ISSN 2304-6295

Climate change and the thermal island effect in the million-plus city

Gorshkov, A.S.[1*]; Vatin, N.I.[2]; Rymkevich, P.P.[3]
1 Saint Petersburg State University of Industrial Technologies and Design, St. Petersburg, Russian Federation
2 Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia
3 A.F. Mozhaysky's Military-Space Academy, Saint Petersburg (ex Leningrad), St. Petersburg, Russian Federation
* alsgor@yandex.ru

Key words: Climate change; Electric power utilization; Energy utilization; Energy Efficiency; Urban planning; Cooling energy consumption; Global climate changes; Heat-related mortality; Integrated assessment; Peak electricity demand; Temperature increase; Urban environmental quality; Urban heat island; Atmospheric temperature

Abstract:

A qualitative and quantitative analysis of changes in the outdoor temperature in St. Petersburg (Russian Federation) for the period from 1743 to 2018 was performed (276 years old). Used data from open sources. It is shown how the annual average outdoor temperature in St. Petersburg, the average monthly air temperatures, as well as the air temperature during the warm and cold periods of the year, changed. Climate change is divided into stages lasting 50, 25, 10 and 5 years. The main sources of thermal pollution of the urban environment, including man-made. A quantitative assessment of the contribution of anthropogenic sources to the thermal pollution of the urban environment, which amounted to about 586 PJ per year. The main contribution to thermal pollution is provided by consumers of thermal energy (220 PJ per year), transport (220 PJ per year), consumers of electric energy (120 PJ per year), population (26 PJ per year).

1 Introduction

The excess of air temperature over urbanized areas compared with suburban areas (the so-called heat islands or urban heat islands) was recorded in more than 400 major cities in the world [1]–[6]. The results of comparative studies show that the average increase in air temperature over urbanized areas can exceed 4-5 ºC. At the peak, it can reach 10 ºC. Elevated ambient temperatures lead to an increase in energy consumption for indoor cooling, peak electricity demand, and have a serious impact on mortality and morbidity, the quality of the urban environment and comfortable living conditions.

A significant number of studies are devoted to assessing climate change in energy systems in various countries and regions. [7]–[15], [16]. Climate change has a negative impact on the efficiency of the Russian power industry [17]. It has been shown that an increase in outdoor temperature worsens the operation of thermal and nuclear power plants throughout Russia. For thermal and nuclear power plants, the power drop of steam turbines is about 0.2–0.3 and 0.4–0.6% by 1 ºC, respectively. This means an additional consumption of 3-4 million tons of standard fuel per year by 2030–2050. Nevertheless, the complex impact of climate change on Russian energy systems remains clearly positive due to annual fuel savings of about 100 million tons of standard fuel as a result of reduced heat demand for heating buildings.

Climate has a significant impact on energy consumption in buildings [18]. In the cold season, to maintain comfortable microclimate parameters in heated rooms, a predetermined amount of heat energy must be supplied to the heating systems of buildings. The greater the difference between the temperature of the inside and the temperature of the outside air, the higher the building's need for thermal energy. But recently, more and more attention has been paid to the thermal pollution of the urban environment. Cities, ensuring the viability of their environment, emit a huge amount of thermal energy into the atmosphere and thus turn into large islands of heat.

This circumstance should be taken into account in assessing the energy-saving potential and the payback period of energy-saving investments [19]–[22]. However, adjustments to such estimates for climate change have not yet been carried out.

The study of climate change, the impact of climate change on humans, various ecosystems, building structures is carried out by various research methods and measuring instruments.

The results of the study of urban heat islands using the results of thermal space surveys are described in publications [2], [23]–[27].

The article [28] is aimed at predicting the surface temperatures of the urban environment of the cities of Kiev (Ukraine) and St. Petersburg, which should be expected in 2024 if the trends of observed climate warming continue. Based on these data, time series of the surface temperature of the urban environment was constructed, trends were calculated, and the forecast of the expected average and maximum surface temperatures of the urban environment was calculated. According to the results of the study, it is shown that, with the current tendency of climate warming in St. Petersburg, we should expect an increase in the average long-term average daily surface temperature of the urban environment to + 28 ° C (an increase of + 3.0 ° C), and on the hottest days - up to plus 37.0 ° C with additional heating of the surface of individual sections of the urban environment to plus 45.1 ° C.

Similar studies of changes in surface temperatures of the urban environment using materials from thermal space imagery are considered in articles [24], [25]–[29]. The experience of using satellite images in environmental studies of Moscow is described in [24], [25]. The research of the urban heat island in polar night conditions using experimental measurements and remote sensing using the example of the city of Norilsk is considered in the study [26]. According to the data from the LandSat series satellites and standard urgent observations at weather stations in [30], a map of the risk of overheating the surface of the urban environment was obtained. It is shown that industrial areas are characterized by high risks of overheating, and recreation zones and territories built up in the second half of the last century by five-story buildings are characterized by minimal risks.

Russian regional features of the impact of climate on various geo-ecological systems are considered in [31]–[34].

In [31] the characteristics of climate, geomorphology, and soils of the Stavropol Territory (Russian Federation) are presented, as well as their changes over the past 30-50 years, based on which the main environmental problems of the soils of the region are identified. Similar studies for the conditions of the city of Moscow (Russian Federation) were performed in [32]. Climate change in the European north of Russia and its impact on water bodies are described in [33]. The biological foundations of the formation of sustainable ecosystems and the rational use of soil and plant resources of megacities on the example of St. Petersburg (Russian Federation) are presented in a dissertation [34].

The influence of climate on the building structures of buildings and structures, the durability of their facing layers and finish coatings, the processes of moisture accumulation in wall envelopes, as well as the assessment of the effects of climate on the temperature and humidity conditions of unheated rooms are considered in [35], [18].

In [36], [37] the influence of climatic characteristics of several settlements on the rate of moisture accumulation in multilayer walling during the heating period is considered. The influence of environmental parameters on the durability of external walls and cladding layers in their composition was studied in [38], [39]–[42]. In [43] it is shown that an increase in the outdoor temperature during the heating period and an increase in the number of temperature transitions through 0 °C increase the risk of ice formation on the roofs of buildings with a pitched roof. For unheated attic rooms, the heat balance equation has been compiled and a list of effective engineering and technical measures has been developed that can significantly reduce the risk of ice accumulation on the roofs of buildings. Besides, active methods to prevent the formation of ice on the roofs are considered [43]. An increase in the number of temperature transitions through

0 ºC leads to the accumulation of damage in structures, for example, in the form of defrosting of facing layers made of porous materials.

The impact of climate change on human health is considered in [44], [45], [2], [1].

Special attention should be paid to studies aimed at conducting a retrospective analysis of climate change over long time intervals. Among these studies [46] should be mentioned specially..

A comprehensive reconstruction of the history of climate change on the territory of the Russian Plain (Russian Federation) over the past 2000 years has been completed [46]. The authors of the study note that over the past millennium, against the background of quasi-cyclic fluctuations, a gradual decrease in the average annual and average seasonal (winter and summer) temperatures was observed, however, in the 20th century, the trend in annual and winter temperatures changed sharply to the opposite. It is noted [46] that the average annual temperatures in Central Russia are currently at a level approximately corresponding to the maximum of the medieval optimum (late X century), and modern winter temperatures are at a record high for the past one and a half millennia, summer temperatures are within the natural variability of the climate of the last millennium. The research [46] is based on earlier works among which the research [47] should be mentioned.

However, a comprehensive assessment of the dynamics of climate change in St. Petersburg and taking into account the influence of anthropological factors of influence on the climate has not yet been performed. In this paper, we performed a comprehensive analysis of the dynamics of climate change and assessed the impact on the climate of the most significant sources of the urban environment thermal pollution.

2 Methods

The research methods were the analysis and comparison of data on the population and climate of St. Petersburg (Russian Federation), as well as the dynamics of its changes over the past 275 years. For this, data obtained from an open-source were used [23].

3 Results and Discussion

3.1 Average annual air temperature changes

St. Petersburg is the northernmost settlement with a population of more than one million people.

The dynamics of the average annual outdoor temperature in St. Petersburg according to observations from 1743 to 2018, as well as a linear approximation of the resulting data array, are presented in Figure 1.

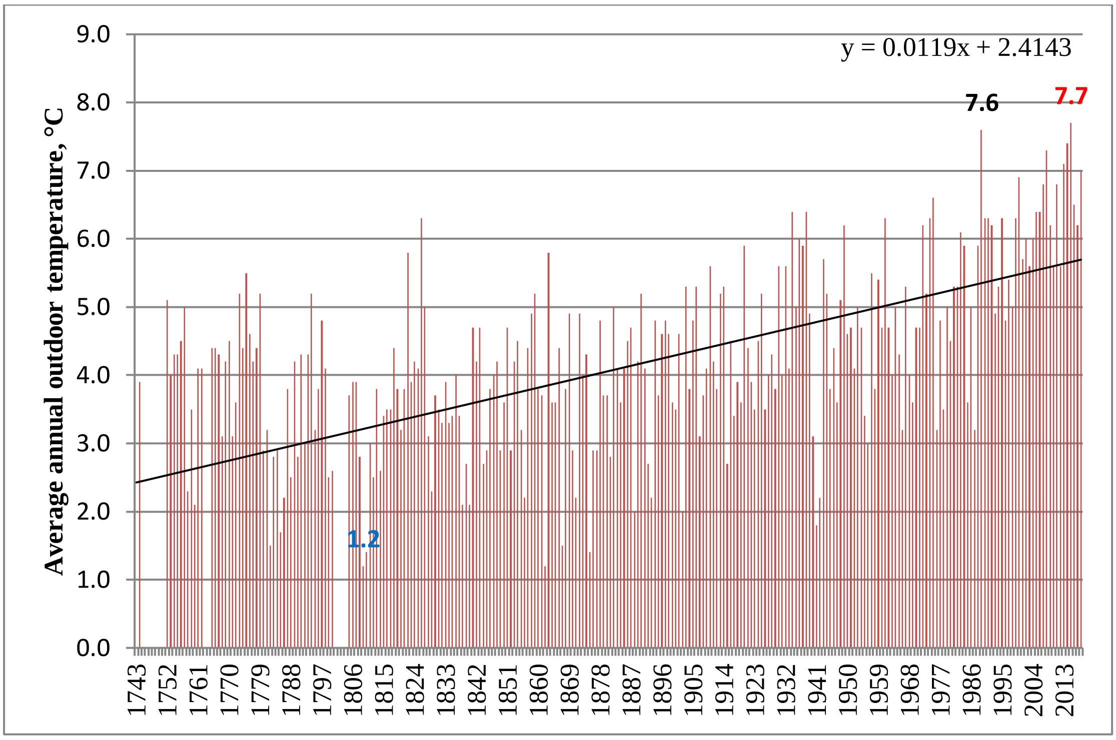

Figure 1 - Dynamics of changes in the average annual outdoor air temperature in St. Petersburg

From the data presented in Figure 1, an increasing trend in the average annual outdoor temperature is observed. The maximum average annual outdoor temperature was recorded in 2015 and amounted to 7.7 ° C. The minimum value of the average annual outdoor temperature was recorded in 1809 (1.2 ° C).

The gaps in Figure 1 are due to the complete or partial absence of baseline data (values of average monthly outdoor temperatures) for several years. In particular, for the periods from 1746 to 1750, as well as from 1801 to 1804. data are not available for all months; in 1745, 1751, 1763, 1764 data are not available for several months. Regardless of the number of missed months in a year, these periods are excluded from the analysis.

It should also be borne in mind that until 1918 the Julian calendar operated in Russia. Therefore, data arrays before 1918 and after 1918 may turn out to be biased relative to each other by two weeks.

Figures 2–13 show similar arrays of data collected for the considered period (from 1743 to 2018) for different months (respectively, from January to December), as well as some peak temperatures.

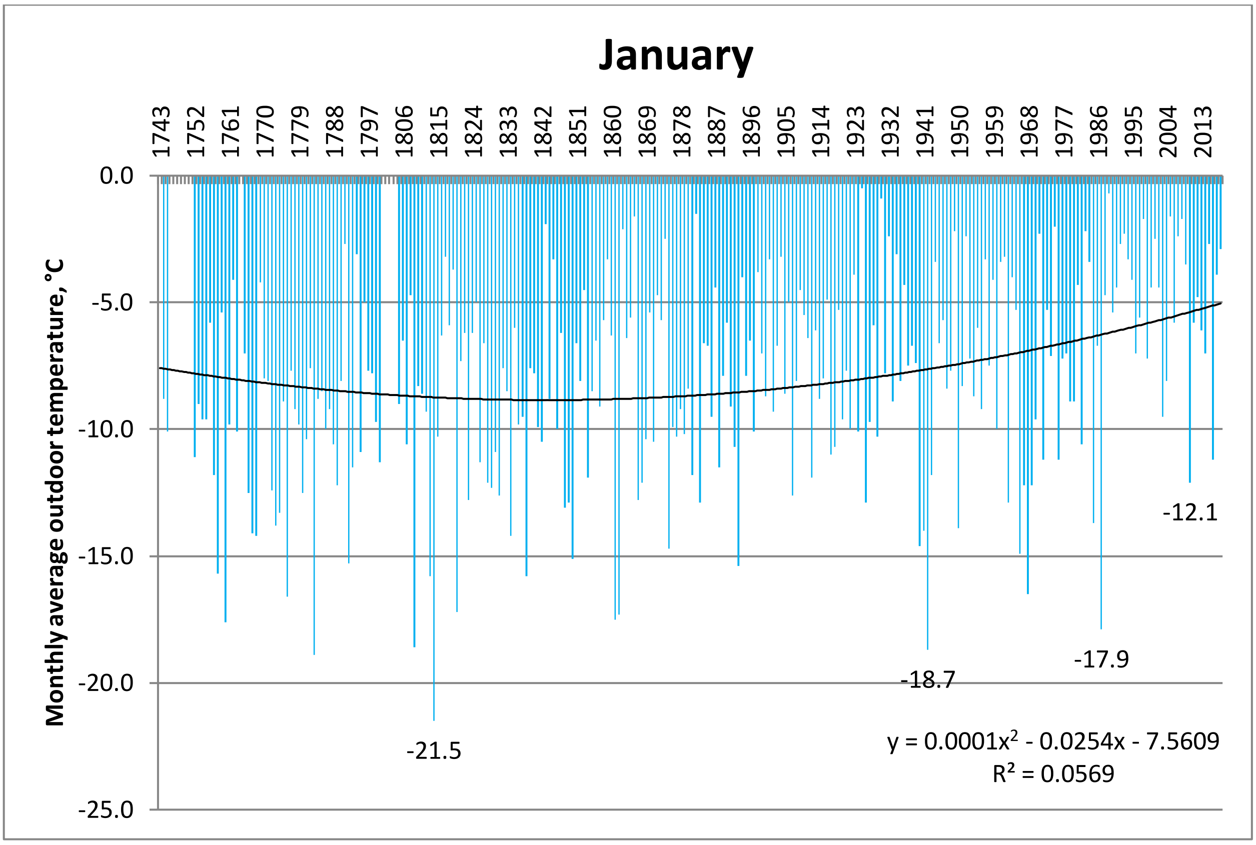

Figure 2 - Dynamics of changes in the average monthly outdoor air temperature in January

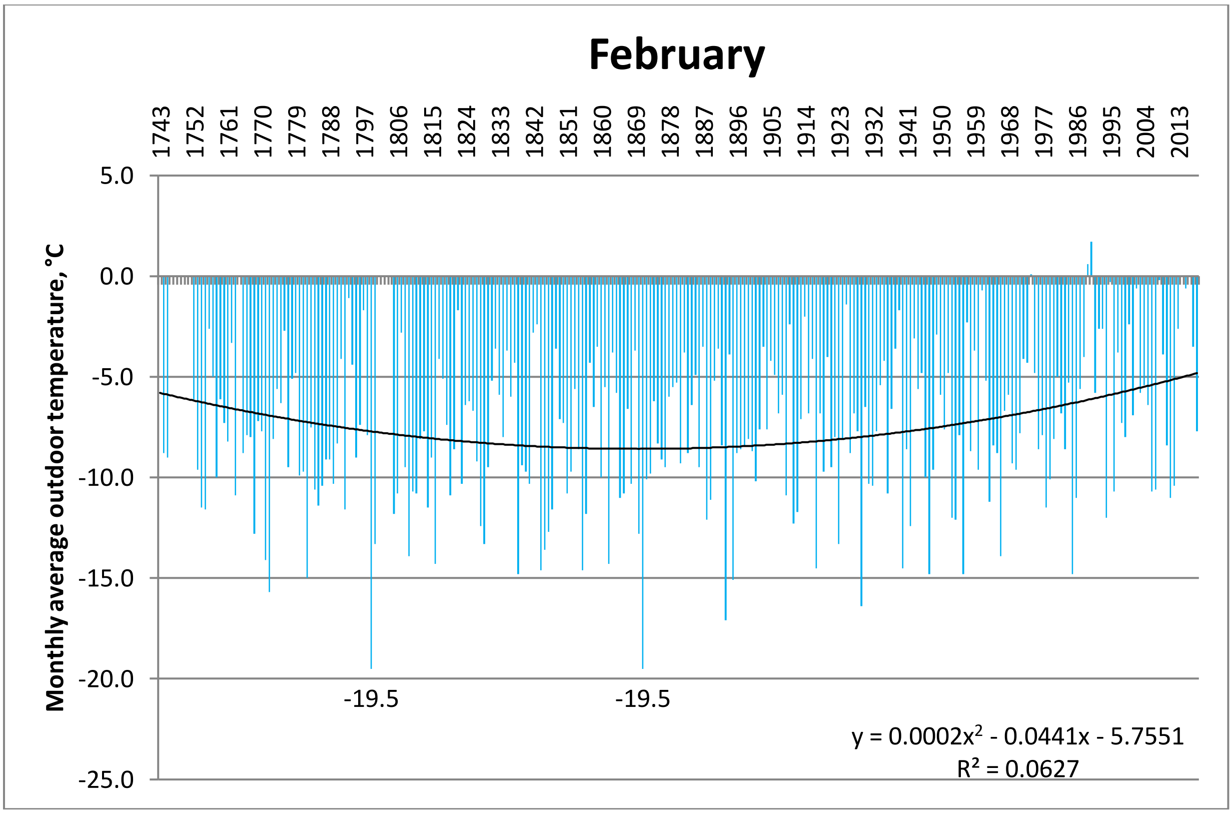

Figure 3 - Dynamics of changes in the average monthly outdoor air temperature in February

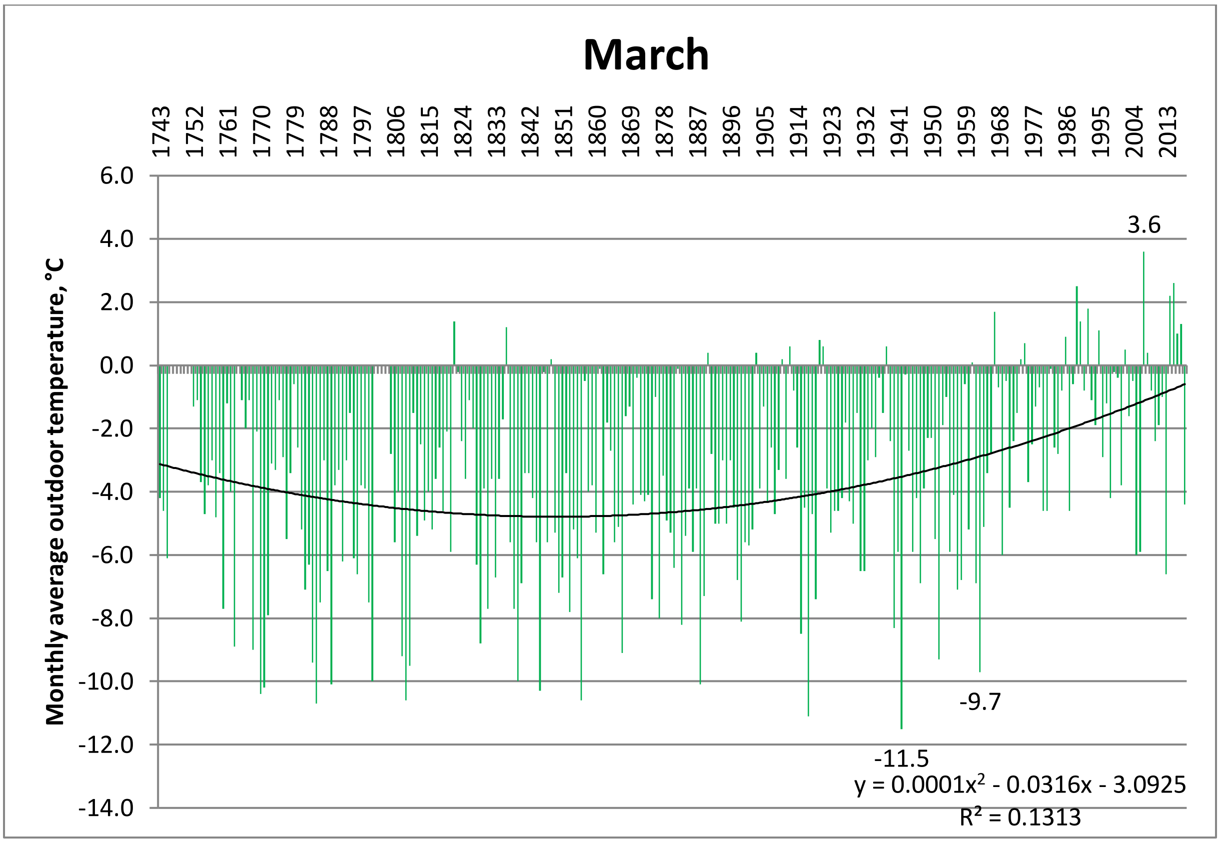

Figure 4 - Dynamics of changes in the average monthly outdoor air temperature in March

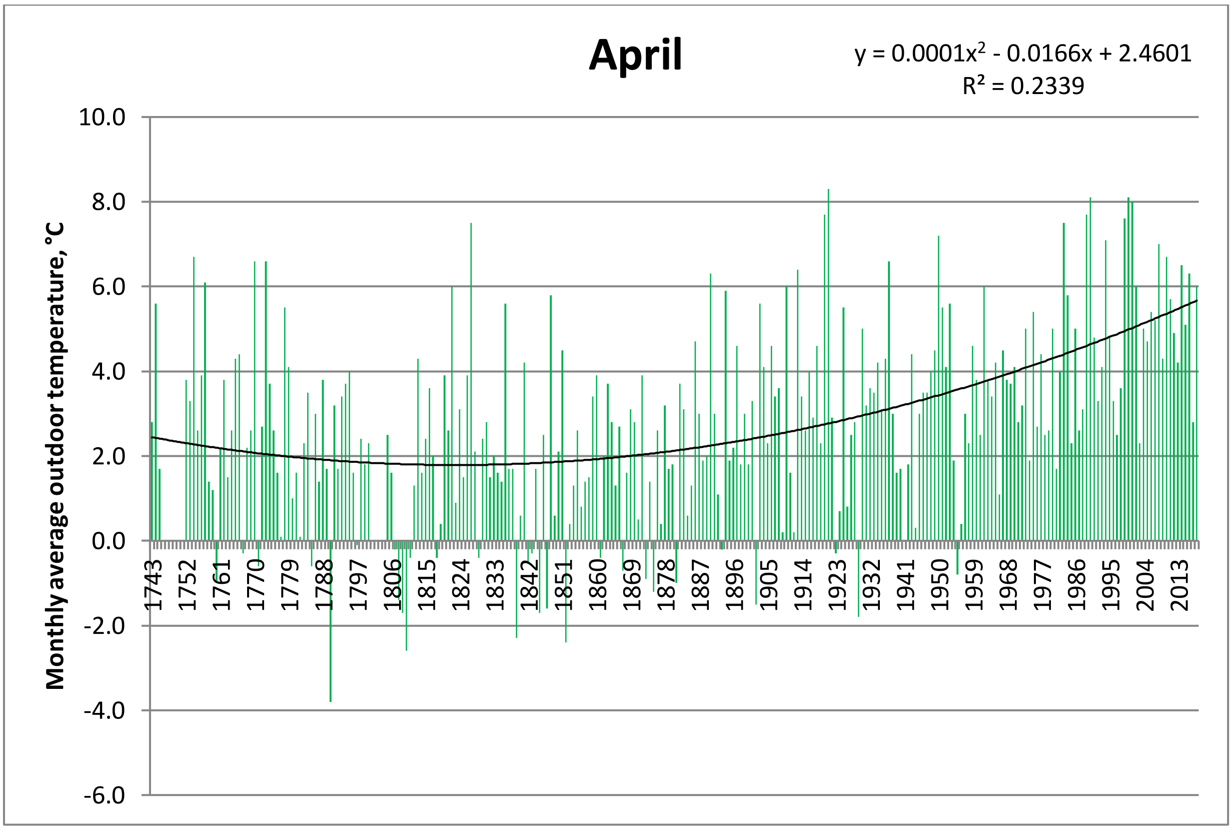

Figure 5 - Dynamics of changes in the average monthly outdoor air temperature in April

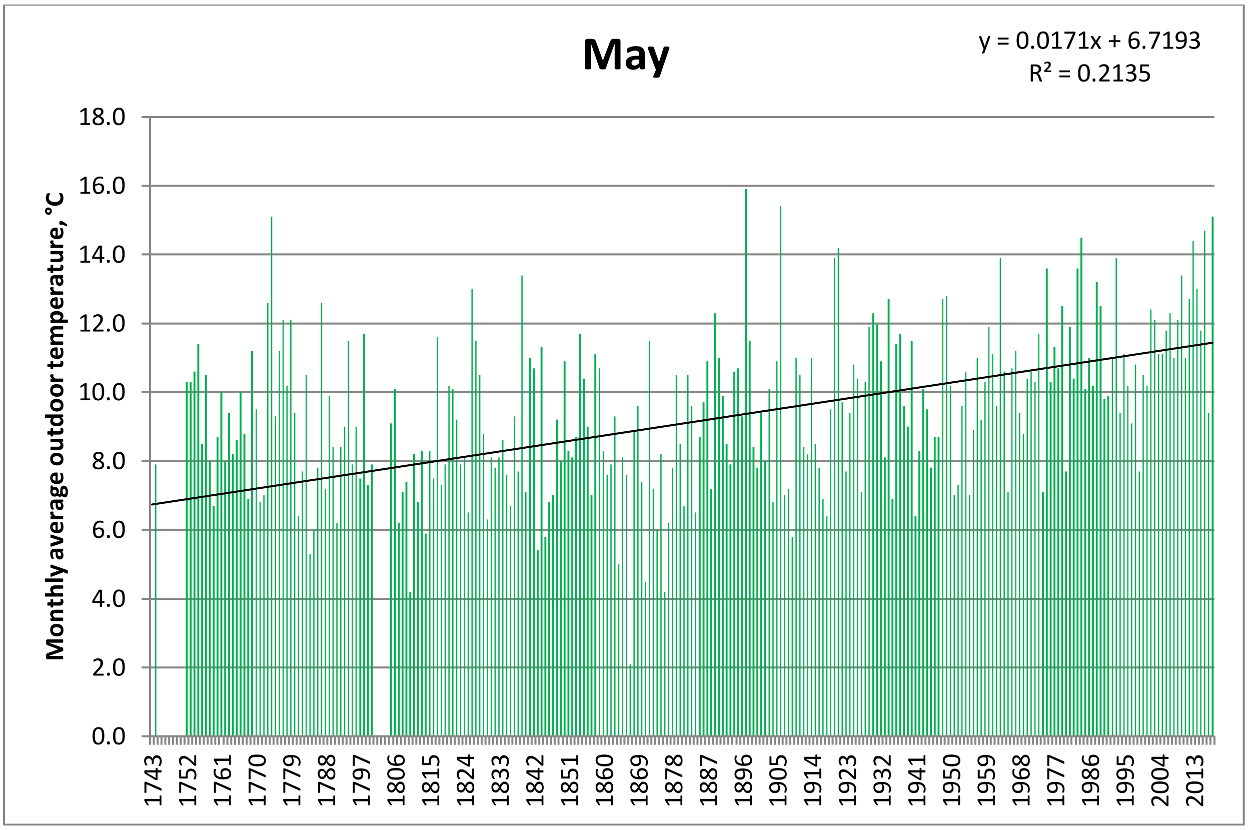

Figure 6 - Dynamics of changes in the average monthly outdoor air temperature in May

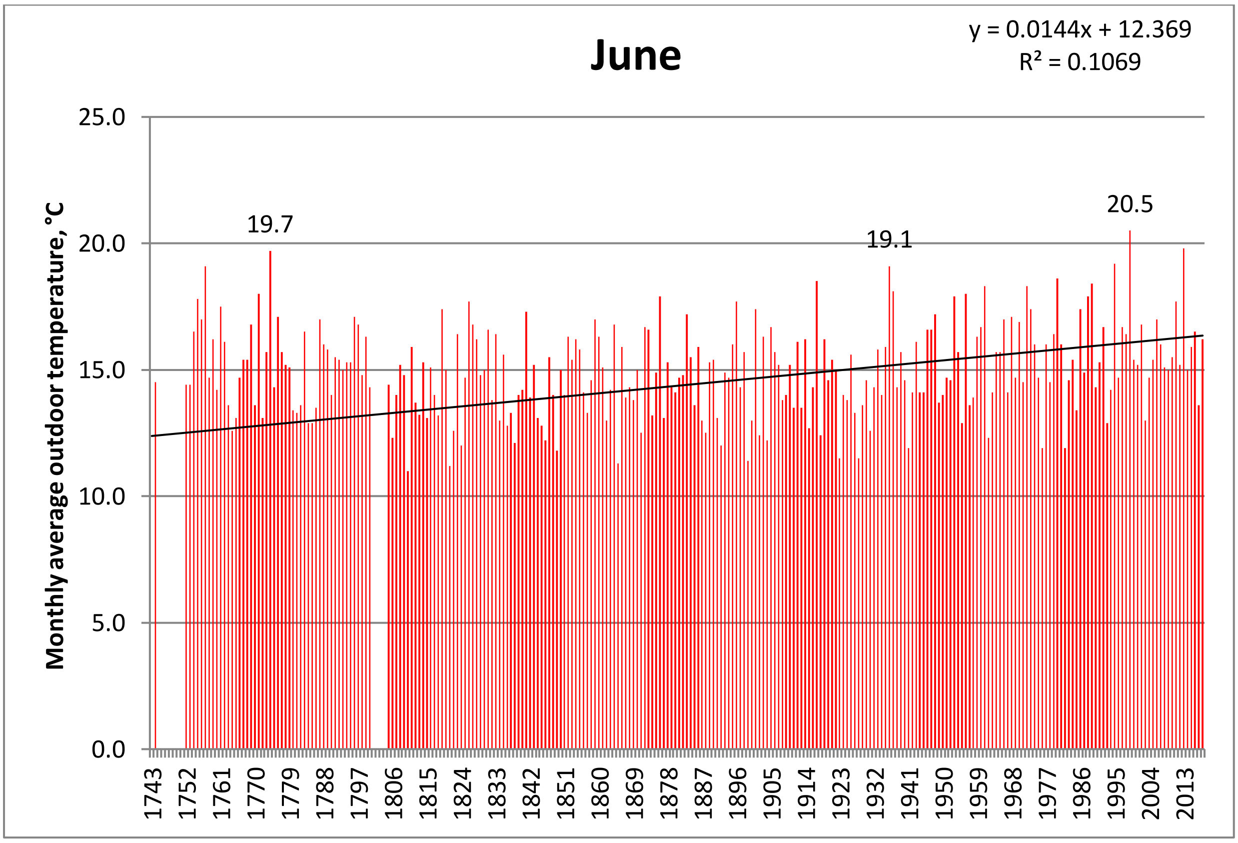

Figure 7 - Dynamics of changes in the average monthly outdoor air temperature in June

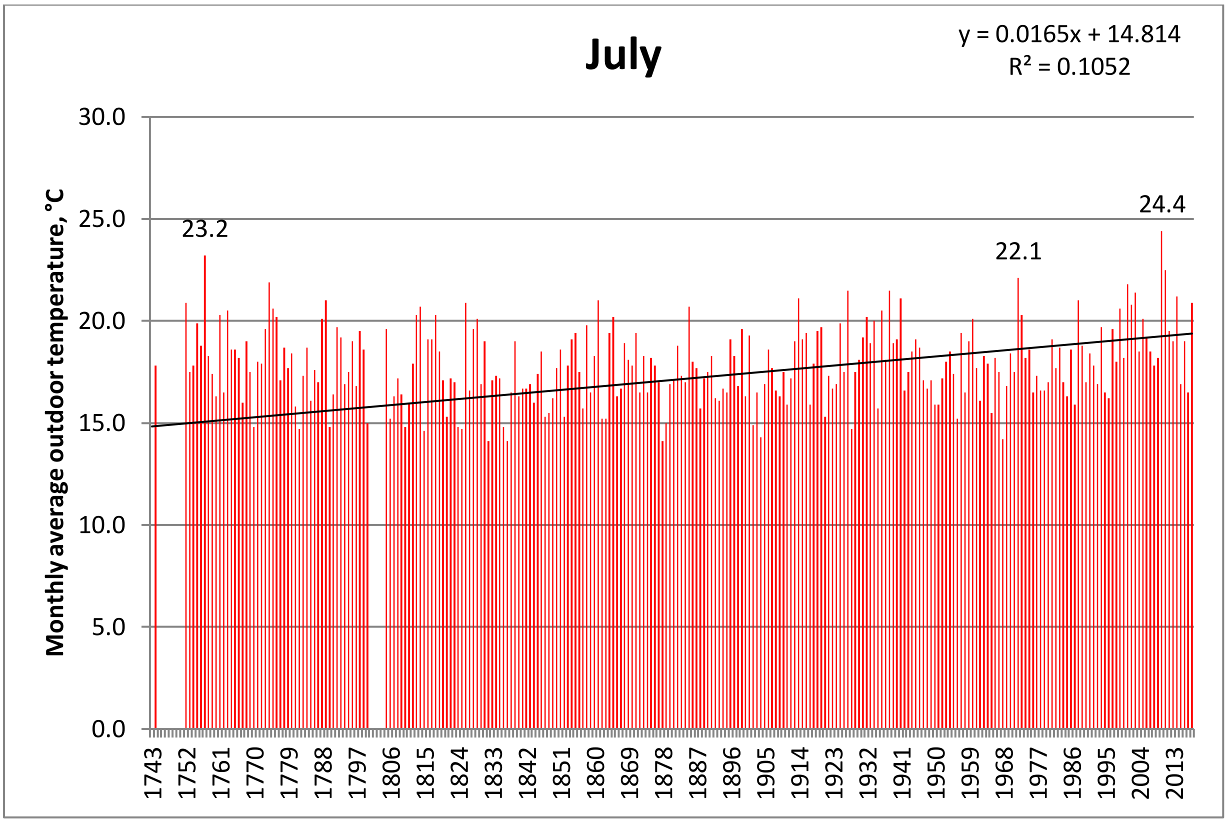

Figure 8 - Dynamics of changes in the average monthly outdoor air temperature in July

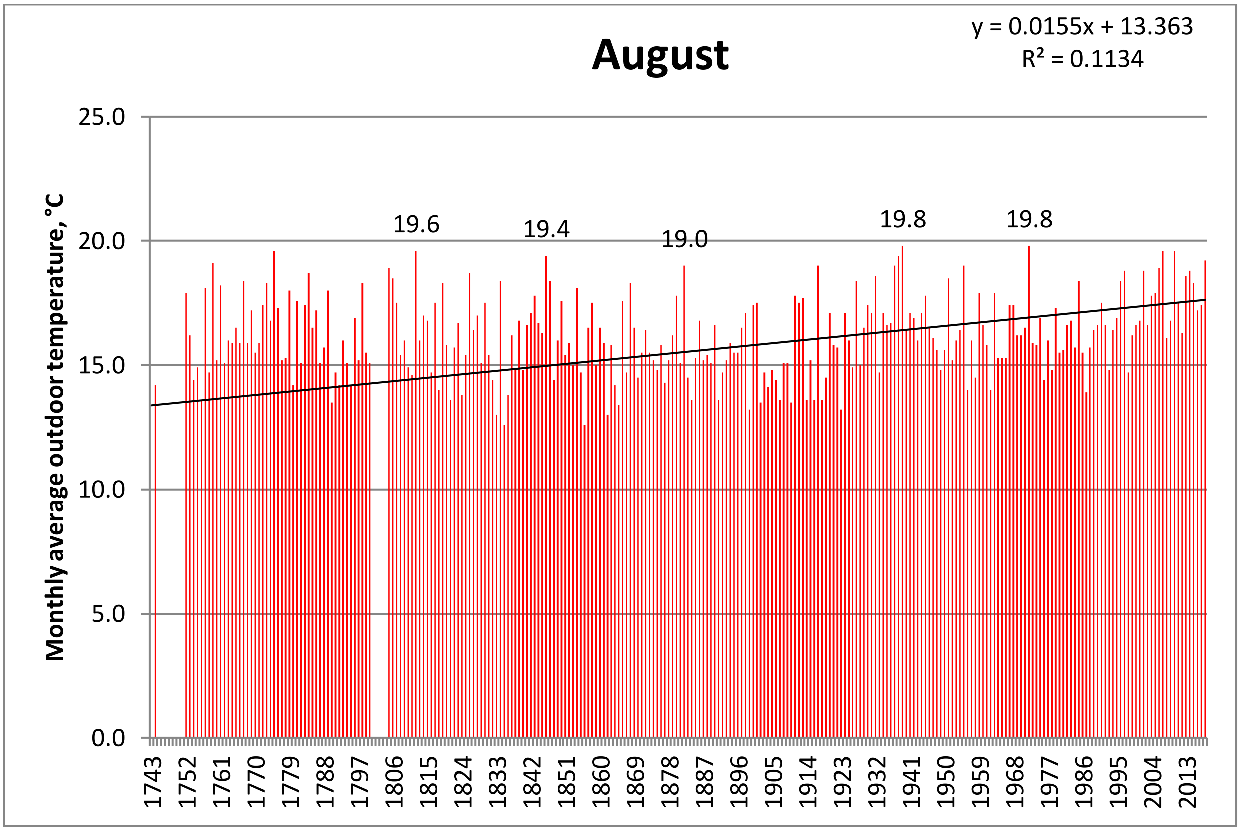

Figure 9 - Dynamics of changes in the average monthly outdoor air temperature in August

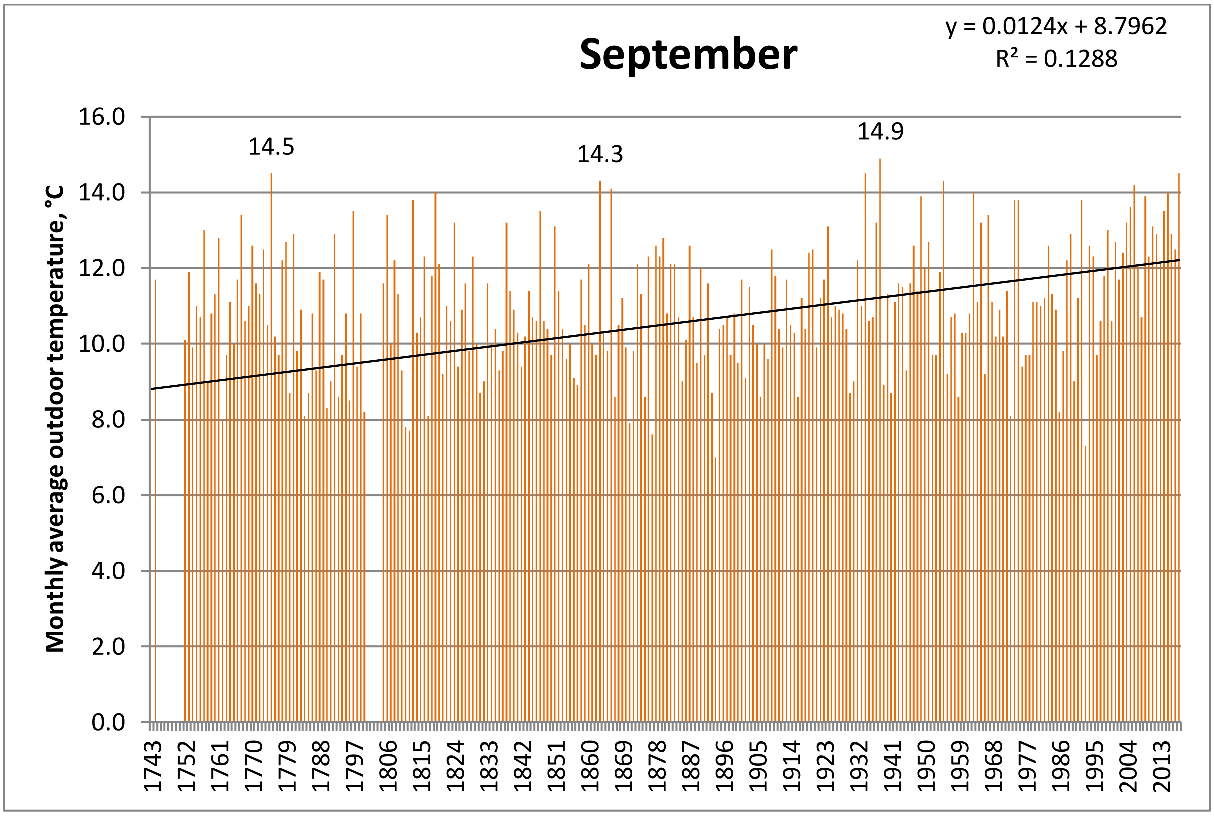

Figure 10 - Dynamics of changes in the average monthly outdoor air temperature in September

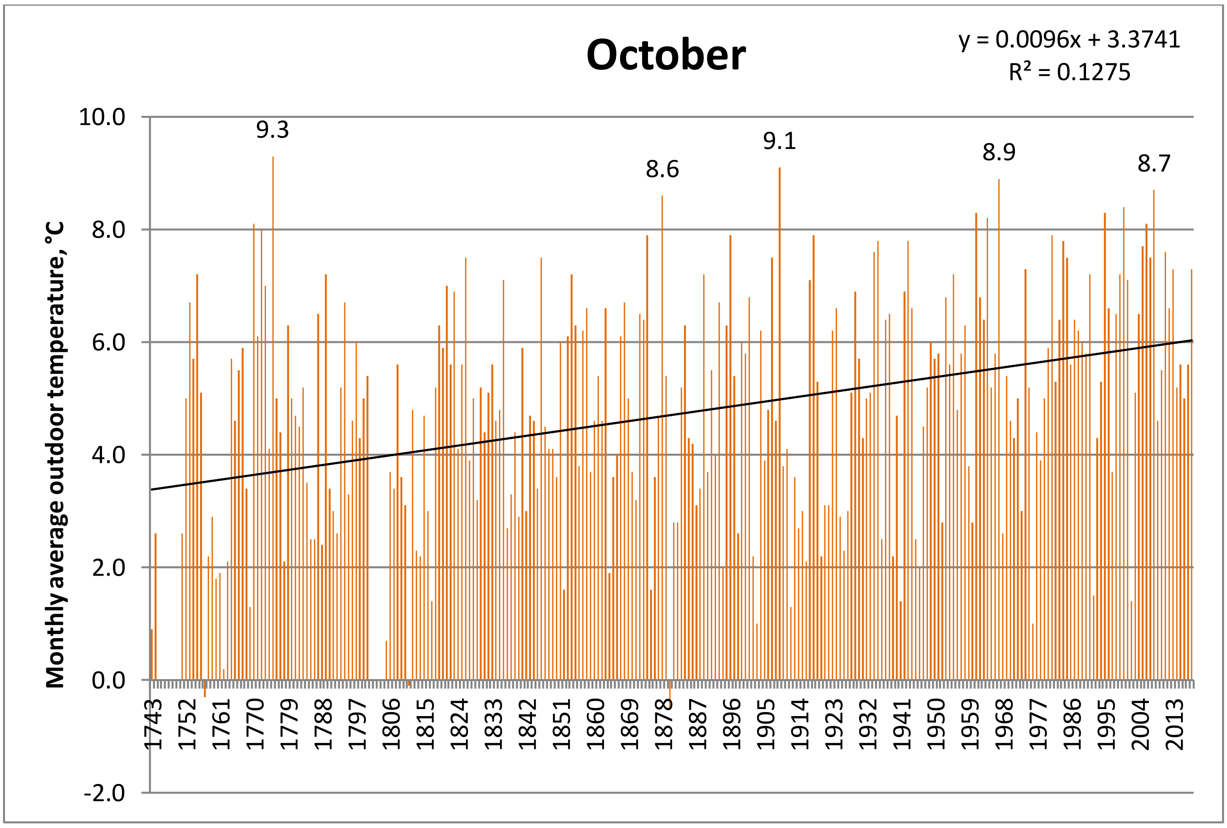

Figure 11 - Dynamics of changes in the average monthly outdoor air temperature in October

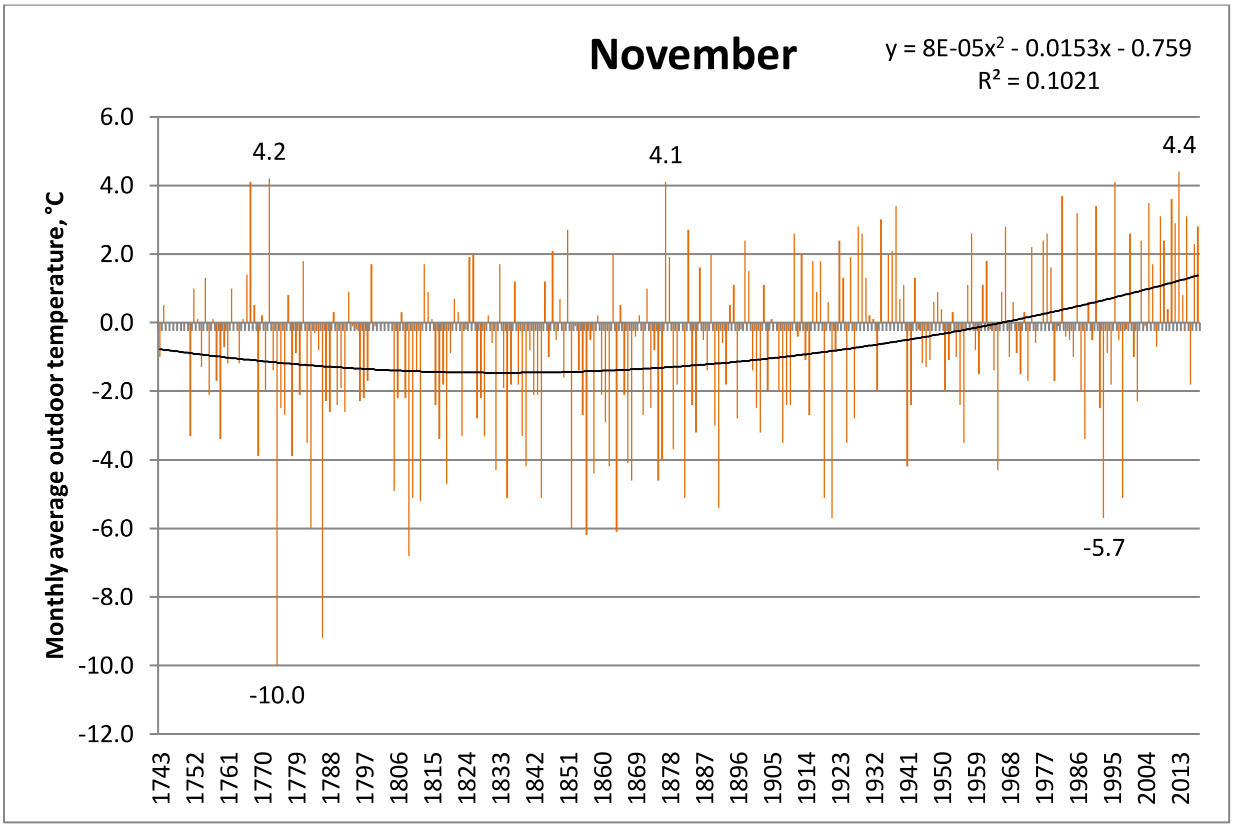

Figure 12 - Dynamics of changes in the average monthly outdoor air temperature in November

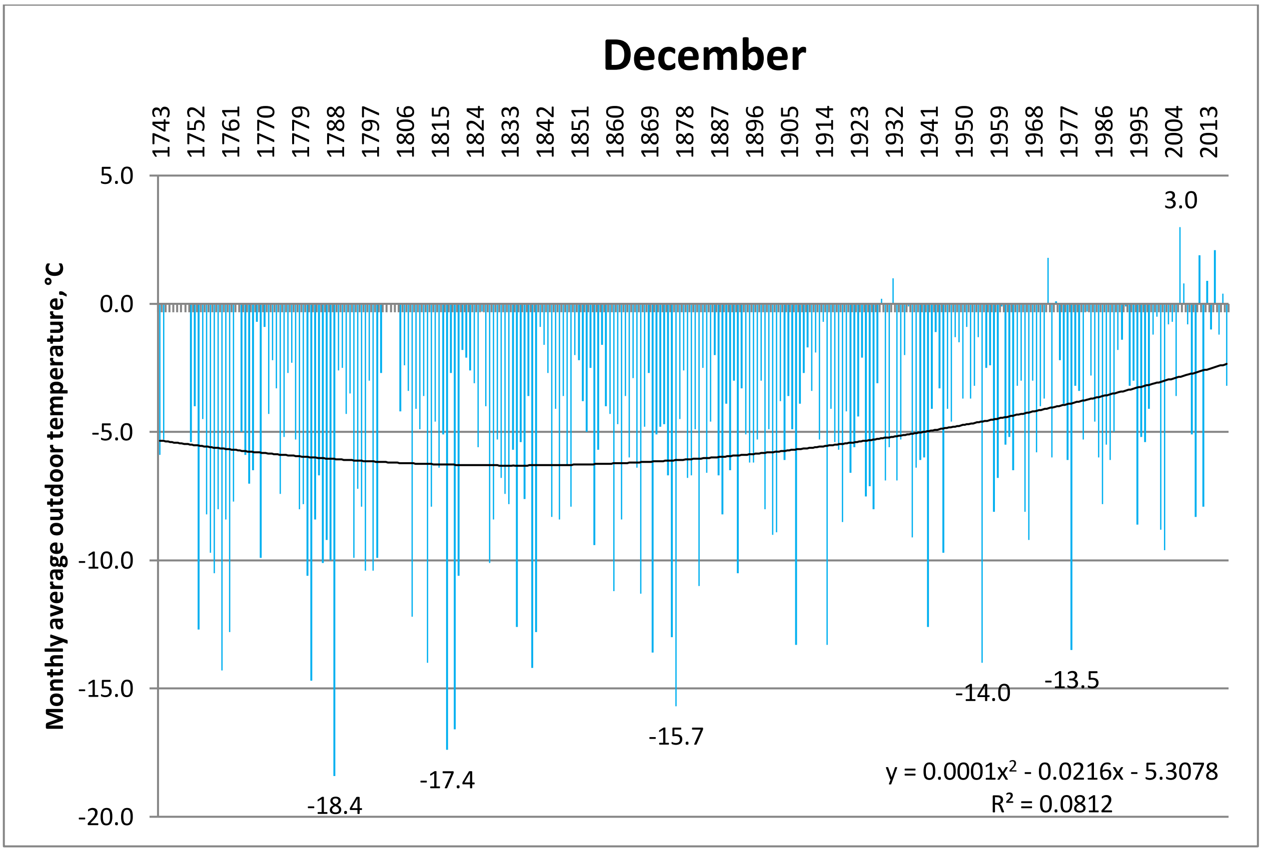

Figure 13 - Dynamics of changes in the average monthly outdoor air temperature in December

The data presented in Figures 1–13 show the general trend of outdoor temperature changes. From the data presented in Figures 2–13, it follows that the coefficient of determination

(R^2) of the closest trend lines, which characterizes the measure of the spread of a random variable relative to its mathematical expectation, is extremely small (less than 0.25). In this regard, an analysis of various time intervals (5, 10, 25, and 50 years) seems more indicative.

3.2 Time intervals

Figure 14 shows a diagram of changes in the average annual outdoor temperature averaged over 50-year intervals. Differentiation of the full data array into shorter time intervals (25, 10, and 5 years) is presented in Figures 15–17, respectively.

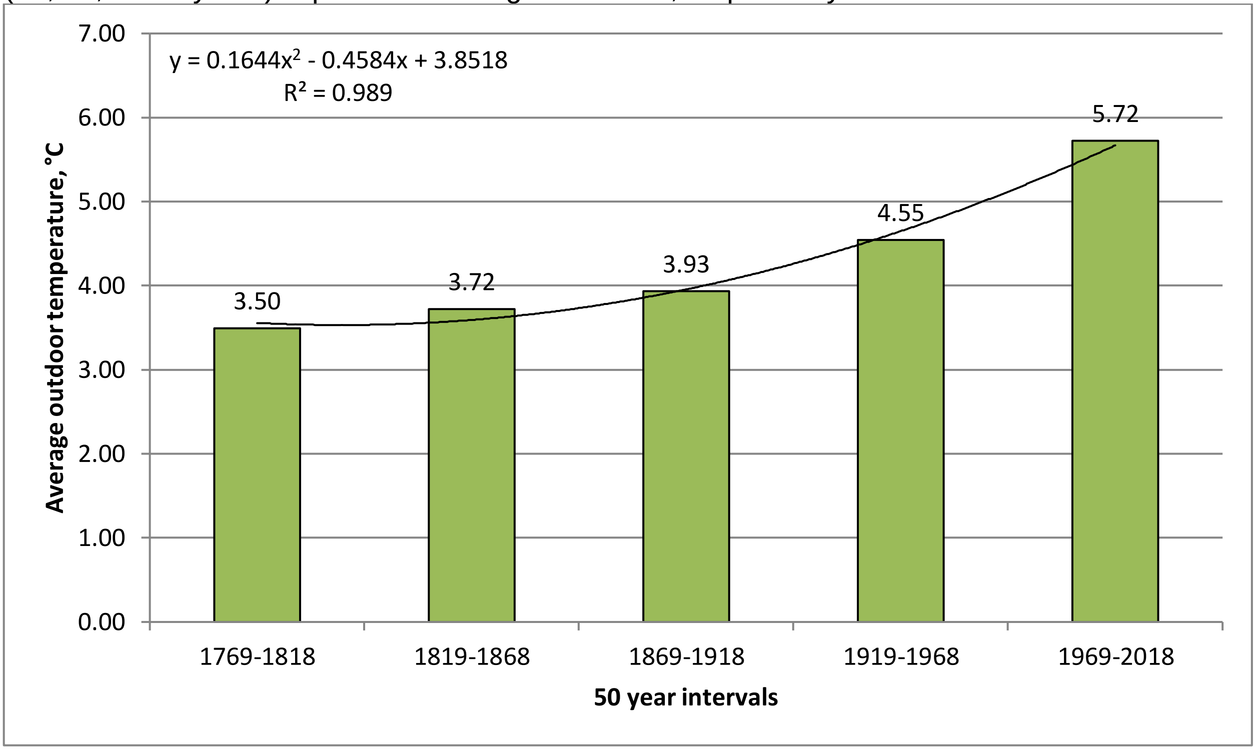

Figure 14 - Change in the average annual outdoor air temperature with differentiation of the data set for 50th-year intervals

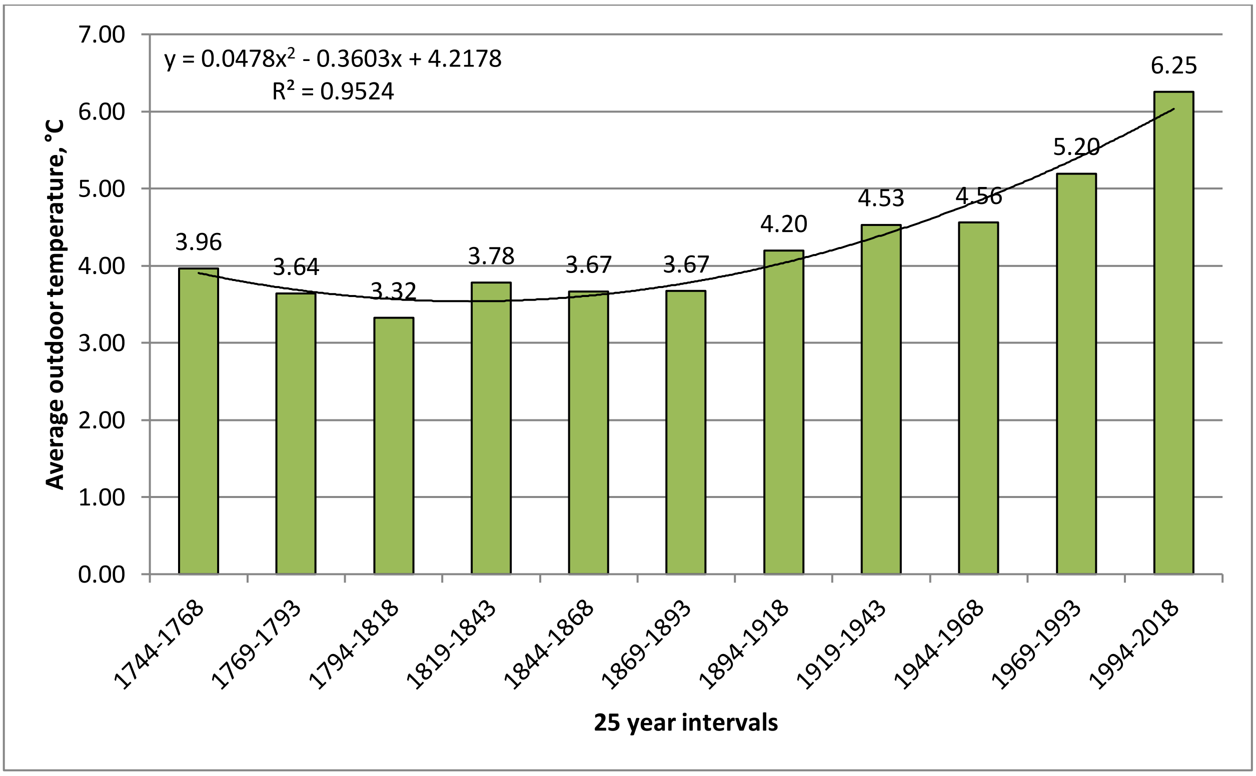

Figure 15 - Change in the average annual outdoor air temperature with differentiation of the data set for 25th-year intervals

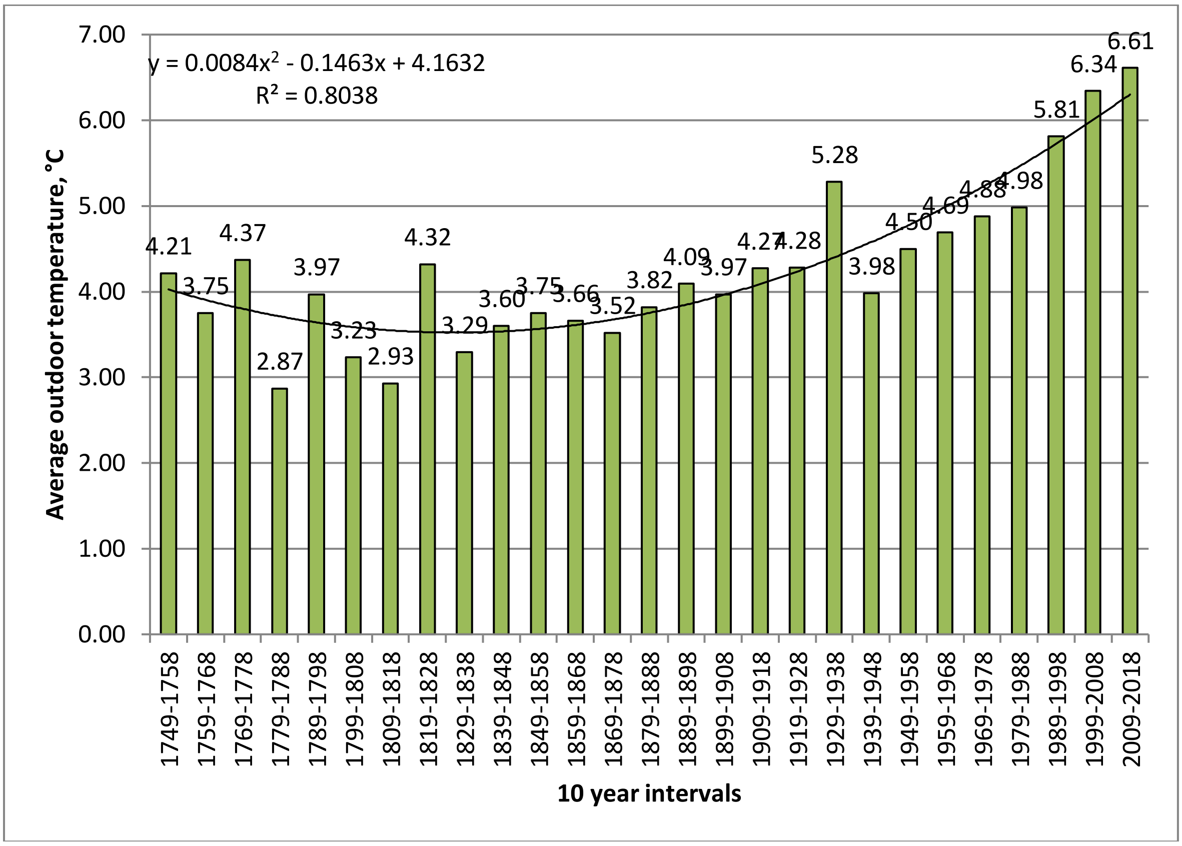

Figure 16 - Change in the average annual outdoor air temperature with differentiation of the data set for 10-year intervals

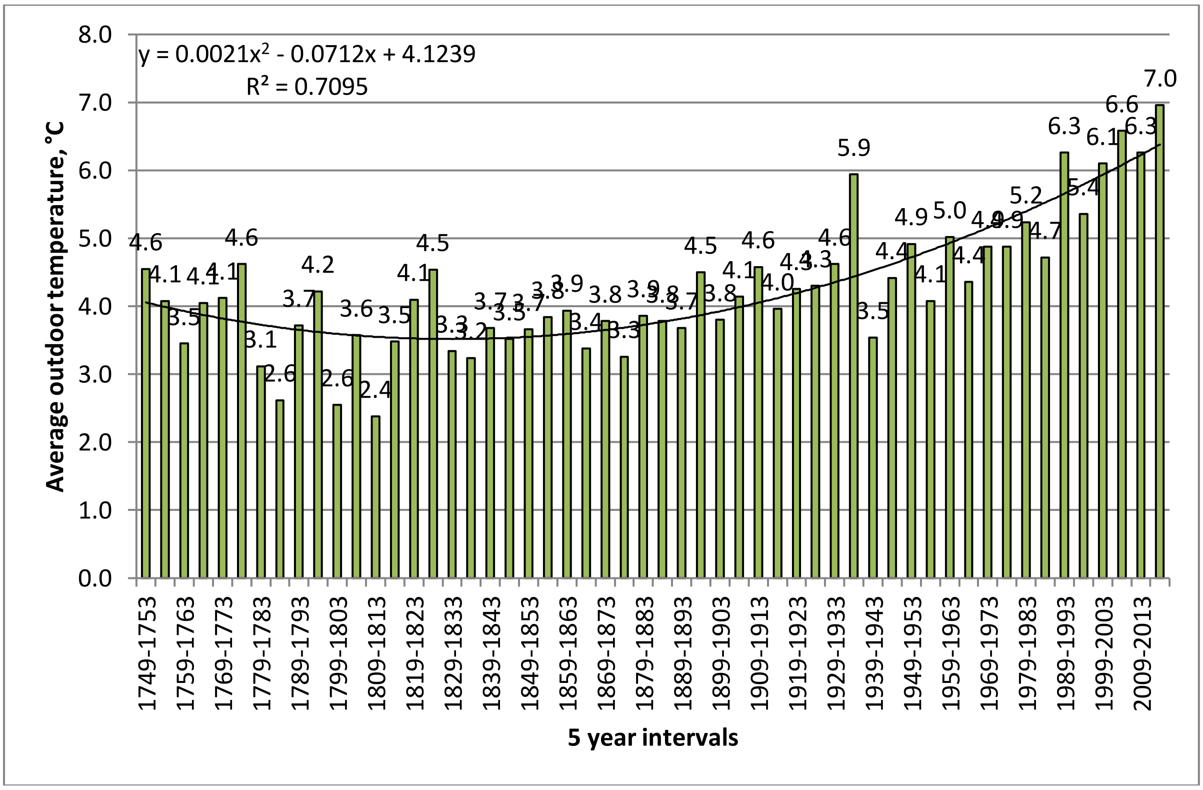

Figure 17 - Change in the average annual outdoor air temperature with differentiation of the data set for 5th-year intervals

From a comparison of the data presented in Figures 14–17, it follows that the obtained arrays most fully correspond to a polynomial approximation of degree 2 with a changing monotonicity of the trend line.

The average annual outdoor temperatures for the period under consideration first decrease, in the period from 1779 to 1813 they reach some minimum values, after which they increase monotonously. At the same time, local minima are noted on the increasing part of the trend, the most noticeable of which are observed in five-year periods from 1874 to 1878 and from 1939 to 1943. It is interesting to note that the time intervals obtained approximately coincide with two major wars, the Russo-Turkish war of 1877–1878. and the Great Patriotic War of 1941–1945, respectively.

A large settlement from the position of heat balance is a significant source of thermal energy. Heated buildings, utilities, transportation, and residents themselves are sources of heat in the city. In this regard, it is interesting to divide the year into two periods - warm and cold. The duration of the cold period can be approximately equal to the length of the heating period in the city, the normative value of which is 213 (for all residential and most public buildings) or 232 days (for general education, children's preschool and medical institutions) [48]. More accurate data on the beginning and end of heating periods from 2011 to 2019. presented in Table 1.

Table 1. Duration of heating periods in St. Petersburg

Heating season	Start	End	Duration, days
2009/2010	05.10.2009	11.05.2010	218
2010/2011	07.10.2010	12.05.2012	217
2011/2012	15.10.2011	12.05.2012	210
2012/2013	15.10.2012	10.05.2013	199
2013-/2014	30.09.2013	12.05.2014	216
2014/2015	04.10.2014	12.05.2015	212
2015/2016	07.10.2015	06.05.2015	205
2016/2017	05.10.2016	19.05.2017	227
2017/2018	04.10.2017	10.05.2018	218
2018/2019	28.09.2018	13.05.2019	228

From the data presented in table 1, it follows that the beginning of the heating period approximately corresponds to the end of September - the beginning of October, the end to the first half of May. The conditionally cold period of the year can be taken from October to April (7 months), warm - from May to September (5 months). Until 1917, in St. Petersburg and Petrograd, the beginning of the heating period was adopted on October 1, the end - April 15 [49], pp. 451-452. Dividing the warm and cold periods of the year into an integer number of months is more convenient for analysis due to the availability of monthly average temperature data of the outdoor air.

3.3 Warm and cold season

On this basis, we consider similar time intervals for the warm and cold periods of the year. Figures 18–21 show graphs of changes in average annual outdoor temperatures, averaged, respectively, at 50-year, 25-year, 10-year, and 5-year intervals for the warm period of the year (from May to September). In the warm season, the production of heat and electricity is significantly reduced. Figures 22-25 show similar data for the cold season.

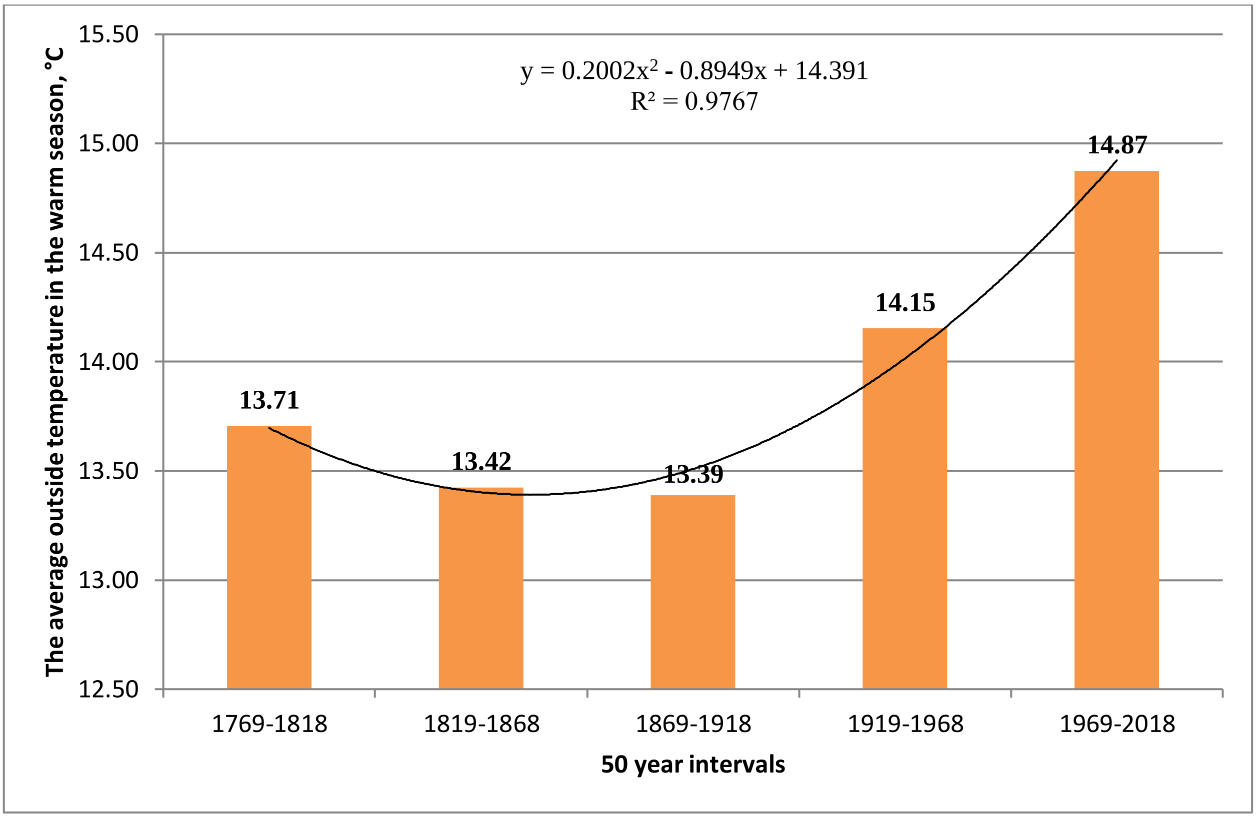

Figure 18 - Changes in the average annual air temperature during the warm period of the year with data distribution over 50th-year intervals

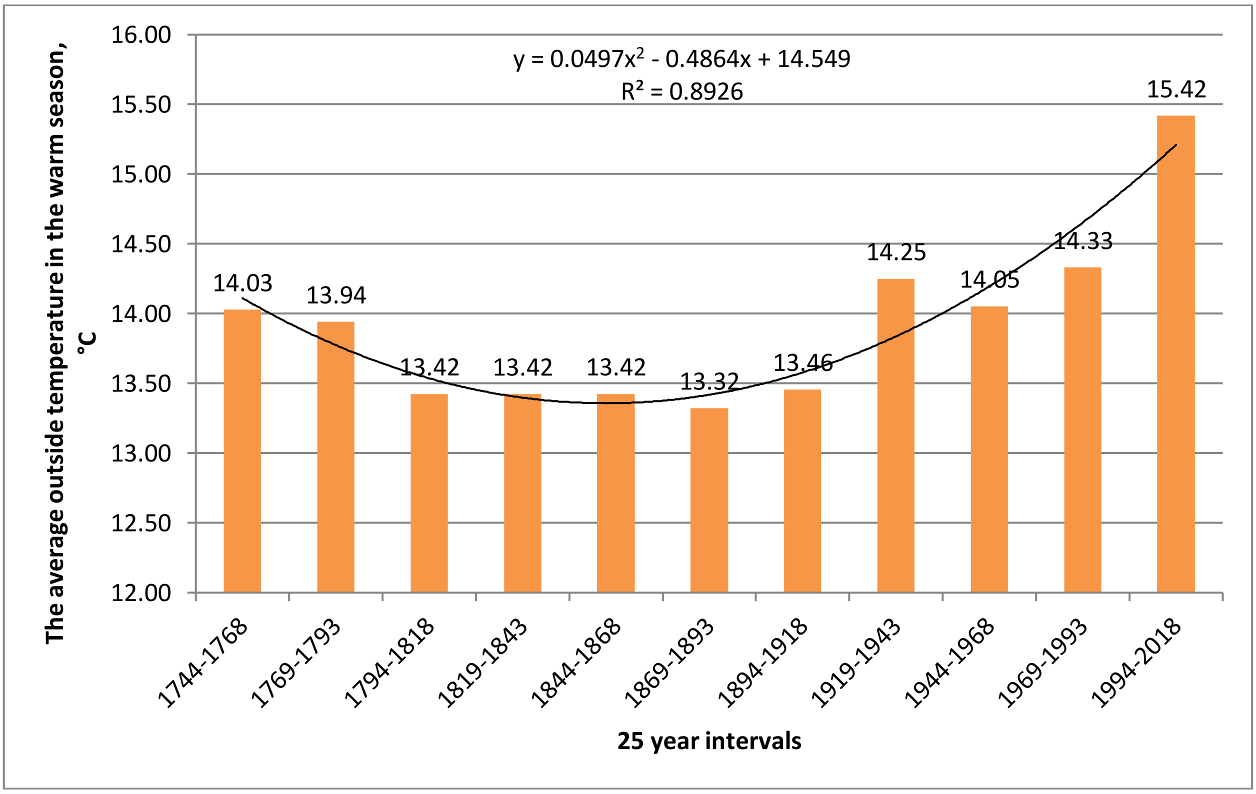

Figure 19 - Changes in the average annual air temperature during the warm period of the year with data distribution over 25th-year intervals

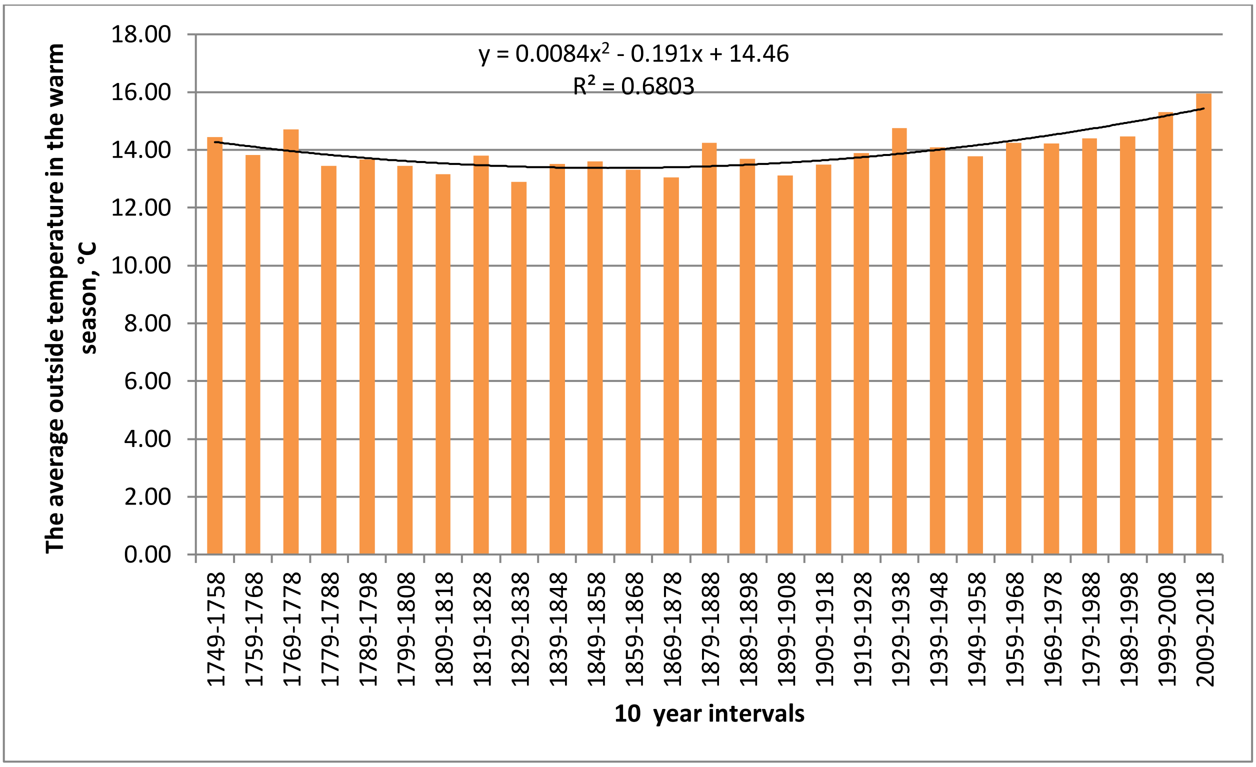

Figure 20 - Changes in the average annual air temperature during the warm period of the year with data distribution over 10th-year intervals

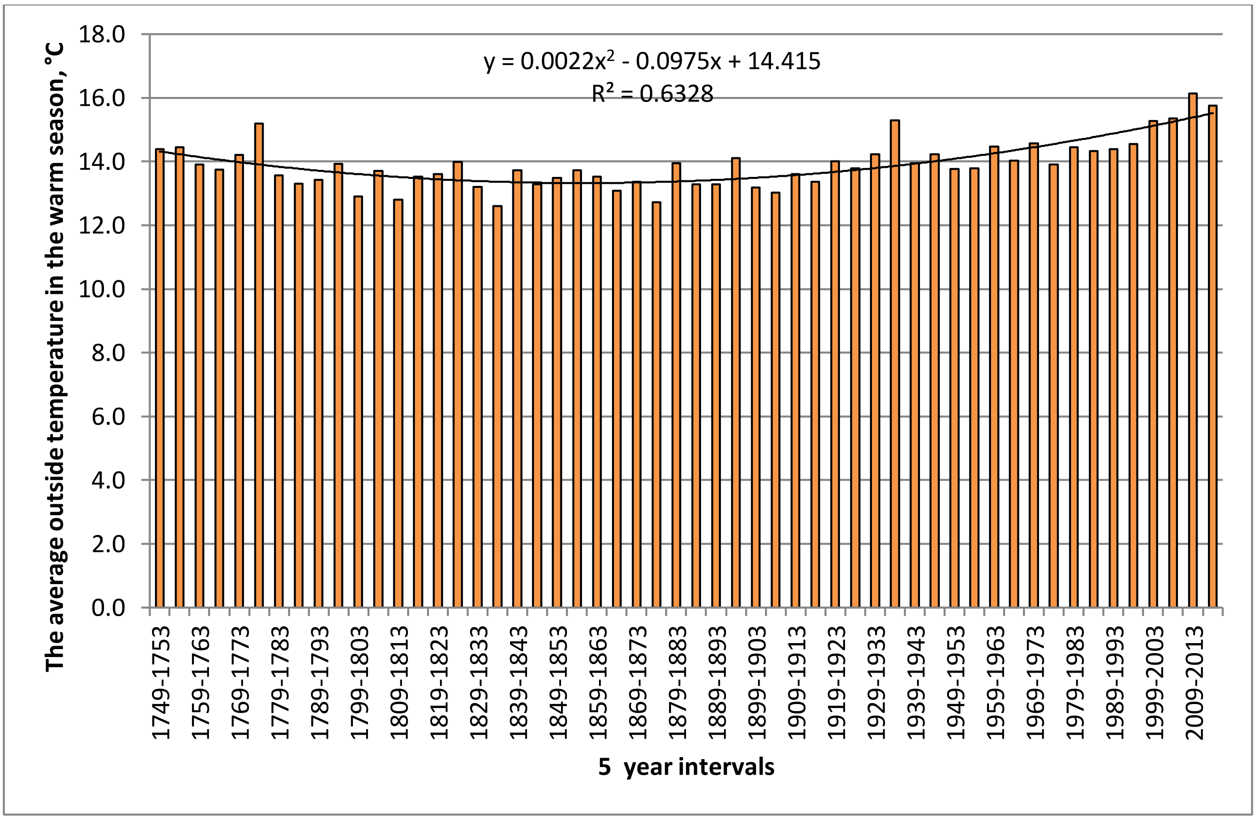

Figure 21 - Changes in the average annual air temperature during the warm period of the year with data distribution over 5th-year intervals

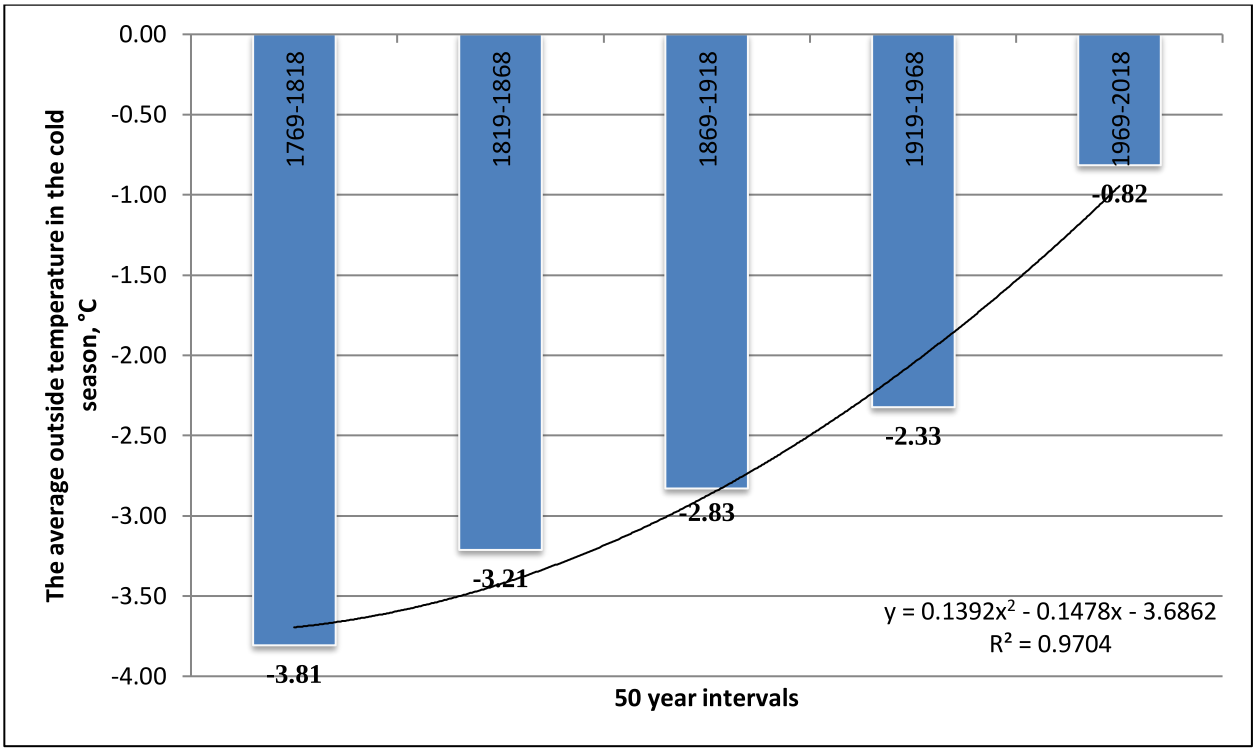

Figure 22 - Changes in the average annual air temperature during the cold period of the year with data distribution over 50th-year intervals

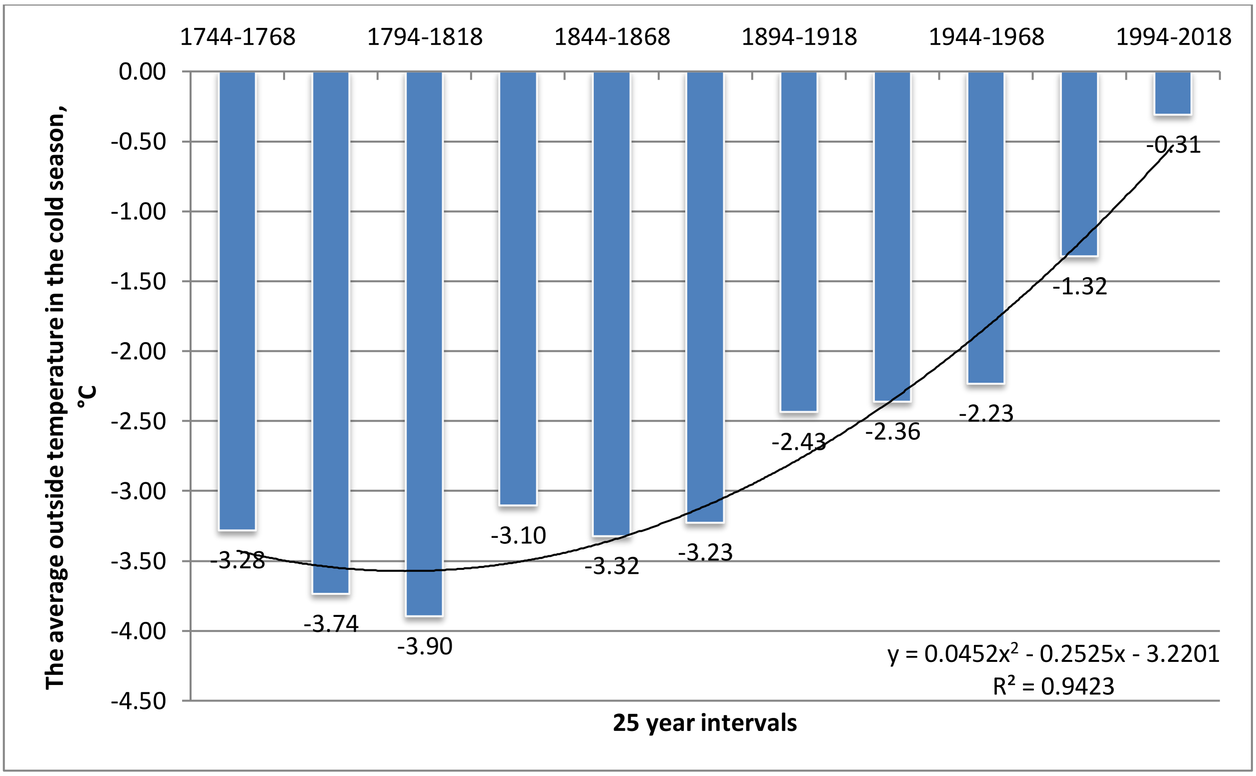

Figure 23 - Changes in the average annual air temperature during the cold period of the year with data distribution over 25th-year intervals

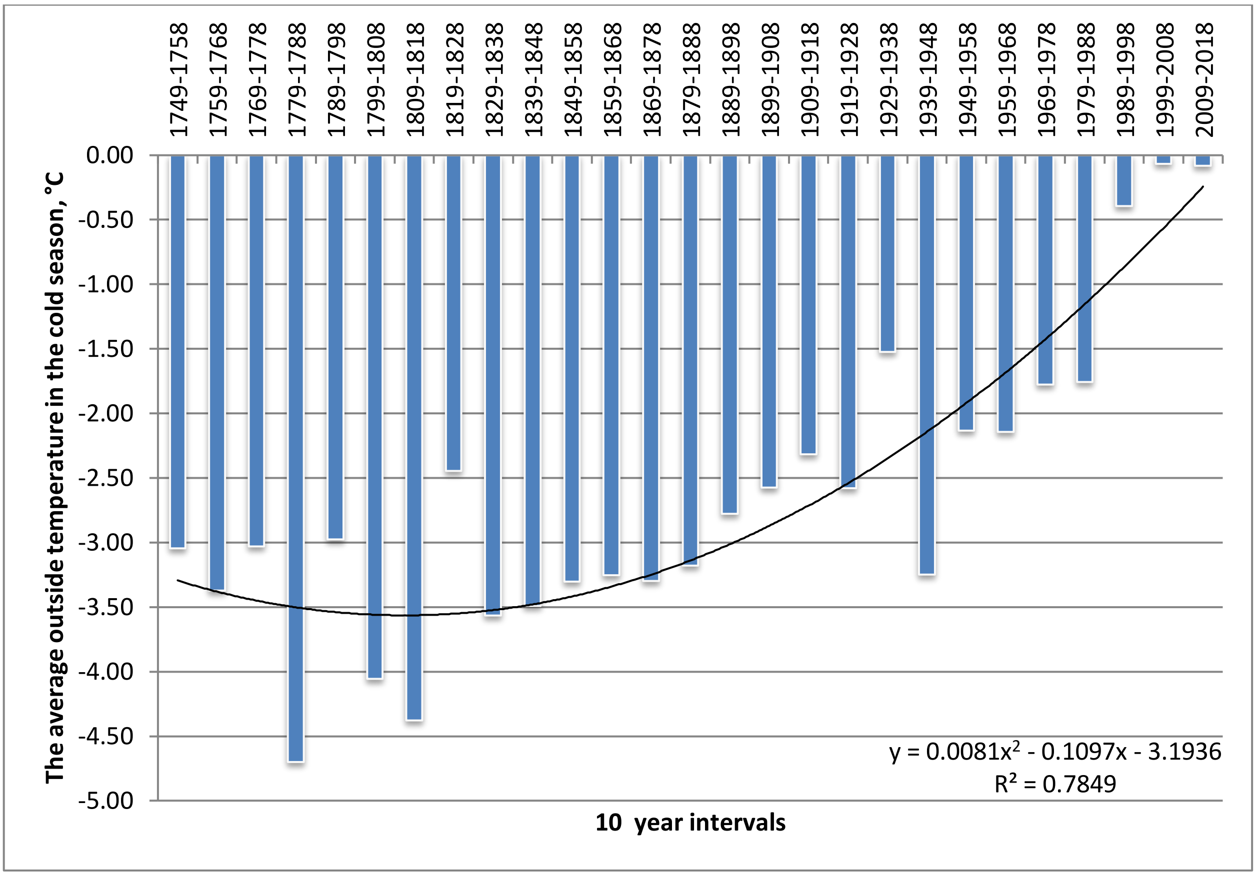

Figure 24 - Changes in the average annual air temperature during the cold period of the year with data distribution over 10th-year intervals

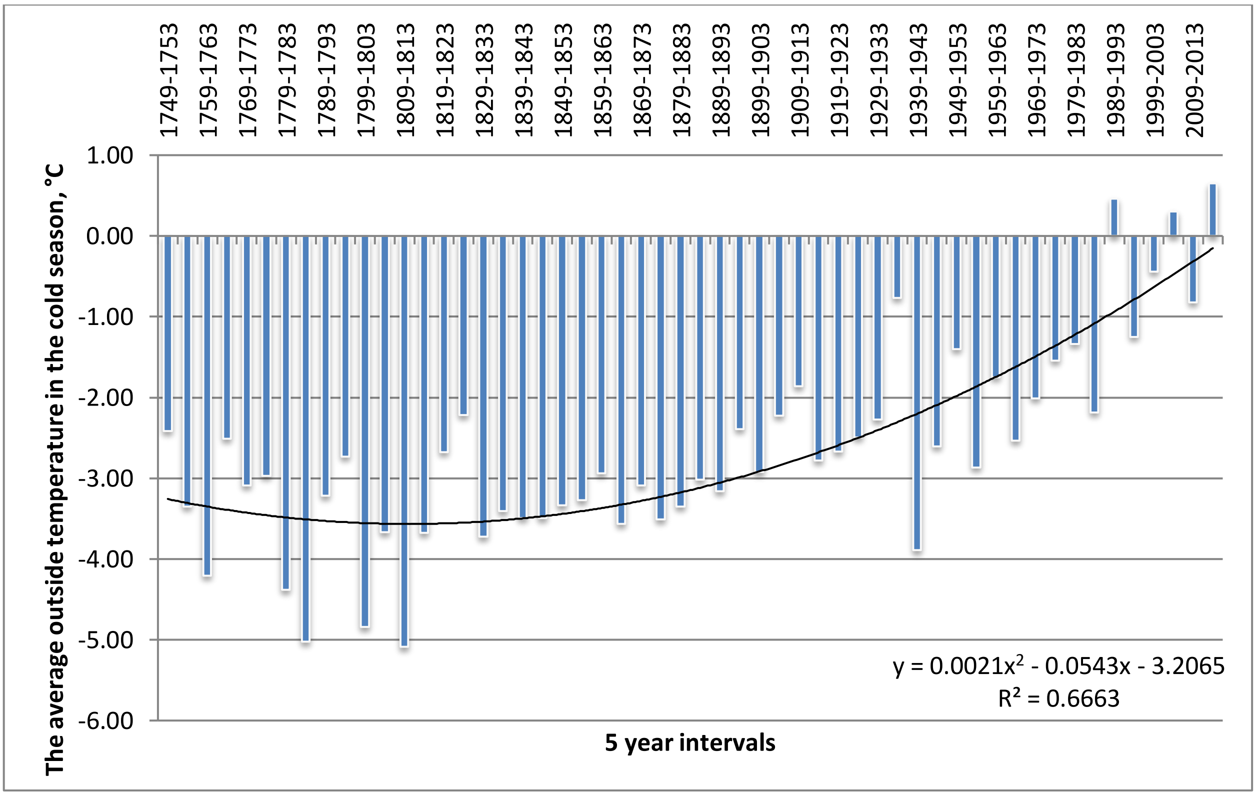

Figure 25 - Changes in the average annual air temperature during the cold period of the year with data distribution over 5th-year intervals

From the data presented in Figures 18–25 it follows that the most closely considered data arrays are described by a polynomial approximation.

In the warm season, the minimum values of the average annual outdoor temperature in St. Petersburg were observed from 1834 to 1908, in the cold season they were observed from 1779 to 1813. Then there is a steady trend of increasing the average annual outdoor temperature, the most intense in the last 50 years.

Due to the minimal impact of internal sources of heat in the warm season, the observed trend can be associated with the global trend of increasing air temperature.

In the cold season, the determination coefficient takes the maximum value for the polynomial approximation of the data array. The trend line of outdoor temperature changes in the cold season coincides with the trend line observed in the warm season, when the average annual outdoor temperature decreases first, reaches its minimum, and then changes its monotony. In this case, the minimum temperature reaches the outside air in the period from 1769 to 1818. Apparently, the change in the monotony of the trend in question is due to population growth and industrial development, as the amount of energy consumed in the village depends on the number of inhabitants. The graph of population changes in St. Petersburg is shown in Figure 26.

These population dynamics show an exponential population growth with three local failures corresponding to two wars and the crisis of the 90s of the XX century:

- from 1916 to 1920. (drop from 2,415,700 to 740,000);
- from 1939 to 1945 (drop from 3 191 304 to 546 000);
- from 1989 to 2008 (drop from 5,023,506 to 4,568,047).

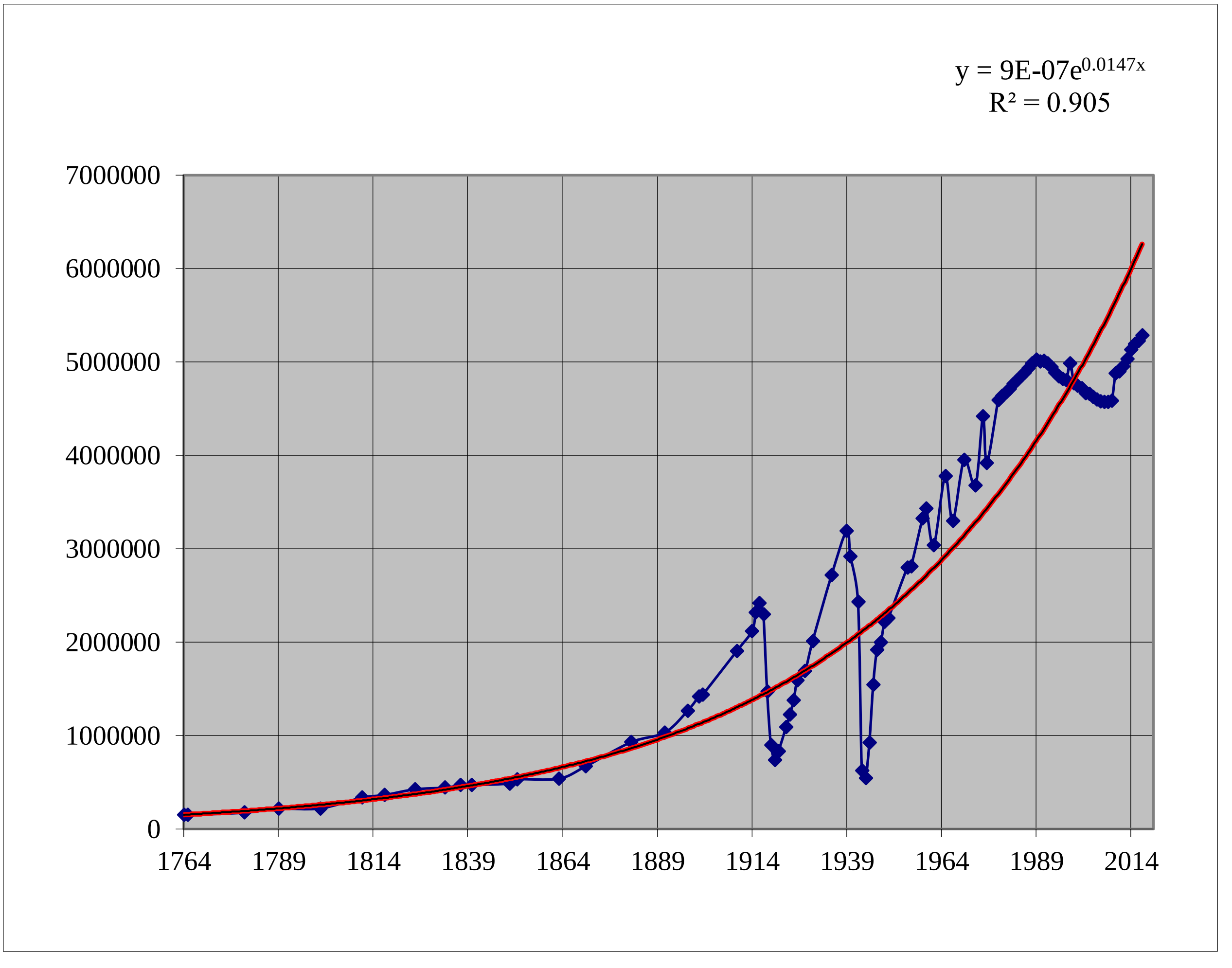

Figure 26 - Dynamics of population change in St. Petersburg for the period from 1764 to 2018

From the data presented in Figures 15–25, it follows that the minimum outdoor temperatures were observed from the end of the XVII to the middle of the XIX centuries. Before this period, average outside temperatures were generally higher. A closer look at the 25-year time intervals shows that the average outdoor temperature for the period from 1744 to 1768 was 3.96 ° C (see Fig. 15). Then, over a long period, the average outside temperature turned out to be lower and was able to reach this level again only at the beginning of the 20th century. Higher outdoor temperatures during this period cannot be explained by the influence of the anthropogenic factor. Most likely, they are due to other factors considered, in particular, in the study [46]. According to this study, during the last millennium, a gradual decrease in the average annual and average seasonal (winter and summer) outdoor temperatures was observed on the territory of the Russian Plain (and, most likely, on the adjacent territories). In the 20th century, the trend has reversed. This assumption is supported by the data presented in Figures 15–17. From the data, it follows that until about the end of the first third of the XIX century, the trend line of outdoor temperature in St. Petersburg was decreasing, after which it changed monotony and became increasing. An unambiguous interpretation of the change in the monotony of the functional dependence under consideration requires additional research. However, it should be noted that the period of change in the monotony of the trend line correlates with some lag with the period of the industrial revolution in Europe and a sharp increase in hydrocarbon consumption.

A comparison of the data presented in Figures 18 and 22 shows that the temperature increase in the warm and cold periods of the year is not equivalent. For example, over the past 50 years (from 1969 to 2018), in the warm season, the increase in outdoor temperature was 0.72 ° C (0.0144 ° C per year), in the cold the increase in outdoor temperature was 1.51 ° C (0.03 ° C per year), i.e. in the cold season, a 2 times more intense increase in air temperature was observed. Hence, it can be assumed that in the cold season, internal heat influences have a more noticeable effect on the climate of the city than in the warm. Some local minima that are identified when considering the graphs of changes in the average annual outdoor temperature confirm this assumption. For example, in the five-year interval (see Figures 21 and 25) in the period from 1939 to 1943. in the warm season, the average annual outdoor temperature decreased by 1.4 ° C (from 15.3 ° C to 13.9 ° C). In the cold season, the average annual outdoor temperature decreased by 3.22 ° C (from minus 0.77 to minus 3.89 ° C). As it is known, during the indicated war period, the vast majority of St. Petersburg buildings lacked or significantly reduced the supply of thermal energy.

3.4 Analysis of monthly data of air temperature changes

Figures 27–38 show the 50-year intervals, differentiated by the months of the calendar year.

From the data presented it follows that over the past 50 years, the largest increase in outdoor temperature by 2.5 ° C (from minus 3.9 ° C to minus 1.4 ° C) was recorded in March. In February, the increase in outdoor temperature was 2.0 ° C (from minus 7.9 ° C to minus 5.9 ° C), in January, the increase was 1.8 ° C (from minus 7.8 to minus 6.0 ° C), in December, the increase was 1.5 ° C (from minus 4.9 ° C to minus 3.4 ° C), in April, the increase was 1.4 ° C (from 3.3 ° C to 4.7 ° C), in May the increase was 1.2 ° C (from 10.1 ° C to 11.3 ° C), in June the increase was 0.8 ° C (from 15.0 ° C to 15.8 ° C), in July the growth was 0.7 ° C (from 18.0 ° C to 18.7 ° C), in August the growth was 0.4 ° C (from 16.5 ° C to 16.9 ° C), in September growth was also 0.4 ° C (from 11.3 ° C to 11.7 ° C). Thus, in the cold months of the year, a significantly more intense increase in the average outside temperature was observed compared to the warm months of the year.

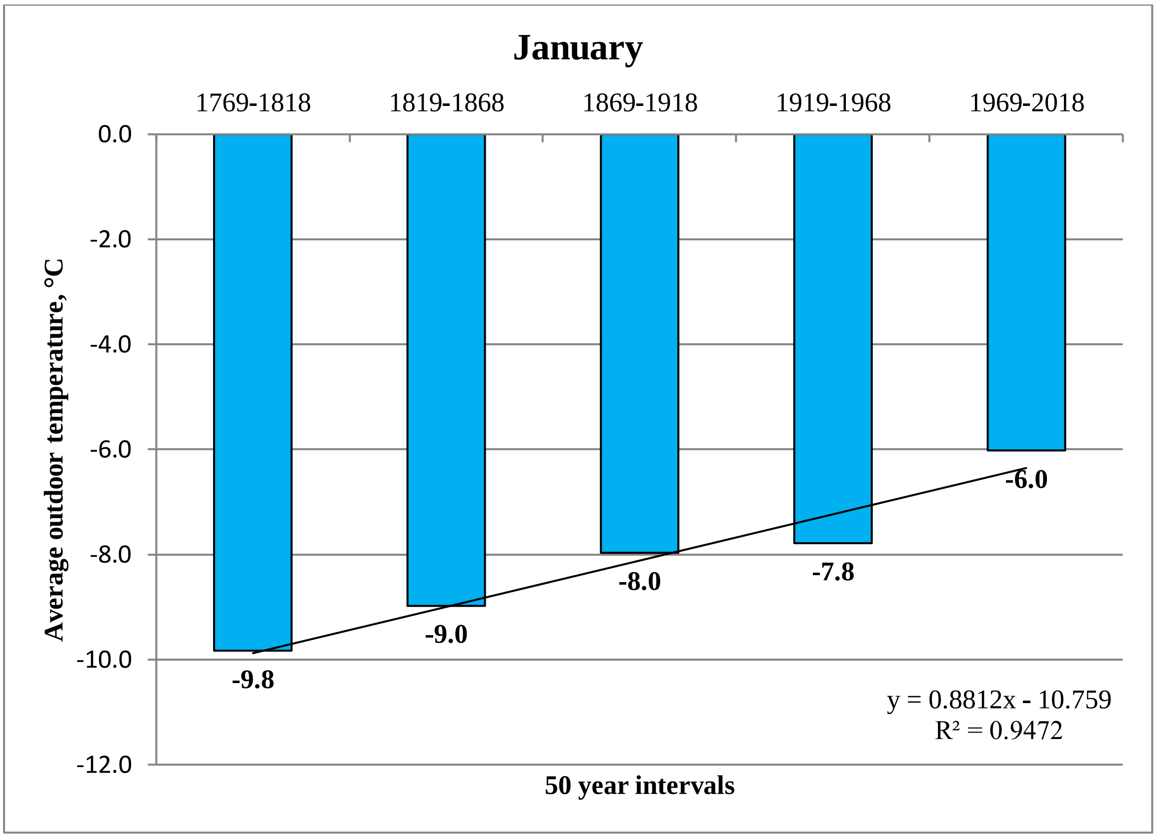

Figure 27 - Change in average air temperature in January with data differentiation for 50th-year

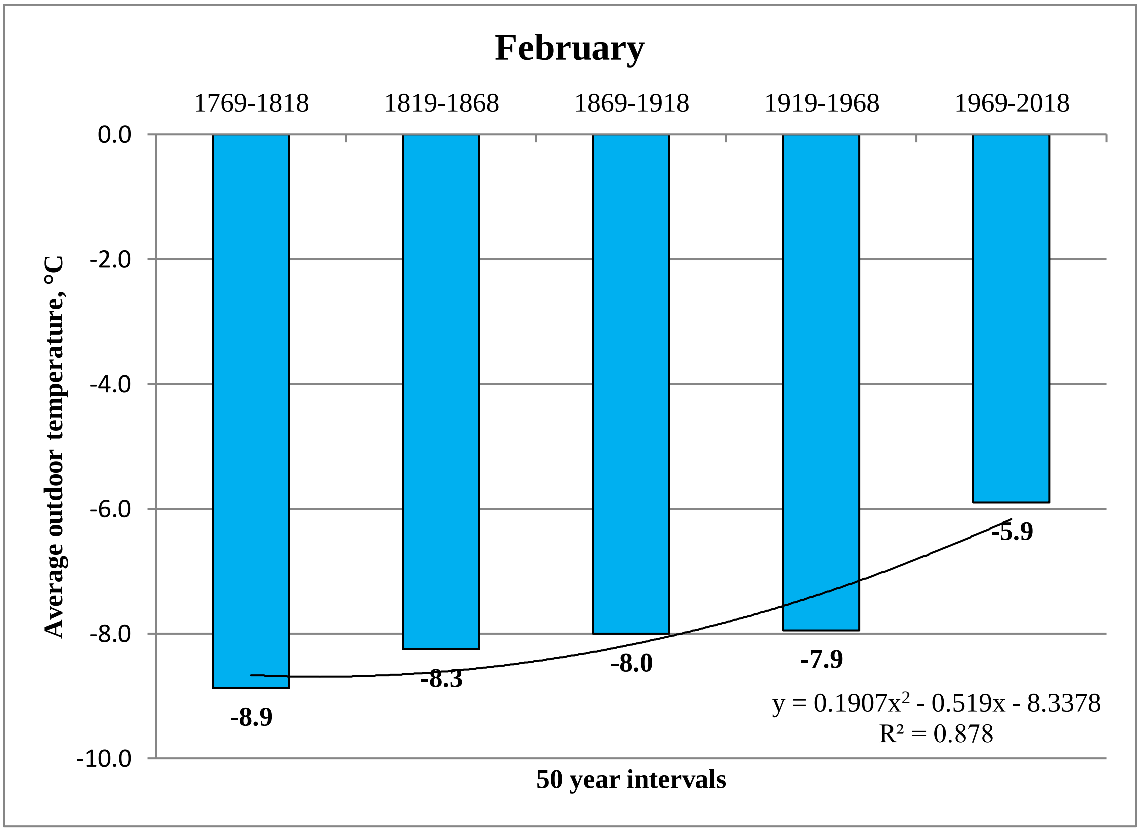

Figure 28 - Change in average air temperature in February with data differentiation for 50th-year

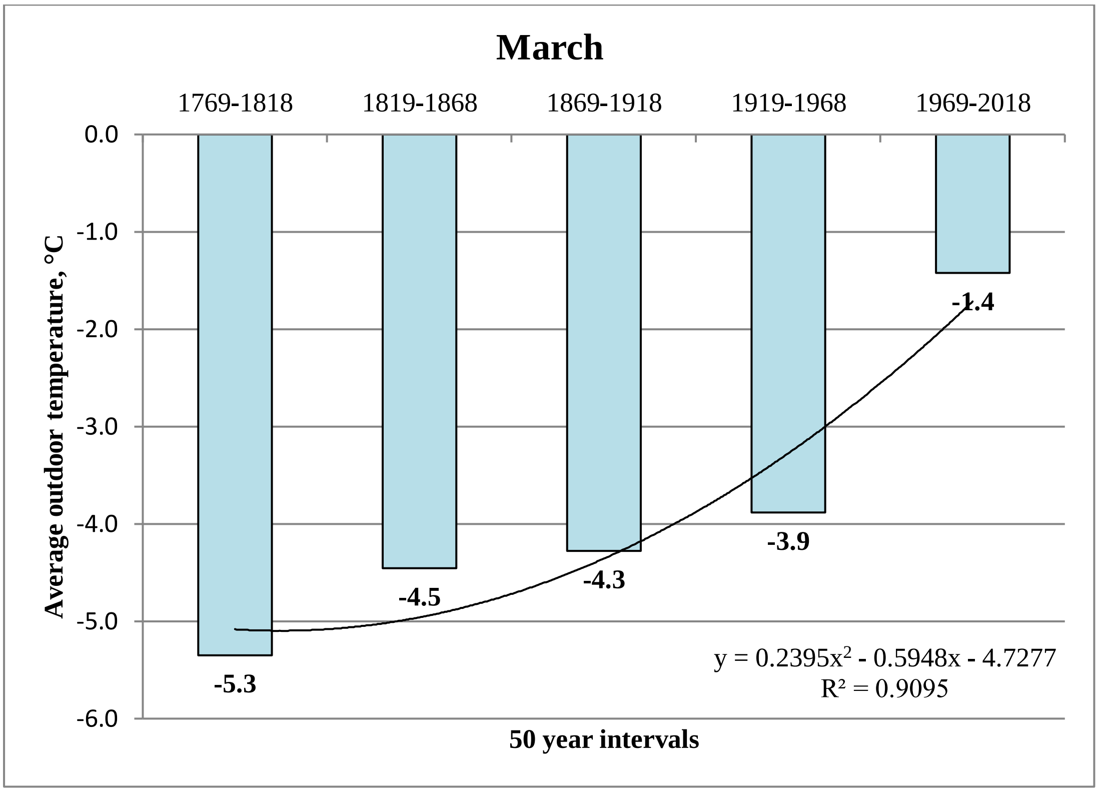

Figure 29 - Change in average air temperature in March with data differentiation for 50th-year

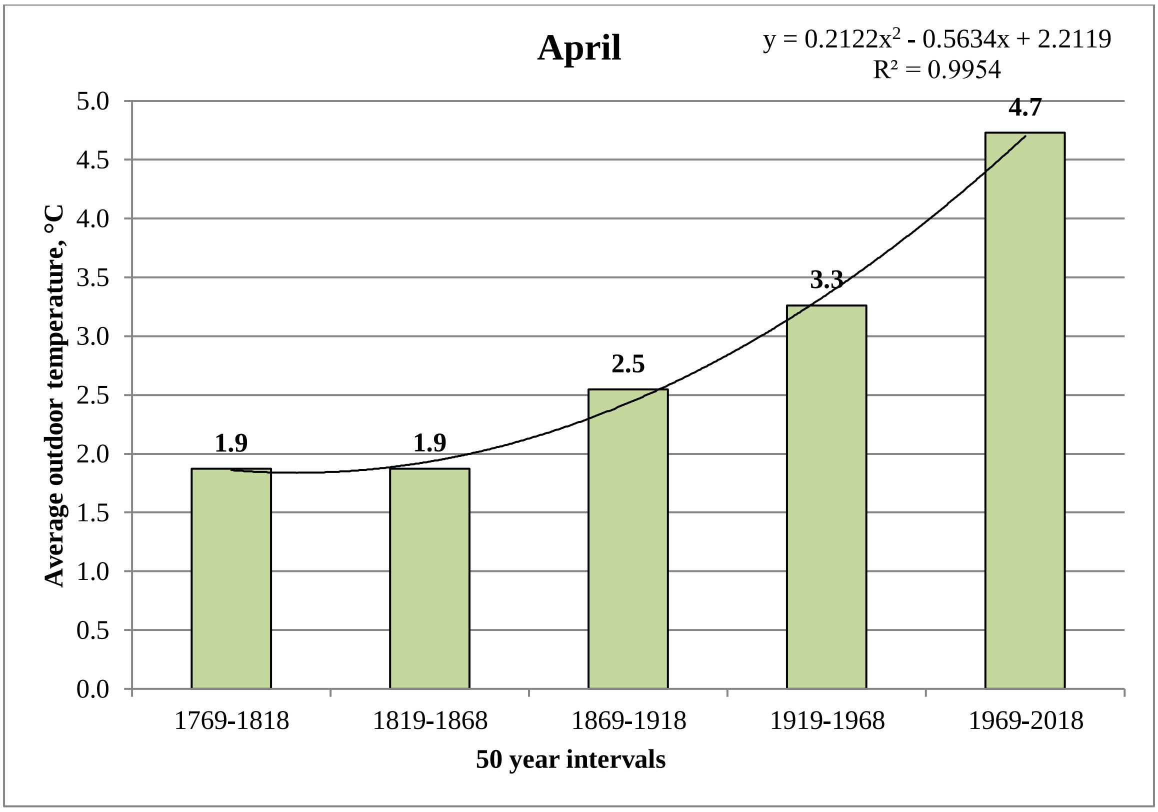

Figure 30 - Change in average air temperature in April with data differentiation for 50th-year

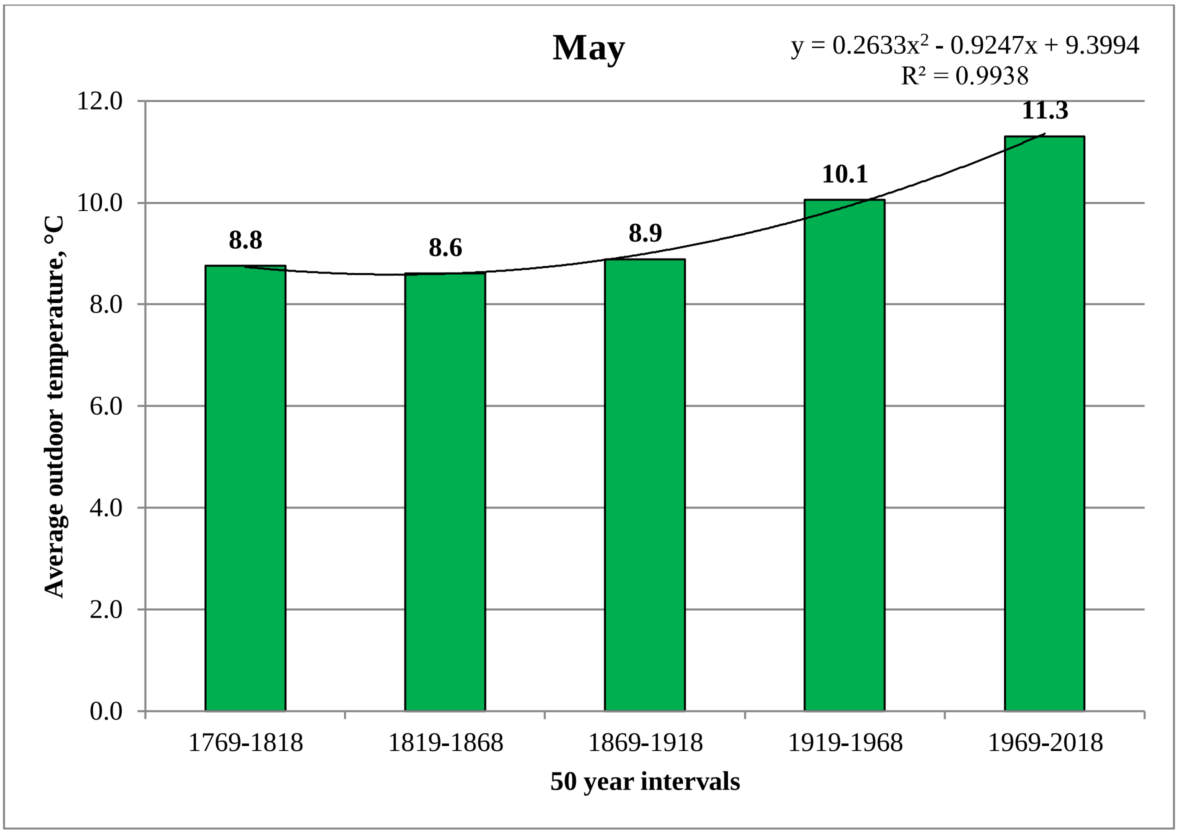

Figure 31 - Change in average air temperature in May with data differentiation for 50th-year

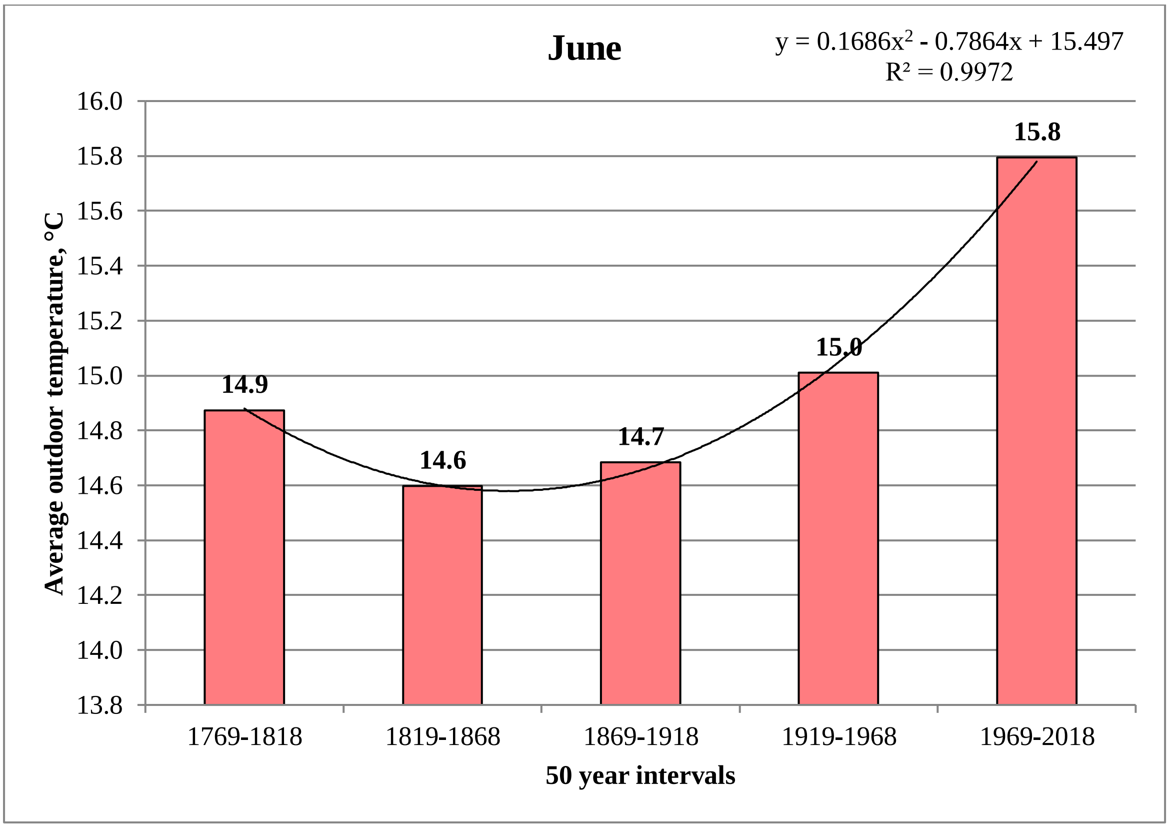

Figure 32 - Change in average air temperature in June with data differentiation for 50th-year

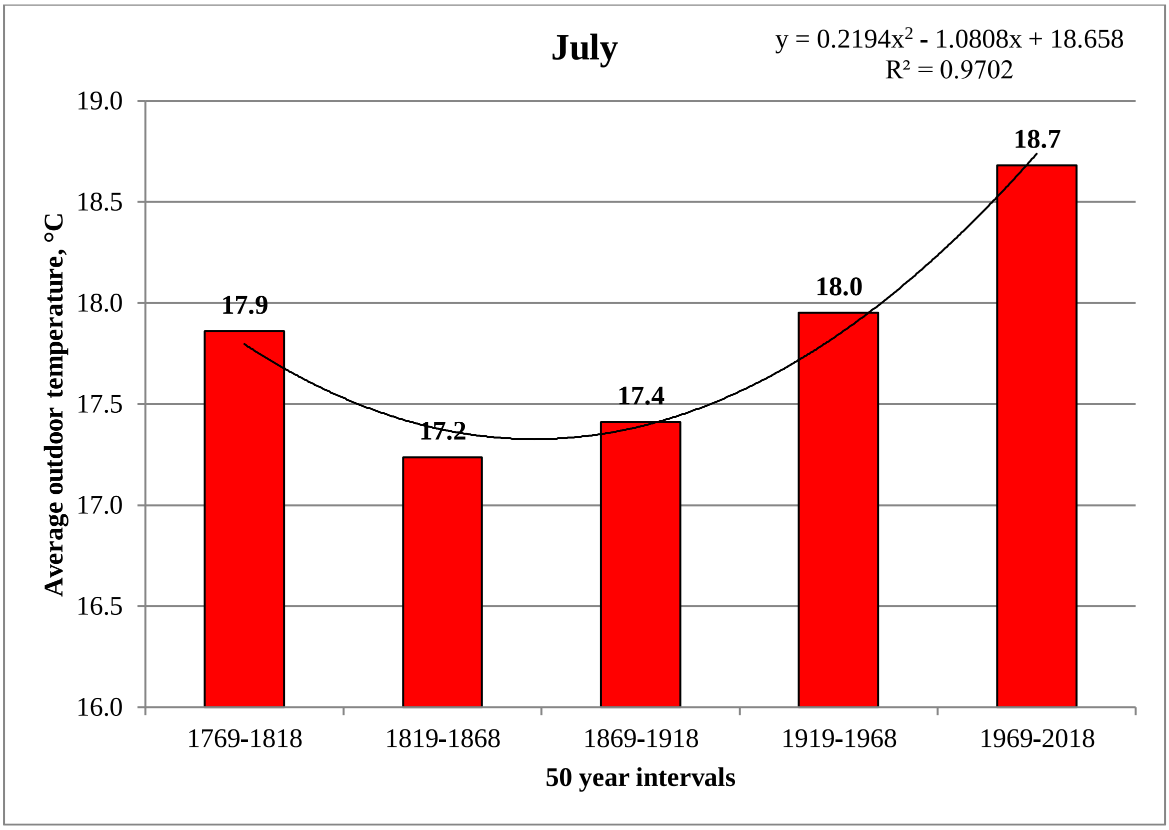

Figure 33 - Change in average air temperature in July with data differentiation for 50th-year

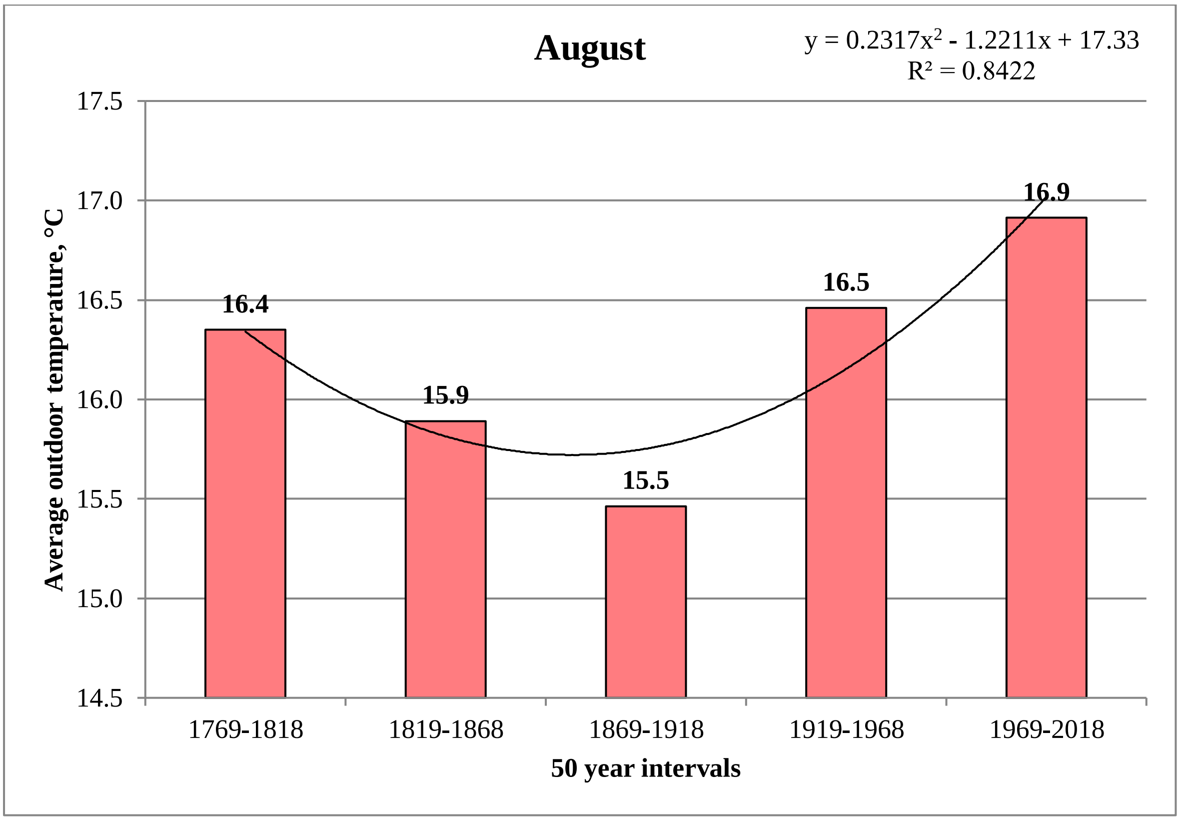

Figure 34 - Change in average air temperature in August with data differentiation for 50th-year

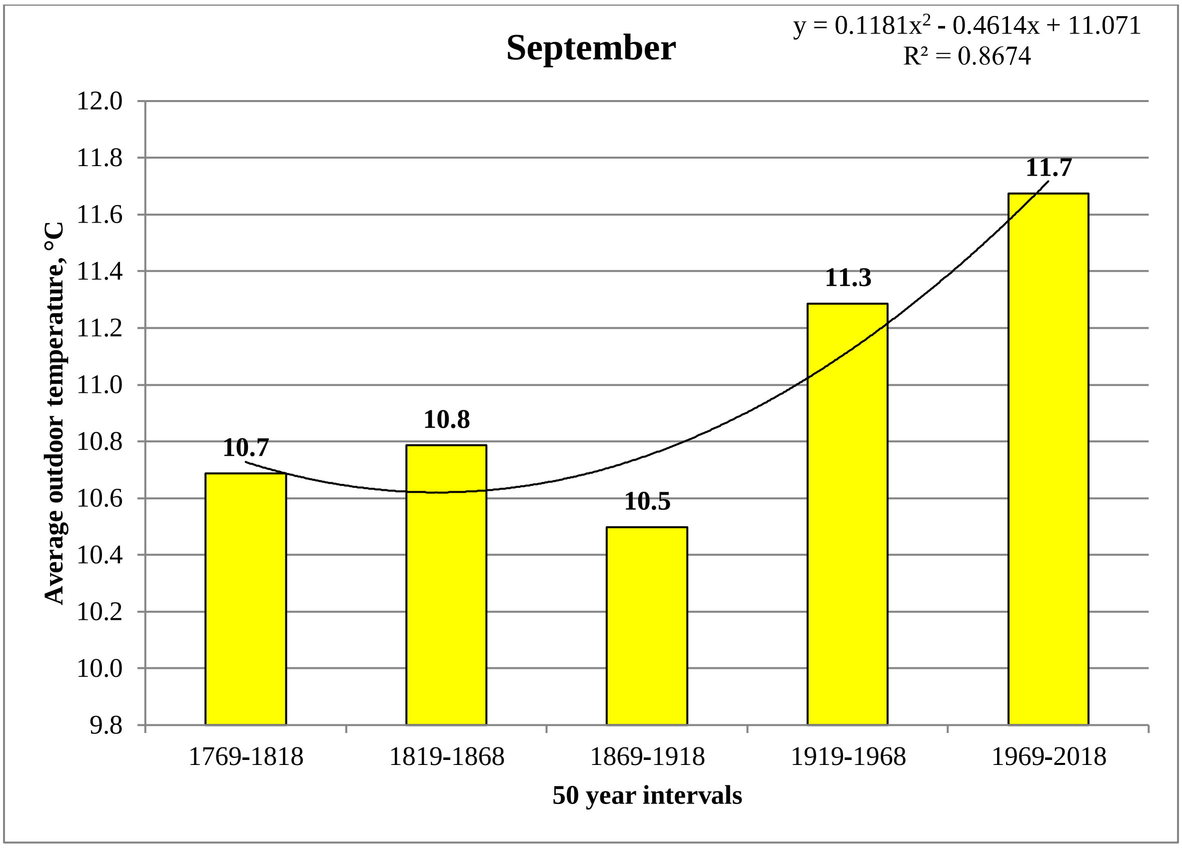

Figure 35 - Change in average air temperature in September with data differentiation for 50th-year

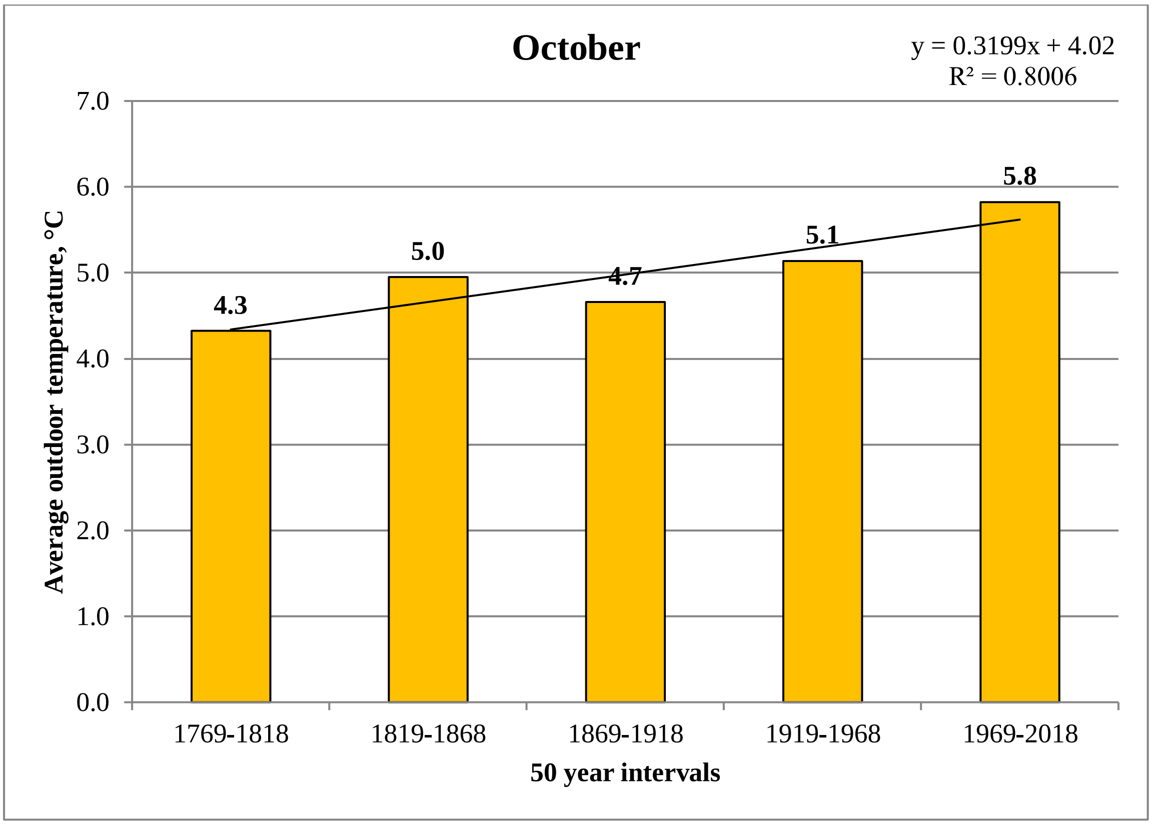

Figure 36 - Change in average air temperature in October with data differentiation for 50th-year

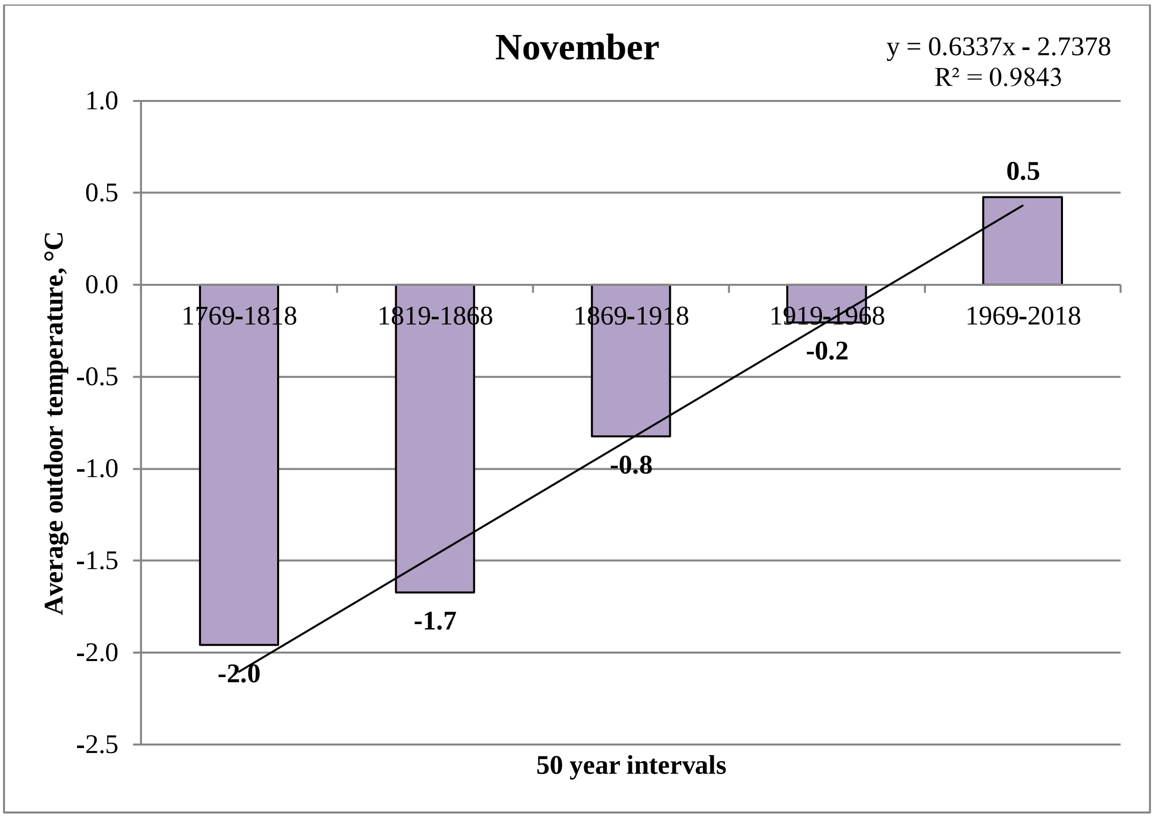

Figure 37 - Change in average air temperature in November with data differentiation for 50th-year

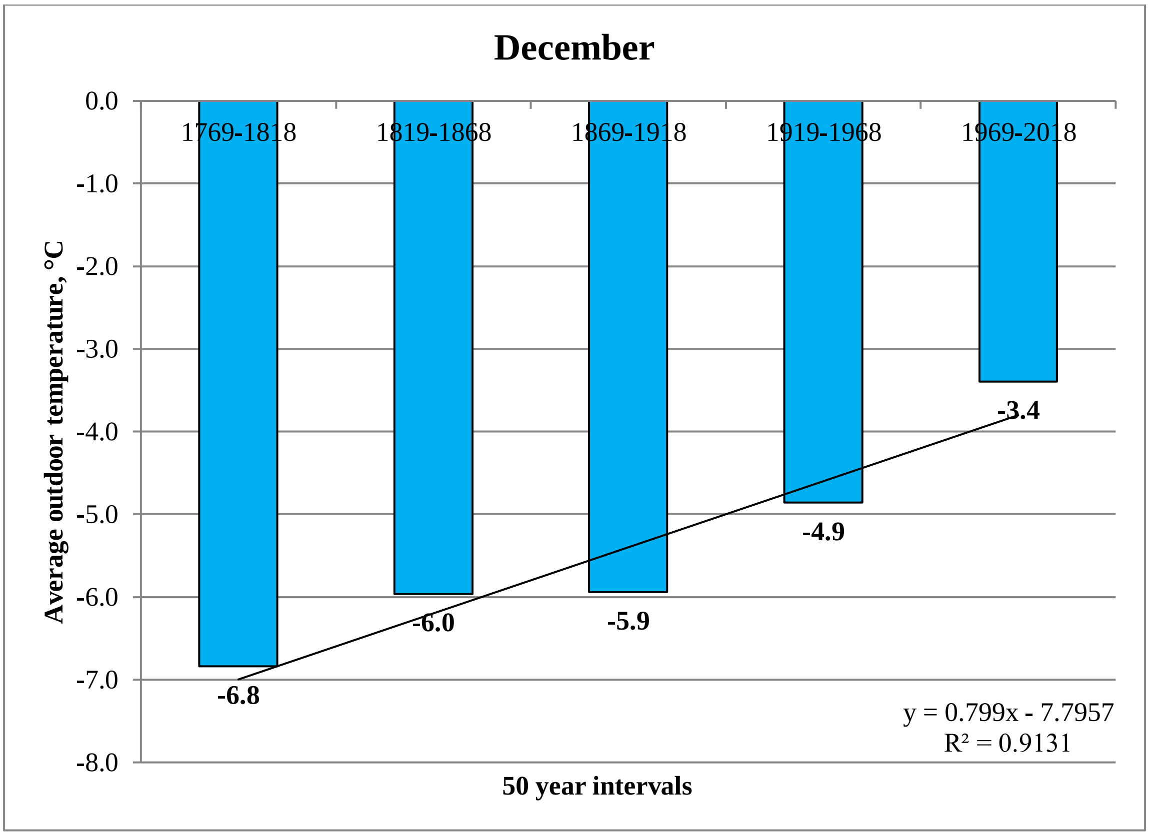

Figure 38 - Change in average air temperature in December with data differentiation for 50th-year

From the data presented in Figures 27-38, it follows that for the warmest months of the year, the trend line most closely corresponds to the polynomial approximation. As the outside temperature decreases, the trend line becomes more and more gentle, approaching a linear one.

Summarized data of outdoor temperatures averaged over 50-year intervals and differentiated by months, indicating the absolute values of the increase in outdoor temperature are presented in Table 2.

Table 2. Summarized data averaged over 50 years by month

Period	**January**		**February**		**March**	
	Absolute value	Growth	Absolute value	Growth	Absolute value	Growth
1769-1818	-9.8	-	-8.9	-	-5.3	-
1819-1868	-9.0	+1.8	-8.3	+0.6	-4.5	+0.8
1869-1918	-8.0	+1.0	-8.0	+0.3	-4.3	+0.2
1919-1968	-7.8	+0.2	-7.9	+0.1	-3.9	+0.4
1969-2018	-6.0	+1.8	-5.9	+2.0	-1.4	+2.5
Period	**April**		**May**		**June**	
	Absolute value	Growth	Absolute value	Growth	Absolute value	Growth
1769-1818	1.9	-	8.8	-	14.9	-
1819-1868	1.9	0	8.6	-0.2	14.6	-0.3
1869-1918	2.5	+0.6	8.9	+0.3	14.7	+0.1
1919-1968	3.3	+0.8	10.1	+1.2	15.0	+0.3
1969-2018	4.7	+1.4	11.3	+1.2	15.8	+0.8
Period	**July**		**August**		**September**	
	Absolute value	Growth	Absolute value	Growth	Absolute value	Growth
1769-1818	17.9	-	16.4	-	10.7	-
1819-1868	17.2	-0.7	15.9	-0.5	10.8	-0.1
1869-1918	17.4	+0.2	15.5	-0.4	10.5	-0.3
1919-1968	18.0	+0.6	16.5	+1.0	11.3	+0.8
1969-2018	18.7	+0.7	16.9	+0.4	11.7	+0.4
Period	**October**		**November**		**December**	
	Absolute value	Growth	Absolute value	Growth	Absolute value	Growth
1769-1818	4.3	-	-2.0	-	-6.8	-
1819-1868	5.0	+0.7	-1.7	+0.3	-6.0	+0.8
1869-1918	4.7	+0.3	-0.8	+0.9	-5.9	+0.1
1919-1968	5.1	+0.4	-0.2	+0.6	-4.9	+1.0
1969-2018	5.8	+0.7	0.5	+0.7	-3.4	+1.5

From Table 2 it follows that the largest increase in air temperature in St. Petersburg was observed:

- in the period from 1969 to 2018, i.e. in the last 50 years;
- within the heating season (from October to April with a maximum increase in average monthly air temperature in March by 2.5 °C compared with the period 1919-1968).

The minimum increase in air temperature in St. Petersburg over the past 50 years compared with the previous 50-year time period is recorded in August and September at 0.4 °C.

Both global and local factors can influence the establishment of the temperature regime in a settlement.

Global factors affecting climate change can be divided into:

- man-made (growth of the planet's population and energy consumption),
- non-anthropogenic (increase in solar activity, volcanic eruption, etc.).

It is known that for the period from 1743 to the present in the world the following largest volcanic eruptions (in chronological order) have occurred:

- October 1766 - Mayon Volcano (Luzon Island, Philippines);
- July 1783 - Laki volcano (Iceland);
- May 1792 - Unzen Volcano (Kyushu Island, Japan);
- April 1815 - Tambora volcano (Sumbawa Island, Indonesia);
- August 1883 - Krakatau volcano (Sunda Strait between the islands of Java and Sumatra);
- May 1902 - Montagne-Pelee volcano (Martinique island);
- June 1912 - Kathmay volcano (Alaska, USA);
- December 1931 - Merapi volcano (island of Java, Indonesia);
- November 1985 - the volcano Nevado del Ruiz (Colombia);
- June 1991 - Pinatubo Volcano (Luzon Island, Philippines).

A comparison of the climatic data analyzed in the work with periods of volcanic activity, including taking into account the delay in their impact on more remote territories, did not reveal a noticeable effect of volcanic eruptions on the climate of St. Petersburg, most likely due to the significant remoteness of St. Petersburg from places eruptions.

Local factors influencing climate change in the settlement in question are discussed in more detail in the next section.

3.5 The city thermal balance

3.5.1 Sources of heat gain and heat loss

The air temperature in the village is set based on the balance of heat influx and heat loss and is determined by the following main reasons:
- characteristics of wind pressure;
- the intensity of solar radiation;
- area of water sources (natural heat accumulators);
- the intensity of the economic activity of residents.

The main sources of heat in the city are:
- heated buildings;
- heat distribution networks;
- power-consuming installations, equipment and instruments;
- electrical networks and communications;
- transport;
- people and animals;
- solar radiation;
- open water sources.

The main reasons for lowering the air temperature in the village are:
- streams of cold air;
- open water sources.

For such large metropolitan areas as St. Petersburg, an uneven distribution of air temperature over its territory should be expected. The temperature in different parts of the city depends on the direction and speed of the wind, proximity to water sources, as well as the density of the heat and electric load of buildings and structures.

The wind flow, depending on the ratio of the flow temperature to the current air temperature in the village, can contribute to both reducing and increasing the weighted average air temperature in the city. It also applies to water bodies.

If the surface temperature of water sources is lower than the ambient temperature using a dry-bulb thermometer, then the heat flow is directed from the environment to the surface of the water. Conversely, if the surface temperature of water sources is higher than the ambient temperature using a dry thermometer, the heat flow is directed from the surface of the water to the environment.

Sources of the urban environment thermal pollution are: buildings, heat distribution networks, electrical networks, power-consuming installations, equipment and devices, transport, people. They can be called artificial sources of thermal pollution. In contrast, wind, open water sources, and solar radiation should be attributed to natural heat sources, the magnitude of which only indirectly depends on human activity.

A more detailed analysis of various sources of heat supply concerning the conditions of St. Petersburg is discussed below. In the framework of this study, a numerical assessment of the thermal pollution of the urban environment only from artificial sources of thermal pollution was made.

3.5.2 The influence of water sources

Figure 39 shows that, within the boundaries of St. Petersburg, the water surface occupies a significant area and, moreover, is unevenly concentrated on the territory of the city agglomeration. The presence of such a powerful natural heat accumulator affects the climate of St. Petersburg. However, its influence would have taken place even if the territory of the city had not been populated. In this regard, a numerical assessment of its impact on climate is not considered in this study. It should be noted that the anthropogenic factor, albeit indirectly, is present here since the temperature of the water discharge (after wastewater treatment) is usually higher than the temperature of the drawdown. But this influence is not so significant in comparison with other factors considered in this paper.

Figure 39 - Schematic map of St. Petersburg [50]

The heat transfer process between the surface of the water source and the environment occurs both due to convection and due to radiation, and in the general case can be described by the following equation:

$$q = \alpha \cdot \left(t_{amb} - t_{w.s.} \right), \tag{1}$$

where α is the heat transfer coefficient.

The heat transfer coefficient is equal to the sum of the convective and radiant components of heat transfer:

$$\alpha = \alpha_{conv} + \alpha_{rad} \,,$$

where α_{conv} is convection heat transfer coefficient; α_{rad} is the coefficient of radiant heat transfer by convection; t_{amb} is ambient temperature; $t_{w.s.}$ is the surface temperature of a water source.

Equation (1) corresponds to the direction of flow from the environment to the surface of the water source. In the opposite direction of the flow, the heat transfer equation takes the form:

$$q = \alpha \cdot \left(t_{w.s.} - t_{amb}\right), \tag{2}$$

where all the notation is the same as in equation (1).

Figure 40 shows an example of actual weather in St. Petersburg and its environs as of 9:00 on December 27, 2019. From the presented data it follows that the air temperature in the city is about 1 ° C higher than in its environs. St. Petersburg City Meteorological Station is located in one of the central areas of the city (Petrogradskiy) on the street. Professor Popov, 48. It should be noted that the station was previously located in a different place (on Vasilievsky Island). The geographical coordinates of the weather station in St. Petersburg are: latitude 59.97 ° longitude 30.30 ° [23]. Geographical coordinates of the city center are 59 ° 57 'north latitude and 30 ° 19' east longitude [51]. It follows that the coordinates of the location of the meteorological station and the geographical center of St. Petersburg practically coincide. Figure 40 also shows that the closer the temperature measurement point to the boundaries of the water source, the higher the air temperature.

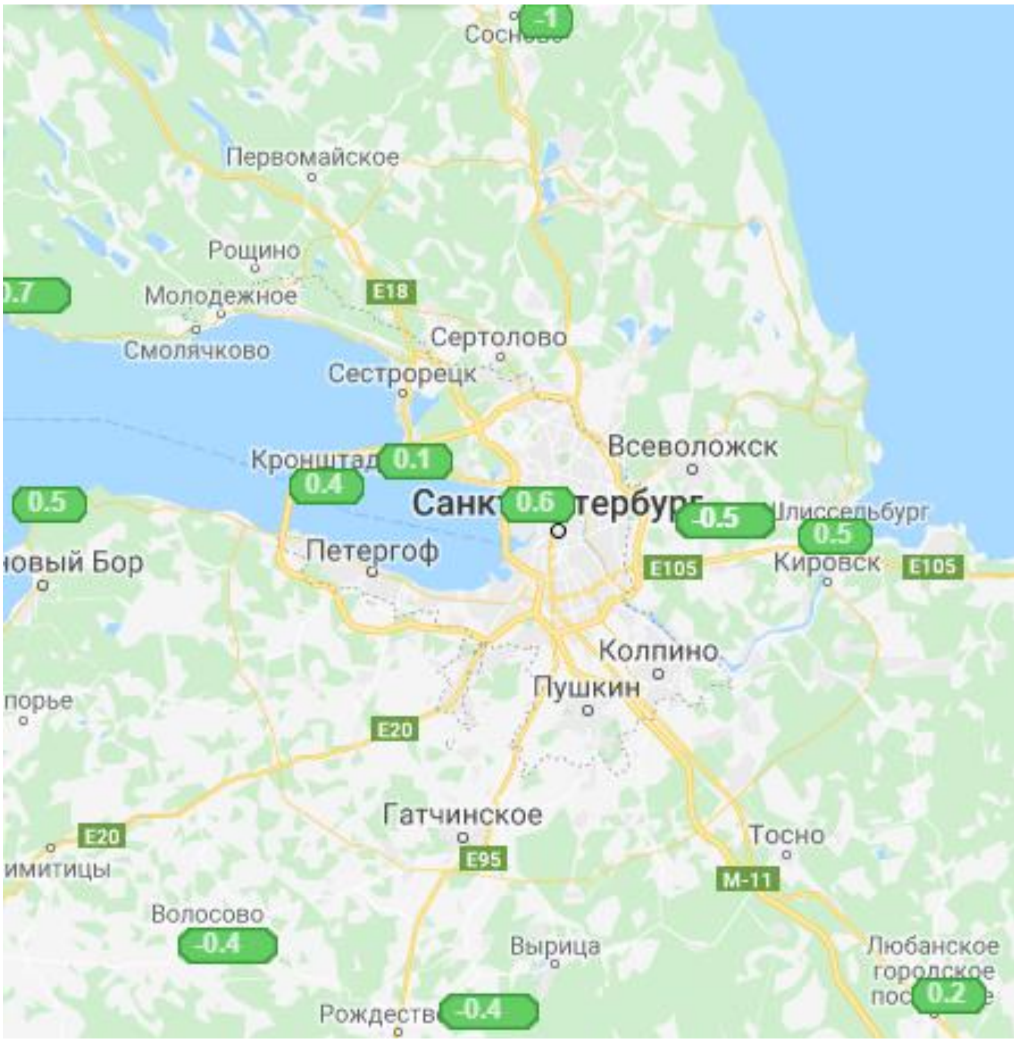

Figure 40 - Actual weather in and around St. Petersburg at 9 a.m (Moscow time) on 27.12.2019 [52]

3.5.3 The effect of solar radiation

The annual amplitude of direct solar radiation on a horizontal surface with a clear sky ranges from 25 MJ/m² in December to 686 MJ/m² in June. Over the year, cloud cover on average reduces the total solar radiation by 21%, direct solar radiation reduces by 60%. The average annual total radiation is 3156 MJ/m² [53], pp. 371–372.

Table 3. Average value of total solar radiation on horizontal and vertical surfaces under actual cloud conditions, MJ/m^2 (kWh/m^2), for the heating period [48]

Name of locality	Horizontal surfaces	Vertical surfaces oriented to:				
		north	northeast / northwest	east/west	southeast/southwest	south
St. Petersburg	808 (224)	391 (109)	415 (115)	583 (162)	831 (231)	938 (261)

It should be noted that this factor indirectly depends on the factor of anthropogenic influence. Cutting down trees and shrubs contributes to a more intense absorption of solar radiation in the city, because Plants use part of the absorbed solar energy in the process of photosynthesis. Road surfaces, facades and roofs of houses absorb a significant part of solar radiation, heat up and reflect it into the surrounding space.

3.5.4 Effect of heat energy production and consumption

Data on the consumption of thermal energy in the city can be extracted from the analysis of the data presented in the heat supply schemes of district heating systems.

The updated version of the heat supply scheme of St. Petersburg is available on the website of the Committee on Energy and Engineering [54]. By the data presented in the updated version of the heat supply scheme, the total annual heat production by sources located in St. Petersburg amounted to 169 PJ in 2018. Of these, 155.3 PJ of thermal energy was produced during the heating period.

The total heat production by sources for the previous several years is presented in Table 4.

Table 4. Total annual heat production in St. Petersburg

Год	Total annual heat energy production per year, PJ
2015	144.0
2016	178.1
2017	173.8
2018	169.0

The data presented in Table 4 are graphically shown in figure 41.

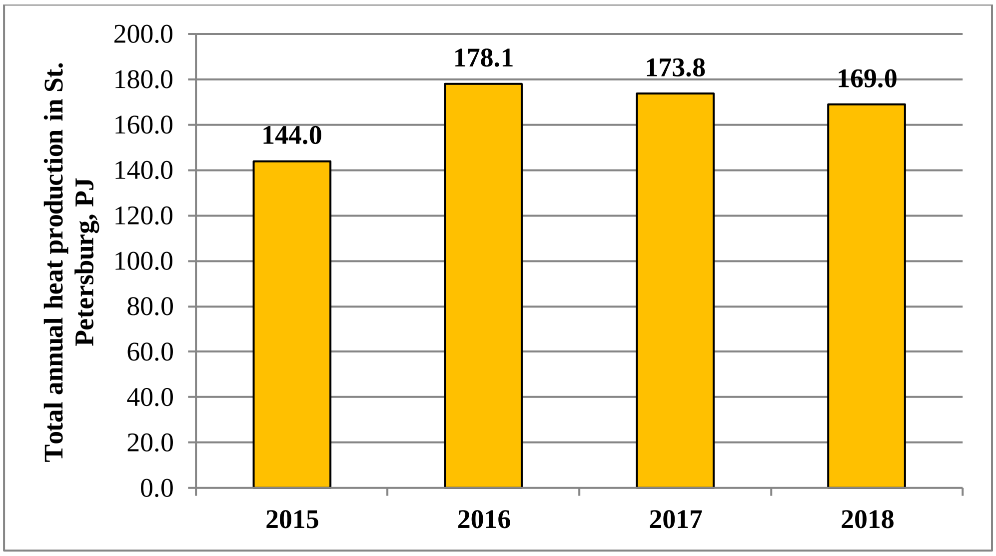

Figure 41 - Total annual heat production in St. Petersburg from 2015 to 2018

In the general case, we can assume that all the thermal energy generated at the sources is spent on maintaining the specified microclimate parameters in heated buildings, on providing residents with hot water, and also on supporting technological processes in industry (taking into account heat energy losses in heating networks). In the conditions of a settlement, heat energy is released into the atmosphere through the external enclosing structures of heated buildings, through the insulation surface of the pipelines of heating networks, usually laid underground, with the emission of flue gases from thermal power plants and boiler houses and by cooling process water in cooling towers. Not all the heat of the burned fuel goes to the production of thermal energy, and therefore, for a more accurate assessment of heat input, the data presented in Table 3 should be increased by 20-30%. Thus, the total contribution of thermal energy sources to the thermal pollution of the urban environment during the year can be estimated at 210 million MJ per year.

A significant part of the heat energy in the annual cycle is spent on heating buildings and the lower the temperature of the outside air, the more significant amount of heat energy is required to compensate for heat losses through the outer shell of buildings and maintain standard microclimate parameters in heated buildings.

When designing buildings, the average outside temperature is taken according to the Russian Building Code of Rules SP 131.13330 [55]. For the conditions of St. Petersburg, the calculated characteristics of the heating period are presented in Tables 5, 6 [48].

Table 5. Calculated values of the outdoor temperature [48]

Name of settlement	Design ambient air temperature, °C		
	The temperature of the coldest five days, t_{ext}	Average temperature for the heating period t_{ht} for the period with average daily air temperature	
		≤ 8 °C	≤ 10 °C
St. Petersburg	minus 24	minus 1.3	minus 0.4

Table 6. Calculated indicators of the duration and intensity of the heating period in St. Petersburg [48]

Name of settlement	Heating degree-days, °C·days/days:				
	Residential buildings, hotels and hostels	Educational institutions	Polyclinics and medical institutions	Preschool institutions	Public, except as indicated in columns 3, 4, 5
1	2	3	4	5	6
St. Petersburg	4537/213	4733/232	4965/232	5197/232	4111/213

The actual values of the average outdoor temperature for the heating period may differ significantly from the calculated value (Figure 42). This circumstance introduces uncertainty in predicting the estimated consumption of thermal energy.

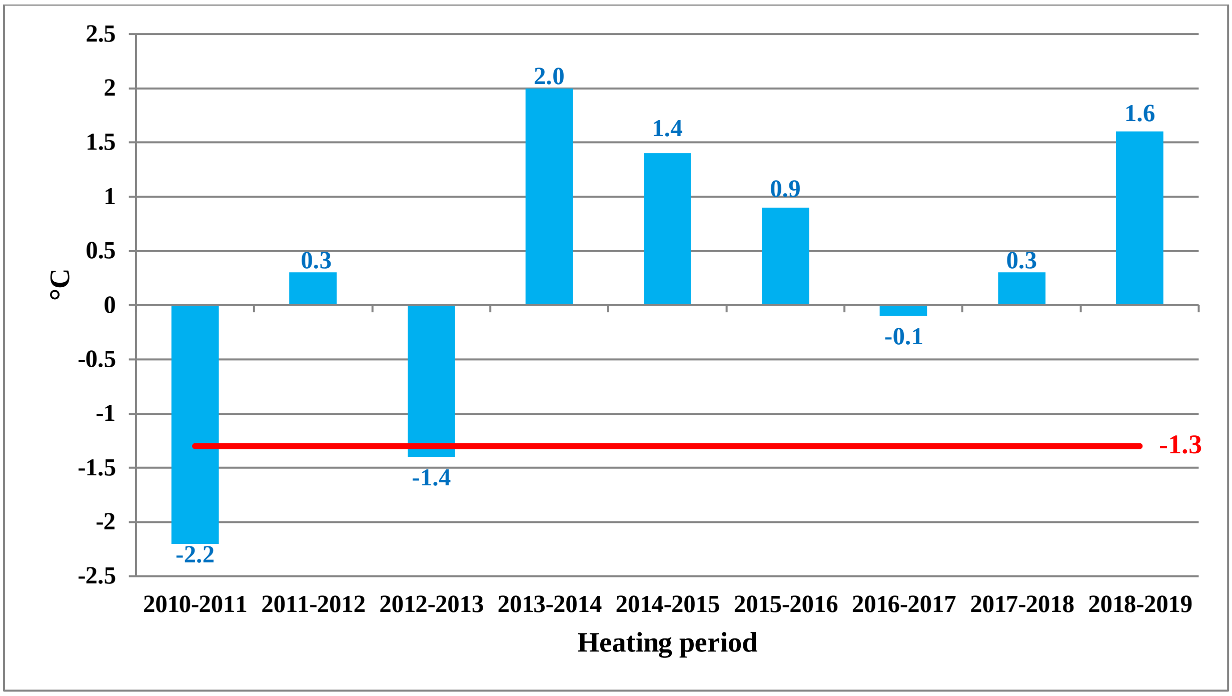

Figure 42 - The average outdoor temperature in St. Petersburg during the heating period

The duration of the heating period is also not constant. The actual values of the duration of the heating period in St. Petersburg are presented in Table 1 and shown graphically in Figure 43.

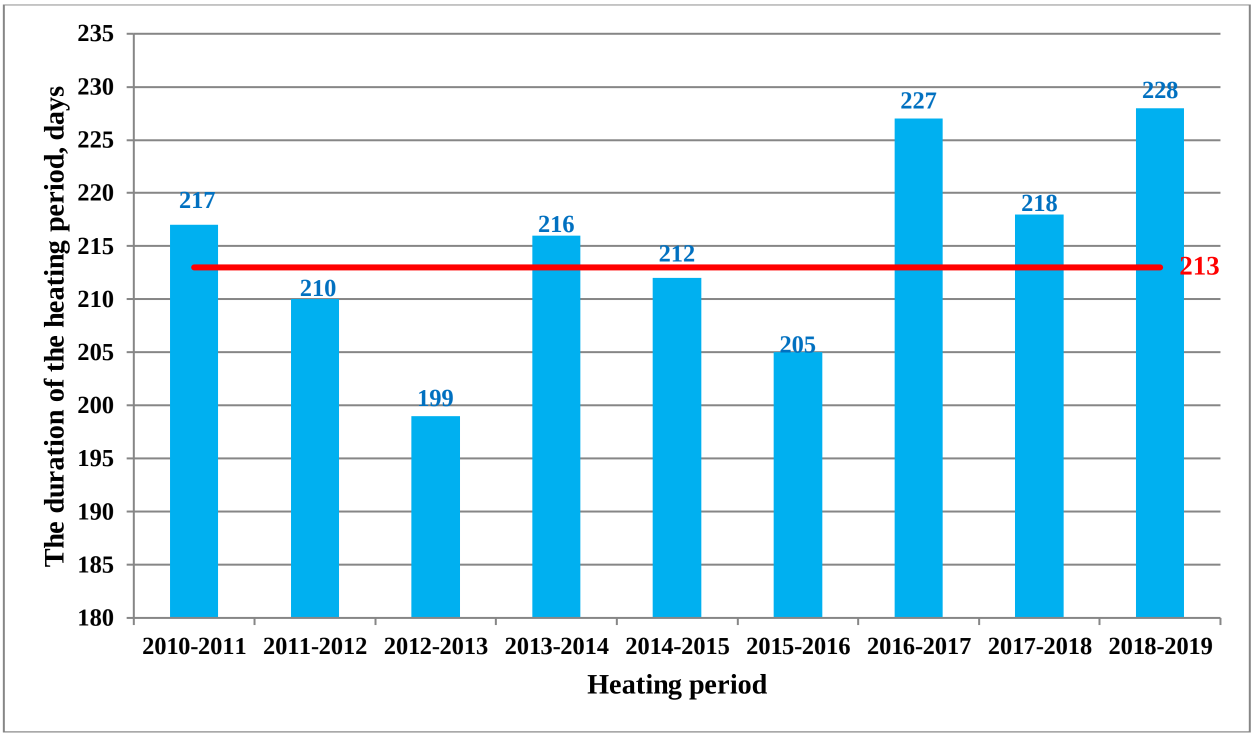

Figure 43 - Duration of the heating period in St. Petersburg from 2010 to 2019

Standard microclimate parameters at the cold period for residential and public buildings are set in Russian State Standard GOST 30494-2011 “Residential and Public Buildings. Microclimate Parameters for Indoor Enclosures” [56].

Standard microclimate parameters at the cold period for industrial buildings are set in Russsian State Standard GOST 12.1.005-88 “Occupational Safety Standards System. General Sanitary Requirements for Working Zone Air”

For residential buildings, the range of permissible internal air temperatures in the cold season is 18 ÷ 24 ° C, the optimal temperature range is 20 ÷ 22 ° C. As a rule, the calculated internal air temperature for residential buildings is assumed to be plus 20 ° C, air temperature for public buildings is assumed to be plus 18 ° C, but in the vast majority of cases, the internal air temperature is higher than the calculated values. This is facilitated, inter alia, by the predominance in St. Petersburg of open schemes for connecting the hot water supply system of buildings to heating networks and the presence of so-called temperature profile cut-off. Within the cut-off of the temperature graph, the temperature of the coolant supplied to the heating system of buildings is usually higher than the required (at a given outdoor temperature) because of which, buildings may experience an excessive consumption of thermal energy for heating compared to the estimated flow.

The area of St. Petersburg is 1439 km^2, of which the territory of high-density development is 650 km^2 [51]. In the zone of high-density development, one should expect a maximum influx of thermal energy from buildings and heating networks.

As of 01/01/2019, more than 58,000 buildings are in operation in St. Petersburg, while the total area of apartment buildings is 134.3 million m^2, the total area of the public and business fund is 73.3 million m^2, and the total area of industrial and warehouse buildings is 25.8 m^2 [54]. The total area of buildings is more than 220 million m^2. It follows that, per year, per square meter of the total area of buildings operated in St. Petersburg, an average of 0.77 GJ of thermal energy is consumed. As new buildings are commissioned, the demand for thermal energy increases, which contributes to an increase in the consumption of thermal energy.

The population in St. Petersburg as of 01.01.2019 is 5,381,736 inhabitants. Thus, on average, about 33.5 GJ of heat energy per year is generated per inhabitant.

The production and consumption of thermal energy in the city is uneven throughout the year, higher in the cold period and lower in the warm season. The highest heat production is observed at the lowest outdoor temperatures, because a significant part of the heat is spent on heating buildings. The Heat Supply Scheme indicates that the maximum calculated heat load in St. Petersburg in 2019 amounted to 17 GW [54]. The summer load turns out to be much less than the winter one, therefore the main contribution of heat sources to the thermal pollution of the urban environment falls on the cold season. This circumstance may be one of the reasons for a noticeable climate warming in St. Petersburg in the cold season and not so significant in the warm season.

3.5.5 The impact of electricity generation

With a sufficient degree of accuracy, it can be argued that all the electrical energy consumed in the city is converted into thermal energy.

The dynamics of electricity consumption and the maximum electricity consumption in St. Petersburg in the period 2013-2017 presented in Table 7 [57], [58].

Table 7. Dynamics of electric energy consumption and changes in maximum capacity in St. Petersburg [57], [58].

Name of indicator	**2013**	**2014**	**2015**	**2016**	**2017**
Electricity consumption, billion MJ	87.2	88.1	87.3	90.4	90.6
Maximum electricity load, MW	4,017	4,283	4,183	4,374	4,011
The number of hours of use of the maximum electricity load, %	6,030	5,715	5,815	5,740	6,270

Annual electricity consumption in St. Petersburg by years is graphically shown in Figure 44, load maxima - in Figure 45.

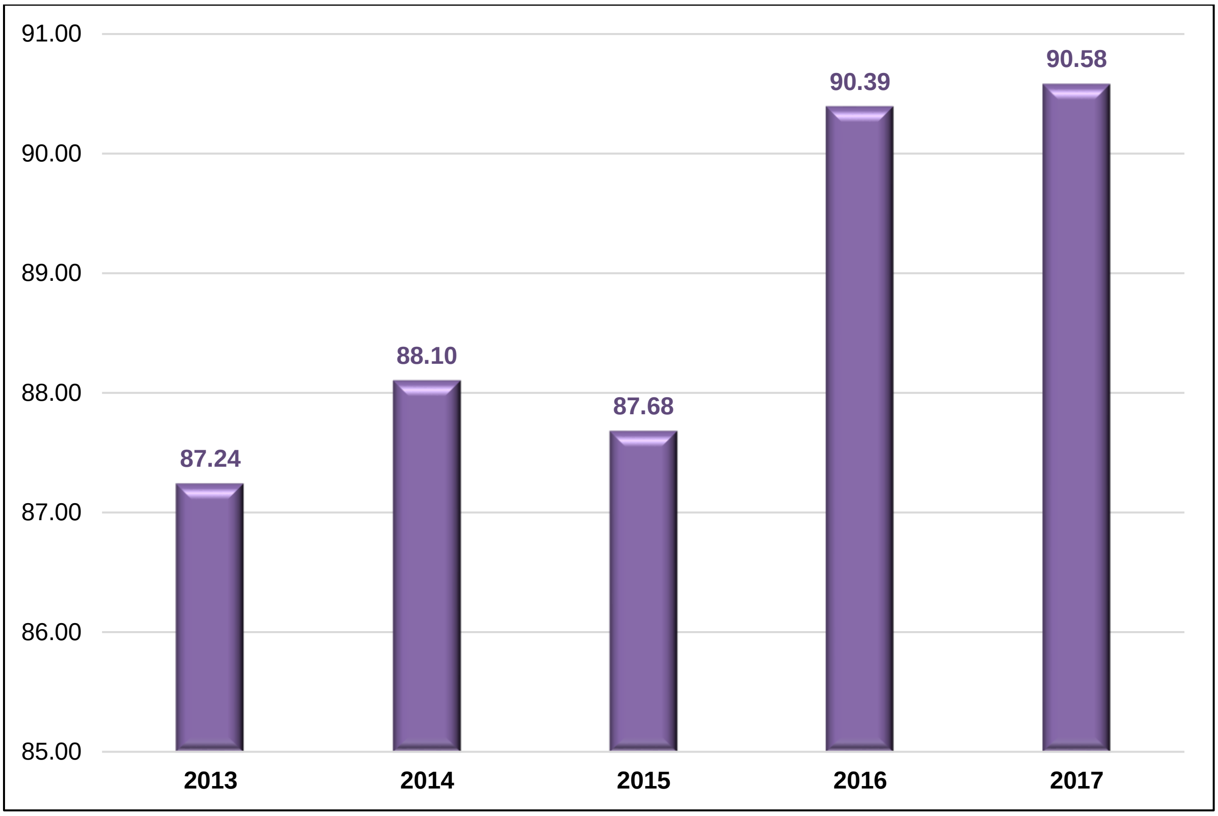

Figure 44 - Annual electricity consumption in St. Petersburg by years, PJ

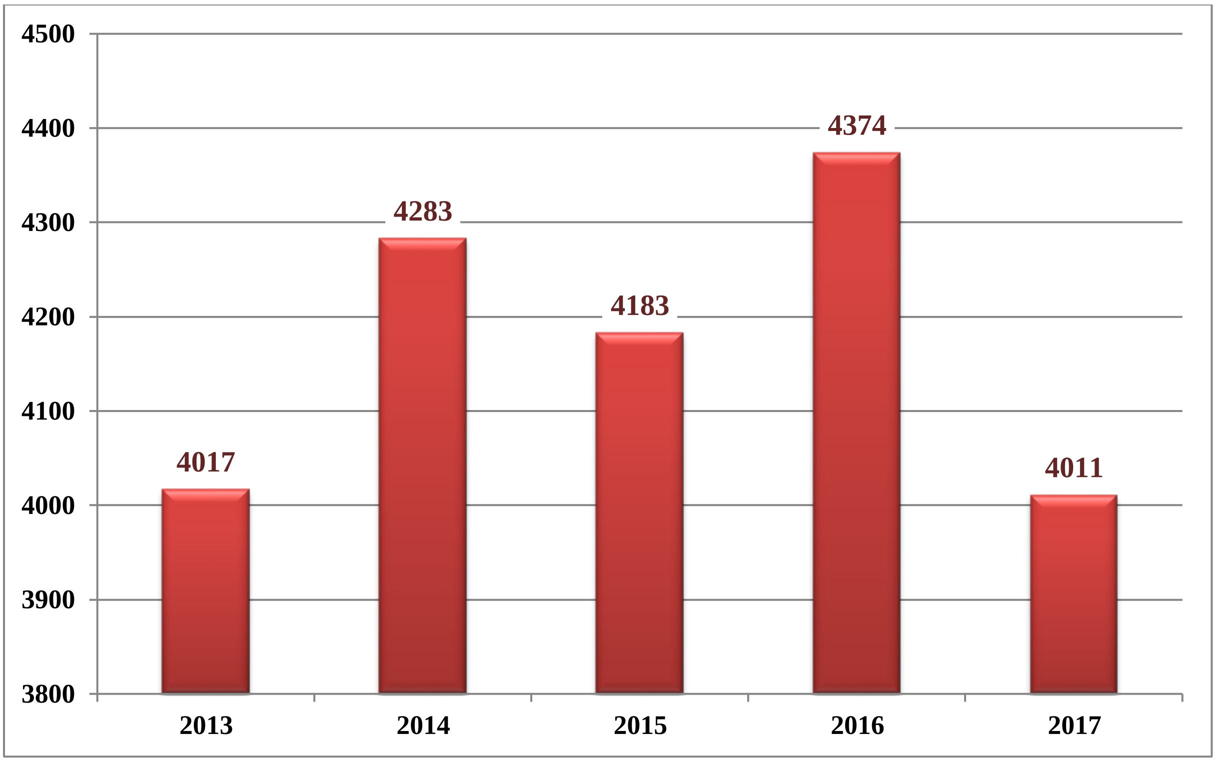

Figure 45 - The maxima of the electric load in St. Petersburg, MW

Typically, the maximum electrical load in St. Petersburg falls during the winter months, when the duration of daylight hours sharply decreases, and the duration of use of artificial lighting in buildings and streets increases. Also, in the winter months, the maximum use of electric heaters occurs. This fact also contributes to more dramatic climate changes in the cold season.

3.5.6 Thermal pollution of the urban environment by motor vehicles

According to the agency AUTOSTAT [59], more than 1.7 million passenger cars were registered In St. Petersburg. The total fleet of vehicles, including commercial vehicles, is 2.5 million vehicles. An objective assessment of the thermal pollution of the urban environment by vehicles is difficult since:

- vehicles are operated unevenly during the year;
- a certain number of vehicles are constantly or temporarily operated during the year outside the city territory;
- there are cars from other regions in addition to registered cars in the city.

Despite these objective difficulties, the thermal pollution of the urban environment as a result of the operation of vehicles was evaluated.

The following assumptions have been made. The number of cars in use assumed to be as:

- 1.8 million units of passenger cars;
- 0.7 million units of commercial vehicles.

The value of the average vehicle mileage per year during urban operation assumed to be as:

- 15,000 km for passenger cars;
- 30,000 km for commercial vehicles.

Average travel fuel consumption, in liters per km, assumed to be as:

- 10 liters for passenger cars;
- 20 liters for commercial vehicles.

Then the total annual fuel consumption, Q_f liter/year, will be:

$$Q_f = N_{p.tr.} \cdot l_{y.p.} \cdot q_{f.p.} + N_{c.tr.} \cdot l_{y.c.} \cdot q_{f.c.} = 7{,}350{,}000{,}000 \;, \tag{3}$$

where

$N_{p.tr.}$ is the number of passenger cars;

$l_{y.p.}$ is the average mileage of passenger cars during the calendar year, km/year;

$q_{f.p.}$ is average travel fuel consumption by passenger car, l/km;

$N_{c.tr.}$ is the number of commercial vehicles, pcs;

$l_{y.c.}$ is the average mileage of commercial vehicles during a calendar year, km/year;

$q_{f.c.}$ is average travel fuel consumption by commercial vehicles, l/km.

The combustion value of fuel assumed to be as $4.36 \cdot 10^7$ J/kg, the density assumed to be as 0.76 kg/dm^3, the completeness of fuel combustion in the internal combustion engine in the conditions of vehicles moving around the city is 75%.

The emission of thermal energy during the operation of cars in urban environments for one year $Q_{h.tr.}$, PJ/year, is

$$Q_{h.tr.} = Q_f \cdot \rho_f \cdot q_f \cdot k_f \approx 182.7 \,, \tag{4}$$

where

Q_f is the same as in formula (3),

ρ_f is fuel density;

q_f is specific by mass heat of fuel combustion;

k_f is coefficient characterizing incompleteness of fuel combustion.

In addition to automobile transport, the sources of thermal pollution in the city are also air, water, underground and rail transport. Thus, the amount of thermal energy released by transport in the city is greater than the numerical estimate obtained above. However, road transport among other modes of transport is the most significant and has a more even distribution over the entire area of the city. Air transport has been moved outside the city, which has a minor effect on the thermal pollution of the urban environment. The duration and intensity of the operation of water transport during the year and in St. Petersburg urban environments are noticeably less than automobile one.

Underground transport is one of the largest consumers of electric energy. The heat generated during the operation of underground transport is carried into the urban environment during ventilation of the underground space.

Rail transport (freight and passenger long-distance and commuter trains) has a more noticeable effect on the thermal pollution of the urban environment compared to air and water transport, but is inferior in intensity to road transport. The assessment of thermal pollution from rail transport is difficult due to the lack of the necessary input data. If we consider trains equipped with electric motors, then they, like underground transport, belong to electric consumers, i.e. are accounted for.

The contribution of other modes of transport to the thermal pollution of the urban environment can be estimated at 20%. If this assumption is accepted, then the total amount of thermal pollution of the urban environment from all types of vehicles can reach 220 PJ/year. It follows that the thermal pollution by vehicles in the annual cycle is comparable to heat consumption.

3.5.7 Heat release from people

People are also sources of heat. The dynamics of the population of St. Petersburg, excluding unregistered citizens, are shown in Figure 26. As of 01.01.2019, the population of St. Petersburg was 5,381,736 people. Also, the number of residents living in the city, including unregistered ones, is much higher and, according to various estimates, can reach 7 million people. On the other hand, not all registered residents of St. Petersburg permanently reside in it.

Heat emissions from people depend on many factors: gender, age, type of human activity, other individual characteristics of his body, the climatic parameters of the environment (temperature, humidity, wind pressure) and the heat-shielding characteristics of his clothes (in the cold season when a person is outdoors).

It is recommended that household heat receipts from one person be estimated from 90 to 160 W, depending on the type of activity [55].

The lower the ambient temperature, the more intense the heat transfer of a person. In this regard, we should expect that the heat generation of people on the street is increasing. To compensate for additional heat loss, a person uses warmer clothes. When on the street, the intensity of heat transfer from a person’s surface depends on the ambient temperature, humidity, wind intensity, thermal insulation properties of clothing, and the intensity of its movement along the street. The heat release of a person when he is outside the heated buildings in the cold season can be taken equal to the heat release of a person under difficult working conditions.

Let us estimate the total annual heat energy input from people in the city. Taking into account the factors discussed above, on average, per year, heat from one person will be taken equal to 150 W. The total number of residents, taking into account unregistered citizens and the temporary absence of registered citizens, we take equal to six million people. Then the total heat dissipation of people during the year will be 26 PJ.

When people are in the building, the heat release from people is added to the heat from the heating systems. The amount of heat release from people does not depend on the generation of thermal energy from heat sources. Therefore, when compiling the heat balance of a city, heat release from people should be considered as an addition to heat from other sources of thermal energy. Thus, heat release from people during the year makes up about one-sixth of the other heat generated.

3.5.8 Total thermal pollution of the St. Petersburg urban environment

The estimation of the St. Petersburg urban environment total thermal pollution is shown in Table 8.

Table 8. Total thermal pollution of the St. Petersburg urban environment

Source	Input in total thermal pollution, PJ

Heat consumption from non-electric district heating systems and non-electric local heating systems	220
Electric power consumption	120
Non-electric transport	220
Population (equal to six million people)	26
Total	**586**

Table 8 does not reflect all, but the most common sources of heat exposure associated with human activities. In the end, an important part of the warm water produced in the city. However, under the conditions of the existence of heat emissions, heat fluxes also propagate into the atmosphere. All these sources are sources of anthropogenic thermal pollution of the planet.

4 Conclusions

The objects of this research were St. Petersburg urban heat island and climate change in St. Petersburg from 1743 to 2018.

The research was aimed to identify the main sources of thermal pollution of the urban environment and to search for a possible connection between thermal pollution and climate change in the city.

Changes in the average annual outdoor temperature, as well as the temperature of the warm and cold periods of the year at different periods, are analyzed. The dynamics of climate change in St. Petersburg, as well as the main factors affecting the heat and heat releases in urban environments, are considered.

The results obtained allow us to draw the following conclusions:

1. For the period from 1743 to 2018 the climate of St. Petersburg has undergone significant changes.
2. In the period from 1743 to 1838, there was a downward trend in the temperature of the outside air, which by the middle of XIX had changed its monotony to increasing. Thus, an upward trend has persisted over the past 180 years. Moreover, in the past 25 years, the increase in outdoor temperature is the most intense.
3. The temperature increase is uneven over the periods of the year is the most intense temperature increase is observed in the cold period of the year (from October to April) and much less pronounced in the warm period of the year (from May to September).
4. The dynamics of changes in the outside temperature in St. Petersburg are affected by both global trends in climate change and local sources of thermal pollution of the urban environment, among which thermal and electric stations that generate heat and electricity, as well as transport.
5. Climate change on the planet has an impact on climate change in St. Petersburg. But the city itself is a major source of thermal pollution.
6. The contribution of St. Petersburg to the thermal pollution of the urban environment and the artificial sources of thermal pollution located on its territory can reach 586 PJ per year.

5 Acknowledgements

This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University.

References

1. Santamouris, M. Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. 207. Elsevier Ltd, 15-01-2020.
2. Zhou, D., Xiao, J., Bonafoni, S., Berger, C., Deilami, K., Zhou, Y., Frolking, S., Yao, R., Qiao, Z., Sobrino, J.A. Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives. 11(1). MDPI AG, 01-01-2019.

3. Giridharan, R., Emmanuel, R. The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. 40. Elsevier Ltd, 01-07-2018.
4. Kotharkar, R., Ramesh, A., Bagade, A. Urban Heat Island studies in South Asia: A critical review. 24. Elsevier B.V., 01-06-2018.
5. Parsaee, M., Joybari, M.M., Mirzaei, P.A., Haghighat, F. Urban heat island, urban climate maps and urban development policies and action plans. 14. Elsevier B.V., 01-05-2019.
6. Sun, R.H., Wang, Y.N., Chen, T.T. Impacts of anthropogenic heat emissions on urban thermal environment: A review. 37(12). Ecological Society of China, 2017.
7. Linnerud, K., Mideksa, T.K., Eskeland, G.S. The Impact of Climate Change on Nuclear Power Supply. The Energy Journal. 2011. 32(1). Pp. 149–168. DOI:10.5547/ISSN0195-6574-EJ-Vol32-No1-6. URL: http://www.iaee.org/en/publications/ejarticle.aspx?id=2411 (date of application: 3.05.2020).
8. Dowling, P. The impact of climate change on the European energy system. Energy Policy. 2013. 60. Pp. 406–417. DOI:10.1016/j.enpol.2013.05.093. URL: https://linkinghub.elsevier.com/retrieve/pii/S0301421513004485 (date of application: 3.05.2020).
9. Bartos, M.D., Chester, M. V. Impacts of climate change on electric power supply in the Western United States. Nature Climate Change. 2015. 5(8). Pp. 748–752. DOI:10.1038/nclimate2648. URL: http://www.nature.com/articles/nclimate2648 (date of application: 3.05.2020).
10. Bonjean Stanton, M.C., Dessai, S., Paavola, J. A systematic review of the impacts of climate variability and change on electricity systems in Europe. Energy. 2016. 109. Pp. 1148–1159. DOI:10.1016/j.energy.2016.05.015. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544216305679 (date of application: 3.05.2020).
11. Ke, X., Wu, D., Rice, J., Kintner-Meyer, M., Lu, N. Quantifying impacts of heat waves on power grid operation. Applied Energy. 2016. 183. Pp. 504–512. DOI:10.1016/j.apenergy.2016.08.188. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261916312971 (date of application: 3.05.2020).
12. Ouedraogo, N.S. Energy consumption and human development: Evidence from a panel cointegration and error correction model. Energy. 2013. 63. Pp. 28–41. DOI:10.1016/j.energy.2013.09.067. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544213008372 (date of application: 3.05.2020).
13. Khan, I., Alam, F., Alam, Q. The global climate change and its effect on power generation in Bangladesh. Energy Policy. 2013. 61. Pp. 1460–1470. DOI:10.1016/j.enpol.2013.05.005. URL: https://linkinghub.elsevier.com/retrieve/pii/S0301421513003376 (date of application: 3.05.2020).
14. Srinivasan, S., Kholod, N., Chaturvedi, V., Ghosh, P.P., Mathur, R., Clarke, L., Evans, M., Hejazi, M., Kanudia, A., Koti, P.N., Liu, B., Parikh, K.S., Ali, M.S., Sharma, K. Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. Applied Energy. 2018. 210. Pp. 673–684. DOI:10.1016/j.apenergy.2017.04.079. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261917304725 (date of application: 3.05.2020).
15. Klein, D.R., Olonscheck, M., Walther, C., Kropp, J.P. Susceptibility of the European electricity sector to climate change. Energy. 2013. 59. Pp. 183–193. DOI:10.1016/j.energy.2013.06.048. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544213005471 (date of application: 3.05.2020).
16. Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., Li, W. Urban heat island impacts on building energy consumption: A review of approaches and findings. 174. Elsevier Ltd, 01-05-2019.
17. Klimenko, V. V., Fedotova, E. V., Tereshin, A.G. Vulnerability of the Russian power industry

to the climate change. Energy. 2018. 142. Pp. 1010–1022. DOI:10.1016/j.energy.2017.10.069.
18. Zhun Min Adrian, C., Nyuk Hien, W., Marcel, I., Steve Kardinal, J. Predicting the envelope performance of commercial office buildings in Singapore. Energy and Buildings. 2013. 66. Pp. 66–76. DOI:10.1016/j.enbuild.2013.07.008. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378778813003964 (date of application: 18.05.2020).
19. Zadvinskaya, T.O., Gorshkov, A.S. Comprehensive method of energy efficiency of residential house. 953–9542014.
20. Gorshkov, A., Vatin, N., Nemova, D., Shabaldin, A., Melnikova, L., Kirill, P. Using life-cycle analysis to assess energy savings delivered by building insulation. Procedia Engineering. 117(1)2015. Pp. 1080–1089.
21. Gorshkov, A., Murgul, V., Oliynyk, O. Forecasted Payback Period in the Case of Energy-Efficient Activities. MATEC Web of Conferences. 532016.
22. Gorshkov, A.S., Vatin, N.I., Rymkevich, P.P., Kydrevich, O.O. Payback period of investments in energy saving. Magazine of Civil Engineering. 2018. 78(2). Pp. 65–75. DOI:10.18720/MCE.78.5.
23. Air temperature and precipitation by months and years: St. Petersburg (Russia). URL: http://www.pogodaiklimat.ru/history/26063.htm (date of application: 2.05.2020).
24. Baldina, E.A., Grishchenko, M.I. STUDY OF THE MOSCOW “HEAT ISLAND” ON SEASON-VARIATE PICTURES LANDSAT-7 / ETM +. Geoinformatika. 2011. (3). Pp. 62–69. URL: https://elibrary.ru/download/elibrary_16850102_51662576.pdf (date of application: 2.05.2020).
25. Labutina, I., Baldina, E., Grischenko, M., Khaybrakhmanov, T. Using satellite images for environmental and geochemical studies of urban area. Zemlia iz Kosmosia. 2012. (12). Pp. 50–55. URL: https://elibrary.ru/download/elibrary_17790255_22234322.pdf (date of application: 2.05.2020).
26. Varentsov, M.I., Konstantinov, P.I., Samsonov1, T.E., Repina, I.A. Investigation of the urban heat island phenomenon during polar night based on experimental measurements and remote sensing of Norilsk city. CURRENT PROBLEMS IN REMOTE SENSING OF THE EARTH FROM SPACE. 2014. Pp. 329–337. URL: http://d33.infospace.ru/d33_conf/sb2014t4/329–337.pdf (date of application: 2.05.2020).
27. Cai, G., Du, M., Xue, Y. Monitoring of urban heat island effect in Beijing combining ASTER and TM data. International Journal of Remote Sensing. 2011. 32(5). Pp. 1213–1232. DOI:10.1080/01431160903469079.
28. Gornyy, V.I., Lyalko, V.I., Kritsuk, S.G., Latypov, I.S., Tronin, A.A., Filippovich, V.E., Stankevich, S.A., Brovkina, O.V., Kiselev, A.V., Davidan, T.A., Lubskii, N.S., Krylova, A.B. Forecast of Saint-Petersburg and Kiev thermal replies on climate change (on the basis of EOS and Landsat satellite imagery). CURRENT PROBLEMS IN REMOTE SENSING OF THE EARTH FROM SPACE. 2016. 13(2). Pp. 176–191. DOI:10.21046/2070-7401-2016-13-2-176-191. URL: http://d33.infospace.ru/d33_conf/sb2016t2/176-191.pdf (date of application: 2.05.2020).
29. Tronin, A.A., Gornyy, V. Long-term remote observations of land surface temperature of the North-Western region of Russia. CURRENT PROBLEMS IN REMOTE SENSING OF THE EARTH FROM SPACE. 2017. 14(6). Pp. 73–96. DOI:10.21046/2070-7401-2017-14-6-73-96. URL: https://www.researchgate.net/publication/322927660_Long-term_remote_observations_of_land_surface_temperature_of_the_North-Western_region_of_Russia.
30. Kritsuk, S.G., Gornyy, V.I., Latypov, I.S., Pavlovskii, A.A., Tronin, A.A. Satellite risk mapping of urban surface overheating (by the example of Saint Petersburg). CURRENT PROBLEMS IN REMOTE SENSING OF THE EARTH FROM SPACE. 2019. 16(5). Pp. 34–44. DOI:10.21046/2070-7401-2019-16-5-34-44. URL: http://d33.infospace.ru/d33_conf/sb2019t5/34-44.pdf (date of application: 17.05.2020).
31. Tskhovrebov, V.S., Faizova, V.I. Soil and Climate Stavropol Region. Agricultural Bulletin of Stavropol Region. 2015. (S2). Pp. 21–34. URL: https://elibrary.ru/download/elibrary_23417068_98820016.pdf (date of application:

2.05.2020).

32. Prokofyeva, T. V., Martynenko, I.A., Ivannikov, F.A. Classification of Moscow soils and parent materials and its possible inclusion in the classification system of Russian soils. Eurasian Soil Science. 2011. 44(5). Pp. 561–571. DOI:10.1134/S1064229311050127.
33. Filatov, N.N., Nazarova, L.E., Georgiev, A.P., Semenov, A.V., Antciferova, A.R., Ozhigina, V.V., Bogdan, M.I. Changes and Variability of Climate in the European Part of the Russian North and Their Effect on Water Facilities. Arctic: ecology and economy. 2012. 6(2). Pp. 80–93. URL: http://arctica-ac.ru/docs/journals/6/izmeneniya-i-izmenchivost-klimata-evropeyskogo-severa-rossii-i-ih-vliyanie-na-vo.pdf (date of application: 17.05.2020).
34. Kovyazin, V.F. Biologicheskie osnovy formirovaniia ustoichivykh ekosistem I ratcionalnogo ispolzovaniia pochvenno-rastitelnykh resursov megapolisov (na primere Sankt-Peterburga) [Biological basis for the formation of sustainable ecosystems and the rational use of soil a. Agrophysical Research Institute. Saint Petersburg, 2008.
35. Allegrini, J., Dorer, V., Carmeliet, J. Analysis of convective heat transfer at building façades in street canyons and its influence on the predictions of space cooling demand in buildings. Journal of Wind Engineering and Industrial Aerodynamics. 2012. 104–106. Pp. 464–473. DOI:10.1016/j.jweia.2012.02.003. URL: https://linkinghub.elsevier.com/retrieve/pii/S0167610512000207 (date of application: 18.05.2020).
36. Korniyenko, S.V., Vatin, N.I., Petritchenko, M.R., Gorshkov, A.S. Evaluation of Hygrothermal Performance of Multilayered Wall Design in Annual Cycle. Construction of Unique Buildings and Structures. 2015. 33(6). Pp. 19–33. DOI:10.18720/CUBS.33.2. URL: https://unistroy.spbstu.ru/userfiles/files/2015/6(33)/2_korniyenko_33.pdf (date of application: 3.05.2020).
37. Korniyenko, S.V., Vatin, N.I., Gorshkov, A.S. Assessment of moisture conditions of walls with façade's thermoinsulation composite systems with external mortar layers. Construction of Unique Buildings and Structures. 2016. 45(6). Pp. 34–54. DOI:10.18720/CUBS.45.2. URL: https://unistroy.spbstu.ru/userfiles/files/2016/6(45)/2_kornienko_45.pdf (date of application: 3.05.2020).
38. Zimin, Z.S., Orlovich, R.B., Gorshkov, A.S. Application of stones of high voidage in the facing layer of the multilayer walls. Magazine of Civil Engineering. 2013. 43(8). DOI:10.5862/MCE.43.3.
39. Vatin, N., Gorshkov, A., Nemova, D., Gamayunova, O., Tarasova, D. Humidity conditions of homogeneous wall from gas-concrete blocks with finishing plaster compounds. 670–6712014.
40. Gorshkov, A.S., Rymkevich, P.P., Vatin, N.I. Simulation of non-stationary heat transfer processes in autoclaved aerated concrete-walls. Magazine of Civil Engineering. 2014. 52(8). DOI:10.5862/MCE.52.5.
41. Gorshkov, A.S., Rymkevich, P.P. A diagram method of describing the process of non-stationary heat transfer. Magazine of Civil Engineering. 2015. 60(8). Pp. 68–82. DOI:10.5862/MCE.60.8.
42. Korniyenko, S.V., Vatin, N.I., Gorshkov, A.S. Thermophysical field testing of residential buildings made of autoclaved aerated concrete blocks. Magazine of Civil Engineering. 2016. 64(4). Pp. 10–25. DOI:10.5862/MCE.64.2.
43. Gorshkov, A.S., Vatin, N.I., Urustimov, A.I., Rymkevich, P.P. Calculation method for substantiating technological measures for prevent the formation of ice dams on roofs of buildings with pitched roof. Magazine of Civil Engineering. 2012. 29(3). Pp. 69–73. DOI:10.5862/MCE.29.9. URL: https://engstroy.spbstu.ru/userfiles/files/2012/3(29)/10.pdf (date of application: 17.05.2020).
44. Furgal, C., Seguin, J. Climate change, health, and vulnerability in Canadian northern Aboriginal communities. Environmental Health Perspectives. 2006. 114(12). Pp. 1964–1970. DOI:10.1289/ehp.8433.
45. Ford, J.D., Willox, A.C., Chatwood, S., Furgal, C., Harper, S., Mauro, I., Pearce, T. Adapting to the effects of climate change on inuit health. 104(SUPPL. 3). American Public Health Association Inc., 2014.

46. Sleptsov, A.M., Klimenko, V.V. OBOBSHCHENIYe PALEOKLIMATICHESKIKH DANNYKH I REKONSTRUKTSIYA KLIMATA VOSTOCHNOY YEVROPY ZA POSLEDNIYe 2000 LET [GENERALIZATION OF PALEOCLIMATIC DATA AND RECONSTRUCTION OF CLIMATE OF EASTERN EUROPE FOR THE LAST 2000 YEARS]. ISTORIYA I SOVREMENNOST'. 2005. 118(1). Pp. 135. URL: https://elibrary.ru/download/elibrary_18059935_78499429.pdf (date of application: 3.05.2020).
47. Buchinskii, I.E. O klimate proshlogo Russkoi ravniny [On the climate of the past of the Russian Plain]. Gidrometeoizdat. Leningrad, 1957.
48. RMD 23-16-2019 St. Petersburg Recommendations for ensuring the energy efficiency of residential and public buildingsSt .Petersburg, 2012.
49. Roshefor, N.I. Illiustrirovannoe urochnoe polozhenie [Illustrated Building Guide]Saint Petersburg, 1906.
50. About St. Petersburg. URL: https://tatspb.tatarstan.ru/o-sankt-peterburge.htm (date of application: 18.05.2020).
51. Petersburg in numbers - Administration of St. Petersburg. URL: https://www.gov.spb.ru/helper/day/ (date of application: 18.05.2020).
52. Northwest Region Actual Weather Map. URL: http://www.meteo.nw.ru/weather/lo_meteod.php (date of application: 18.05.2020).
53. St. Petersburg: Encyclopedia. Russian political encyclopedia. Moskow, 2006.
54. Heat supply scheme for the period until 2033 - Administration of St. Petersburg. URL: https://www.gov.spb.ru/gov/otrasl/ingen/shemy-razvitiya-inzhenerno-energeticheskogo-kompleksa/aktualizaciya-shemy-teplosnabzheniya-na-2019-god/ (date of application: 18.05.2020).
55. Russian Building Code SP 131.13330.2012 Building climatology2012.
56. Russsian State Standard GOST 30494-2011 “Residential and public buildings. Microclimate parameters for indoor enclosures.”
57. Russsian State Standard GOST 12.1.005-88 “Occupational safety standards system. General sanitary requirements for working zone air.”
58. On approval of the scheme and program for the prospective development of the electric power industry of St. Petersburg for 2020-2024, Resolution of the Governor of St. Petersburg dated April 30, 2020 No. 39-PG2020.
59. 10 constituent entities of the Russian Federation have a fleet of more than 1 million cars. . 31-03-2020URL: https://www.autostat.ru/news/43449/ (date of application: 26.06.2020).