewness is observed in winter due to the snow cover.

The end of the Little Ice Age in Moscow in the 18th century was manifested in extremely low values of winter minimum temperatures close to –40 C.

The climate warming in Moscow in winter and spring, on average over the 243-year period, occurred more rapidly, and this change is statistically significant, while the centennial changes in summer and early autumn are insignificant. The continentality of the Moscow climate has generally been decreasing since the 1780s.

The increase in the average annual temperature in the rural zone for the Moscow region over the period 1780–2022 is at least 1.6 C.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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