Soil temperature response to modern climate change at four sites of different latitude in the European part of Russia

O V Reshotkin* and O I Khudyakov

Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences, Pushchino 142290, Russian Federation

*E-mail: reshotkin@rambler.ru

Abstract. Soil temperature is a sensitive climate indicator. In this paper, we used data from weather stations located in various natural zones of the European part of Russia to demonstrate how the soil temperature responded to modern climate change. The most intensive warming is observed at the beginning of the 21st century. The average annual air temperature for the period 2001–2015 increased compared to the period 1961–1990 by 1.2–1.4°C. The average annual soil temperature has increased in all studied soils and at all depths by 0.5–1.0°C. Soil warming is observed in both warm and cold periods of the year. However, soil temperatures have changed differently in different seasons of the year. The increase in air and soil temperature leads to a shift of the soil-climatic zones to the north.

1. Introduction

Global climate change is one of the main challenges of the 21st century which has been widely discussed in the recent decades. Global warming is observed from the second half of the 1970s. Climate in Russia is more sensitive to global warming than that of many other regions of the world. The average warming rate for the Earth and the land of the Northern Hemisphere is 0.166 and 0.328°C/decade, respectively. For the whole of Russia, the average rate was 0.43°C/decade for the period 1976–2012 [1].

The soil temperature is an important indicator of a climate change [2, 3]. It has been demonstrated that soil temperature trends are more stable and unbiased than air temperature trends for the assessment of the global warming effect [4]. The soil temperature reacts to the climate change in a complex way. Changes in air temperature, precipitation and snow depth affect the soil temperature in a combined way [5].

The recent papers display a trend towards soil temperature increase in different parts of the world [6–9] including the territory of Russia [10–12]. Meanwhile there are regional differences in temperature increase. For instance, in China soil temperature increase at all depths was more intense in the colder northern and western regions while it was quite negligible in the warmer southern and eastern regions [8]. In the whole of Canada, air temperature and soil temperature at a depth of 20 cm increased by 1.0°C and 0.6°C, respectively, meanwhile the regional differences observed are attributed to the different changes of seasonal air temperatures, precipitation and snow depth [9].

The goal of this work was to analyze the long-term trends, yearly and seasonal cycles of precipitation, air and soil temperature data for different regions and soil types of the European part of Russia, and to compare the dynamics of soil temperature to the modern climate change.
2. Objects and methods

In this work, we used observation data of air and soil temperature, precipitation, and snow cover at four weather stations of the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) network. In Russia and the former USSR, soil temperature at weather stations is measured at standard depths of 20, 40, 80, 160 and 320 cm according to a unified method using mercury thermometers at the plots of virgin soil, preserved vegetation cover and snow cover in winter.

Four soil types from several natural zones of the European part of Russia were studied: Gleyic Podzol, Umbric Albeluvisol, Albic Luvisol and Calcic Chernozem (table 1). The climatic conditions of soil formation are characterized by observational data at weather stations Mezen (Arkhangelsk region), Totma (Vologda region), Elatma (Ryazan region) and Gigant (Rostov region), respectively, located in the north, center and south of the East European Plain. Weather stations are located at approximately the same longitude, but at different latitudes. The choice of weather stations was based on the availability of the most complete series of systematic observations and the location of weather stations outside large cities to reduce the impact of urbanization.

Information on the precipitation, snow depth, air and soil temperatures was obtained from the former USSR monthly meteorological bulletin [13], and from the website of the Russian Research Institute of Hydrometeorological Information – World Data Center (RIHMI – WDC) [14].

To analyze the response of soil temperature to modern climate change, we compared the soil temperature (mean annual, monthly, seasonal, warm/cold period values) averaged over the period 2001–2015 with the average values over the period 1961–1990. A similar comparison was made for air temperature, precipitation, and snow cover to determine how the climatic conditions in the study area changed. The period 1961–1990 was recommended by the World Meteorological Organization (WMO) as the climatic norm (CN) for meteorological parameters, and it is used as a standard baseline period for long-term assessments of climate change [15]. In this work, the climatic norms of precipitation, snow depth, air and soil temperature are considered as quantitative characteristics of the climatic conditions of soil formation and as quantitative criteria regarding to which changes in the conditions of soil formation under modern warming are characterized.

To assess the rate of the changes, the linear trends of the average annual temperature of air and soil at standard depths for the period 1966–2015 were calculated for all four stations.

3. Results and discussion

3.1. Air temperature

The average annual air temperature for the period 1961–1990 (taken as climatic norm, CN) in Mezen is negative (-0.8°C). In Totma, Elatma and Gigant, it is positive and amounts to 1.9, 4.3 and 9.8°C, respectively. Over the entire period of observations, the dynamics of air temperature is oscillatory in
nature with alternating periods of cooling and warming with an overall stable tendency to the temperature increase (figure 1). In the modern period, the growing trend in air temperature has markedly increased its rate.

**Figure 1.** The time series of annual average air temperature at (a) Mezen, (b) Totma, (c) Elatma, (d) Gigant weather stations. Dotted lines – average temperature of 1961–1990 period (climatic norm). Blue lines – 11-year moving average. Red lines are linear regression trends.

The average values of mean annual air temperatures for each 10-year period show that since the 1970s each subsequent decade was warmer than the previous in Mezen, Totma, and Elatma. Since the 1980s the ten-year average annual air temperature began to exceed CN and reached its maximum values in 2011–2018. In Mezen, the air temperature became positive. In Gigant, the growth of the ten-year average annual air temperature started a decade later, and it stopped in the current decade, with the average annual air temperature staying at the level of 2001–2010. Linear trends of the average annual air temperature increase for the period 1966–2015 were 0.46°C/decade in Mezen and Totma, 0.41°C/decade in Elatma, and 0.33°C/decade in Gigant. The rate of warming tends to decrease in the European part of Russia from north to south.

The beginning of the 21st century was the warmest over the entire observation period. The average annual air temperature in 2001–2015 compared to 1961–1990 increased by 1.4°C in Totma, by 1.3°C in Mezen and Elatma, and by 1.2°C in Gigant. Air temperature increased unequally in different seasons of the year. The largest increases in air temperature are observed in the winter season in Mezen, Totma and Elatma (by 1.7–1.9°C), and in the summer season in Gigant (by 1.6°C).

In the cold season, the average sum of air temperatures below 0°C for the period 1961–1990 was -1856°C in Mezen, -1428°C in Totma, -1115°C in Elatma, and -411°C in Gigant. In 2001–2015 the sum of air temperatures below 0°C decreased compared to 1961–1990 by 292, 251, 226 and 98°C, respectively, and the duration of the period with an average daily air temperature below 0°C decreased by 17, 14, 15 and 16 days, respectively. This indicates a general trend of warming of the cold season in the study area.

A similar trend of warming is observed in the warm season. The average sum of air temperatures above 0°C for the period 1961–1990 was 1544°C in Mezen, 2152°C in Totma, 2699°C in Elatma, and 4011°C in Gigant. During 2001–2015 the sum of air temperatures above 0°C increased by 220, 257, 266 and 363°C, respectively. The average sum of effective air temperatures above 10°C for the period 1961-1990 was 1007°C in Mezen, 1658°C in Totma, 2282°C in Elatma, and 3555°C in Gigant. In 2001-2015 the sum of air temperatures above 10°C increased by 190, 281, 279 and 301°C, respectively, while the duration of the period with an average daily air temperature above 10°C increased by 13, 16, 13 and 6 days, respectively.
3.2. Precipitation and snow cover

Average annual precipitation for the period 1961–1990 was 497 mm in Mezen, 632 mm in Totma, 621 mm in Elatma, and 505 mm in Gigant. Trends in annual precipitation are not as straightforward as trends in air temperature. Average annual precipitation in 2001–2015 compared to 1961–1990 increased in Mezen and Elatma by 67 and 22 mm, respectively, while it decreased slightly in Totma and Gigant by 7 and 3 mm, respectively. Precipitation increased unequally in the warm and cold periods of the year and in different seasons. In Mezen, precipitation increased both in the warm and cold periods of the year, and the main increase (76% of the annual growth) occurred in the warm period. Precipitation raised in all seasons, especially in the summer season. In Totma, an increase in precipitation is observed in the cold period, and a decrease in precipitation in the warm period. In Elatma, precipitation increased in all seasons except summer, and the cold season accounts for 70% of the annual growth in precipitation. In Gigant, a decrease in precipitation was observed in the winter and especially in the summer season, and an increase in precipitation was observed in the autumn season. In the spring season, precipitation changed slightly.

Trends in snow cover depth are as ambiguous as precipitation trends. The highest average monthly snow depth for the period 1961–1990 was 49 cm in Mezen, 47 cm in Totma, 29 cm in Elatma, and 6 cm in Gigant. In 2001–2015 compared to 1961–1990 average monthly snow depth in Mezen increased by 2–5 cm in February – April, and it decreased by 2–8 cm in the remaining months with snow cover. In Totma, the snow depth increased by 3–5 cm. In Elatma, the snow depth increased by 3–9 cm in all months except November and December. In these two months, it almost did not change. In Gigant, snow depth decreased by 1–2 cm during all months.

3.3. Soil temperature

Average annual soil temperature for the period 1961–1990 (CN) in Mezen (Gleyic Podzol) was 3.0°C at depths of 20 and 80 cm, 2.9°C at 160 cm, and 2.7°C at 320 cm. In Totma (Umbric Albeluvisol), the average annual soil temperature was 5.6°C at depths of 20 and 40 cm, 5.7°C at 80 cm, and 5.8°C at 160 cm. In Elatma (Albic Luvisol), the average annual soil temperature was 6.9°C at a depth of 40 cm, and 7.0°C at all other depths. In Gigant (Calcic Chernozem), the average annual soil temperature was 11.6°C at depths of 20, 40, 80 and 160 cm, and 11.7°C at 320 cm.

Figure 2. The time series of annual average soil temperature at the depth of 160 cm at (a) Mezen (Gleyic Podzol), (b) Totma (Umbric Albeluvisol), (c) Elatma (Albic Luvisol), (d) Gigant (Calcic Chernozem) weather stations. Dotted lines are linear regression trends.

The time series of average annual soil temperature demonstrate a pronounced tendency for increase (figure 2). Linear trends of average annual soil temperature for the period 1966–2015 in all studied locations and at all depths were positive. At a depth of 20 cm, linear trend in Mezen was 0.29°C/decade,
in Totma 0.26°C/decade, in Elatma 0.21°C/decade, and in Gigant 0.23°C/decade. At a depth of 160 cm, linear trend in Mezen was 0.27°C/decade, in Totma 0.21°C/decade, in Elatma 0.15°C/decade, and in Gigant 0.16°C/decade.

Average annual soil temperature for the period 2001–2015 increased compared to 1961–1990 in all locations. The highest increase was observed in Mezen, and the lowest one in Gigant. Generally, there is a tendency of decrease of soil warming in the direction from north to south, similar to the change in air temperature. In Mezen, the average annual soil temperature increased at all depths by 0.8–1.0°C, and in the other locations by 0.5–0.8°C.

Soil temperature increased in all seasons (figure 3). Meanwhile, in different seasons of the year, soil temperature changed unequally and not always in the same direction as air temperature. In Mezen, the most noticeable warming is observed in the summer and autumn seasons, when the temperature increased over the entire soil profile by 1.1–1.4°C. In the spring season, the soil temperature increased by less than 0.3–0.6°C. In the winter season, the soil temperature increased very unevenly along the soil profile ranging from 0.3°C at a depth of 20 cm to 1.2°C by 320 cm. On the contrary, the air temperature in Mezen increased most in the winter season, and generally in the cold season, but it changed less in the summer season. The response of Gleyic Podzol soil in Mezen to an increase in average air temperature varies significantly in the warm and cold periods of the year, when the soil is in a different state (frozen/unfrozen). A slight increase in soil temperature in the cold season at depths of 20–160 cm responding to a significant increase in average air temperature is probably due to the properties of the snow cover and the soil itself. A more significant increase in temperature at a depth of 320 cm is due to the fact that the thermal wave of the warm season reaches this depth. A similar response is observed in Umbric Albeluvisol of Totma station.

![Figure 3](image-url)

**Figure 3.** Soil temperature profiles in different seasons at (a) Mezen (Gleyic Podzol), (b) Gigant (Calcic Chernozem) weather stations.

In Elatma, soil temperature increased more significantly during the cold season, in the same way as air temperature. An increase in the temperature of Elatma Albic Luvisol during the cold season can result from an increase in the snow cover depth, together with an increase in air temperature. In Gigant,
the soil temperature at a depth of 20 cm increased by 0.9–1.0°C in the autumn and winter seasons, and by 0.4–0.5°C in the summer and spring seasons, while the air temperature increased most in the summer season. At other depths, soil temperature in Gigant increased more evenly over the seasons. Increase in average air temperature for the period 2001–2015 together with the unchanged or decreased (in the summer season) precipitation result in aridization of the climate and the formation of soil droughts in Calcic Chernozem during the vegetation period.

The sum of soil temperatures above 0°C at a depth of 20 cm for the period 1961–1990 was 1277°C in Mezen, 2095°C in Totma, 2640°C in Elatma, and 4288°C in Gigant. For the period 2001–2015 it increased by 267, 264, 253, and 274°C, respectively, which indicates an increase in the amount of heat in the soil. The sum of soil temperatures below 0°C at a depth of 20 cm for the period 1961–1990 was -165°C in Mezen, -53°C in Totma, -43°C in Elatma, and -35°C in Gigant. During the period 2001-2015 it decreased by 34°C in Mezen, Totma and Elatma, and by 20°C in Gigant, which, in turn, indicates a decrease in the amount of cold in soils.

For the period 1961–1990 the sum of effective soil temperatures above 10°C at a depth of 20 cm was 583, 1586, 2142, and 3807°C in Mezen, Totma, Elatma and Gigant, respectively. For the period 2001-2015 the sum of soil temperatures above 10°C at a depth of 20 cm increased by 250, 258, 176, and 163°C, respectively. Temperature above 10°C penetrates the soil on average to a depth of 61 cm in Mezen. In 2001–2015 the depth of penetration into the soil of the 10°C isotherm increased to 108 cm, which is 47 cm deeper than in the 1961–1990 period (figure 4). At Albic Luvisol of Elatma the penetration depth of the 10°C isotherm was 295 cm the 1950s (figure 5). In the subsequent decades, it increased, and temperatures above 10°C began to penetrate the soil to a depth below 320 cm, meaning that the thickness of the soil stratum with effective temperatures increased.

Figure 4. Yearly average soil temperature profiles during 1961–1990 and 2001–2015 period at (a) Mezen (Gleyic Podzol), (b) Gigant (Calcic Chernozem) weather stations.

Figure 5 shows the time series of soil temperature in Elatma Albic Luvisol over the past six decades, starting with the 1950s. As one can see from the time series, the depth of the penetration of the zero isotherm the soil for the first three decades was 40–52 cm, when it gradually decreased, and beginning from the 1980s the zero isotherm is not observed in the soil at a depth of 20 cm and below. This indicates a significant decrease in the freezing depth of Albic Luvisol during the study period. Deeper freezing of Albic Luvisol in the 1950s–1970s was accompanied by the accumulation of ice. In the spring, frozen moisture compensated for the deficit of spring precipitation. In the modern period, the depth of seasonal freezing of Albic Luvisol is less than 20 cm, and in some years the soil practically does not freeze. In the spring, soil moisture is lost due to physical evaporation, which results in spring drought in the soil.
Figure 5. Average monthly sums of air temperatures (top panel), snow depth (middle panel) and yearly average soil temperature profile (bottom panel) per decade at Elatma weather station.

In Gleyic Podzol of Mezen the temperature penetration depth of 0°C was 84 cm during 2001–2015, which is 38 cm less than in the period 1961–1990. In Calcic Chernozem of Gigant station, the average depth of 0°C temperature penetration was 21 cm for the period 1961–1990. In 2001–2015 the isotherm of 0°C was not observed in the soil at a depth of 20 cm and below.

Thus, our analysis of meteorological data shows that in the modern period in European Russia the climatic conditions of soil formation are changing, which is reflected in the temperature regime of soils changing at a higher rate under the influence of climate than other more inert soil properties [11].

4. Conclusions
Using data from four weather stations, we assessed temperature changes in various soils in the European Russia responding the modern climate change. We have shown that during the last decades, a steady trend towards warming is observed, with its rate decreasing from north to south. The average annual air temperature for the period 2001–2015 increased by 1.2–1.4°C compared to the period 1961–1990. Precipitation and snow depth changes have different trend directions. The average soil temperature at 20 cm increased by 0.7–0.9°C, and at 160 cm by 0.5–0.8°C. Soil warming is observed throughout the soil profile both in warm and cold periods of the year. During the warm season, it is characterized by an increase in the sum of soil temperatures above 0°C by 253–274°C, by the extended growing season, by an increase in the sum of soil temperatures above 10°C by 163–258°C and the depth of their penetration the soil. During the cold period, there is a decrease in the sum of negative soil temperatures by 20–34°C, a decrease in the seasonal freezing depth and the freezing period. The results of our study can be used
to assess and forecast changes in soil temperatures, to organize monitoring, and to study current and expected changes of soil climate, conditions of cultivating crops, and for other goals.

Acknowledgements
The work was carried out within the framework of the State Assignment No. 0191-2019-0046.

References
[1] Second Roshydromet assessment report on climate change and its consequences in the Russian Federation 2014 (Moscow: Roshydromet) p 1009 (in Russian)
[2] Chendev Y G, Petin A N, Lupo A R 2012 Soils as indicators of climatic changes Geogr. Environ. Sustain. 5 (1) 4–17
[3] Fang X, Luo S and Lyu S 2019 Observed soil temperature trends associated with climate change in the Tibetan Plateau, 1960–2014 Theor. Appl. Climatol. 135 169–81
[4] Gilichinsky D A, Bykhovets S S, Sorokovikov V A, Fedorov-Davydov D G, Barry R G, Zhang T, Gavrilova M K and Alexeeva O I 2000 Use of the data of hydrometeorological survey for century history of soil temperature trends in the seasonally frozen and permafrost areas of Russia Earth’s Cryosphere 4 (3) 59–66 (in Russian)
[5] Zhang T, Barry R G, Gilichinsky D A, Bykhovets S S, Sorokovikov V A and Ye J 2001 An amplified signal of climatic change in soil temperatures during the last century at Irkutsk, Russia Clim. Change 49 41–76
[6] Knight J H, Minasny B, McBratney A B, Koen T B and Murphy B W 2018 Soil temperature increase in eastern Australia for the past 50 years Geoderma 313 241–49
[7] Yeşilirmak E 2014 Soil temperature trends in Büyük Menderes Basin, Turkey Meteorol. Appl. 21 859–66
[8] Zhang H, Wang E, Zhou D, Luo Z and Zhang Z 2016 Rising soil temperature in China and its potential ecological impact Sci. Rep. 6 35530
[9] Zhang Y, Chen W, Smith S L, Riseborough D W and Cihlar J 2005 Soil temperature in Canada during the twentieth century: Complex responses to atmospheric climate change J. Geophys. Res. 110 D03112
[10] Khudyakov O I and Reshotkin O V 2014 Temperature dynamics in sandy and loamy forest-tundra soils of the Polar Urals in relation to climate change Eurasian Soil Sci. 47 (12) 1245–58
[11] Kudeyarov V N, Demkin V A, Gilichinskii D A, Goryachkin S V and Rozhkov V A 2009 Global climate changes and the soil cover Eurasian Soil Sci. 42 (9) 953–66
[12] Streletskiy D A, Sherstikuok V A, Frauenfeld O W and Nelson F E 2015 Changes in the 1963–2013 shallow ground thermal regime in Russian permafrost regions Environ. Res. Lett. 10 125005
[13] Meteorological monthly of the USSR 1961–1990 (in Russian)
[14] http://www.meteo.ru (accessed 11.04.2019)
[15] WMO Guidelines on the calculation of climate normals 2017 (Geneva: WMO) p 18