GROUND TEMPERATURE VARIABILITY IN POZNAŃ (2011–2020)

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Abstract: The manuscript concerns the analysis of the ground temperature in Poznań in the years 2011–2020. Data generally available on the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) website were used. The ground temperature was measured at five depths: 5 cm, 10 cm, 20 cm, 50 cm and 100 cm. The highest variability of ground temperature occurred in summer and the lowest in winter. The ground temperature was closely correlated mainly with air temperature, but also with insolation and water vapour deficit. There is a statistical increase in the air temperature in Poznań – the trends at the whole soil profile are positive although not statistically significant.

Keywords: ground temperature, agroclimatology, correlation, Poznań, Poland

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Introduction

The thermal regime of soils is determined by mass and energy exchange between land and atmosphere (Zhang et al. 2001). The course of ground temperature depends on a number of meteorological factors. It is primarily determined by the amount of heat reaching the Earth's surface. It is also largely shaped by air temperature, cloudiness, atmospheric precipitation, evaporation volume, snow cover, albedo and vegetation cover. Soil temperature is also affected by the moisture and thermal properties of the ground (Araźny 2001). Soil temperature changes may lead to alterations in land and hydrological conditions, thawing of permafrost, changes in the distribution of vegetation, acceleration of organic carbon decomposition in the soil and an increase in CO_2 release from the soil to the atmosphere (Zhang et al. 2005), as well as affect seed germination, fertiliser efficiency, plant growth and insect and disease emergence (Jacobs et al. 2011).

Research concerning ground temperature and its relationship with other factors is a subject of publications analysing soils in open areas and areas covered with vegetation, as well as on permafrost. Usowicz and Rejman (2000) determined temperature variability in the near-surface layer of silt soil on a loess slope, and Michalska and Nidzgorska-Lencewicz (2010) in overgrown soil. Further, Nieróbca (2005) compared soil temperature in bare fallow and under lawn. Kossowski (2005, 2007) analysed the relationship of daily amplitudes of soil temperatures in the near-surface layer with amplitudes of air temperatures and other meteorological elements. The variability of ground temperature on the Polish coast was analysed by Jakusik and Owczarek (2008). Ciaranek (2013) described the effect of weather conditions on the course of soil temperatures, pointing to

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its dependencies on air temperature, insolation, state of the ground and persisting snow cover. Wojkowski and Skowera (2017) described the relationship of the temperature of active soil surface with air temperature in the conditions of a Jurassic river valley. Publications by Szyga-Pluta (2018) described the specificity of annual and daily variability of ground temperature in a forest clearing in the Wielkopolski National Park. The study of differences between soil temperatures of grass-covered and bare soil conducted by Bryś (2004, 2008) permitted identification of the buffering role of the vegetation factor relative to the ongoing climatic changes. A strong correlation between solar radiation and soil temperature was found by Bednorz and Kolendowicz (2010) based on research made in the chosen ecosystems within the Słowiński National Park. Examples of publications concerning the thermal regime of the ground in polar areas are papers by Miętus and Filipiak (2001), as well as Pokladníková et al. (2008) and Przybylak et al. (2010). Zhang et al. (2005) analysed the changes in soil temperature in Canada. Another example is the research made by Hu and Feng (2003) concerning the differentiation of the soil climatology in the United States. The study of Plauborg (2002) presents empirical and simple models for soil temperature at 10 cm depth in grass-covered soils. Research on the influence of selected meteorological elements shaping the temperature of the soil, including bare soil and under various crops, was carried out, among others, by Koźmiński (1983), Bryś (2004, 2008), Michalska and Nidzgorska-Lencewicz (2010), Kossowski (2005, 2007) and Ciaranek (2013).

The soil heat regime is primarily regulated by the radiation balance, exposition, water and air content in the soil, soil type and soil cover. These elements influence changes in heat flow in the soil, inhibiting or causing an increase in its intensity. The ground cover with vegetation or snow cover in winter has a huge impact on the thermal conditions of the soil; it is an obstacle in the absorption of solar radiation energy and inhibits heat transfer by the soil. Rainfall is capable of either increasing or decreasing soil temperatures depending upon the temperature of the rain in comparison with the soil. It is also capable of transporting heat as it percolates down through the soil (Oke 1987). Rainfall or soil moisture plays an important role in soil temperature in that an increase in soil moisture results in an increase in evaporation rate, which absorbs energy from the surrounding soil, creating a soil temperature decrease despite air temperature increases (Garcia-Suarez, Butler 2006). This effect is called the soil moisture feedback mechanism (Zhang et al. 2001). Low soil moisture supply and high atmospheric water demand (vapour pressure deficit) are considered as the two main drivers of dryness stress on vegetation, which can cause large threats to agricultural production and drive widespread tree mortality (Allen et al. 2010).

Although affected by atmospheric circulations, variations in soil temperature result primarily from the radiation and sensible and latent heat exchanges at the surface and heat transfer in the soils of different thermal properties. Thus, soil temperature and its variation at various depths are unique parameters that provide useful insights into the understanding of both the surface energy processes and regional environmental and climatic conditions (Hu, Feng 2003). Yet, despite the importance, long-term quality data on soil temperatures are not available for many places.

This paper aims at the determination of the variability and course of ground temperature at various depths in Poznań in the years 2011–2020. The research was supplemented with the analysis of dependency between the variability of the ground temperature course and chosen meteorological elements.

Material and methods

Ground temperature measurements, the results of which were used in this research, were performed in an airport meteorological station of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Poznań-Ławica (52°25'16"N, 16°49'35"E). The station is located in the western part of the city of Poznań and the eastern part of Poznań Lakeland. It is located approximately 7 km from the city centre at an altitude of 94 m a.s.l. Data, verified in terms of quality, generally available on the IMGW-PIB website, were used.

The ground temperature was measured at five depths: 5 cm, 10 cm, 20 cm, 50 cm and 100 cm. The measurements were on a plot with no vegetation on light sandy loam soil. Available measurements of ground temperature, i.e., in the period 2011–2020, were conducted in terms of climatological observations at 6:00, 12:00 and 18:00 UTC at the depth of 10 cm, 20 cm and 50 cm, and once a day at 00:00 UTC at a depth of 5 cm. A measurement at a depth of 100 cm was performed, also once a day at 12:00 UTC.

In the next step, mean values of ground temperature were determined for the annual, seasonal, monthly and daily scale. The chart of the ground temperature on the base of mean daily values was made to show the temporal changes. Temperature gradients were calculated for mean annual values. The thermal gradient in individual soil layers was calculated as the temperature difference at the deeper and shallower levels, e.g., in the layer from 5 cm to 10 cm, using the following formula:

$$TG = (T_{10} - T_5) / (H_{10} - H_5)$$

where T_{10} represents the air temperature at the depth of 10 cm, T_5 the air temperature at the depth of 5 cm; H_{10} the depth of 10 cm; and H_5 the depth of 5 cm.

Based on the above data, the start and end dates and the length of the periods with assumed soil temperature threshold values were designated. Next, the sum of the soil temperatures above the thresholds at various depths was calculated. In order to meet the needs of agricultural practice, the following threshold values of soil temperature were adopted (Koźmiński, Michalska 1979):

- >0°C – to determine the beginning of the thawing period,
- >2.5°C – to determine the agriculture period,
- >5°C – to determine the growing season,
- >6°C – for plants with relatively low thermal requirements,
- >8°C – for plants with average thermal requirements,
- >10°C – for plants with high thermal requirements,
- >12°C – for plants for thermophilic plants,
- >15°C – to determine the period of intense plant growth and development.

In addition, measurements of air temperature, precipitation, relative humidity, snow cover thickness and water vapour pressure as well as the observations of cloud cover in climatological terms were considered. As a supplement to the analysis, the Pearson correlation coefficients – of soil temperature and air temperature (2 m a.g.l.), cloudiness, precipitation, snow cover, insolation, relative humidity and vapour pressure deficit – were calculated. The result was confirmed with a correlation significance test.

Finally, the daily averages and absolute maximum and minimum values of ground temperature were determined at particular depths in three observation terms – 06:00, 12:00 and 18:00 UTC.

Results

Characteristic of meteorological elements in the period 2011–2020

The mean annual air temperature in the study period was 10.1°C. The temperature varied from 11.1°C in the warmest (2019) to 9.2°C in the coldest year (2013) (Fig. 1A). The highest mean daily temperature in the analysed period was 30.0°C (26 June 2019) and the lowest −15.3°C (11 February 2012). The warmest months were June 2019, with a mean temperature of 23.3°C, and August 2015, with one of 22.7°C. The coldest months were January 2011 (−3.1°C) and February 2012 (−4.5°C). The mean annual air temperature amplitude in the years 2011–2020 was 22.3°C. It reached the highest value in 2012 and 2018 (24.3°C) and the lowest in 2020 (18.6°C). In the analysed period, there was a statistically significant increase in air temperature in Poznań ($\alpha > 0.01$).

The highest air temperature fluctuations in the studied period occurred in winter and were somewhat lower in spring and summer. The lowest air temperature fluctuations were characteristic of autumn (Fig. 1B). The mean air temperature in spring was 9.6°C. The warmest spring occurred in 2018 (10.8°C) as well as in 2012 and 2014 (10.6°C), and the coldest in 2013 (7.2°C). In summer, the mean air temperature in the study period was 19.4°C. The warmest summer occurred in 2018 (20.6°C) and the coldest in 2012 (18.5°C). The mean air temperature in autumn in the years 2011–2020 was 10.1°C. Autumn in 2020 was the warmest, with a mean temperature of 10.9°C, and the coldest was in 2016 (9.5°C). In the winter season, the mean air temperature was

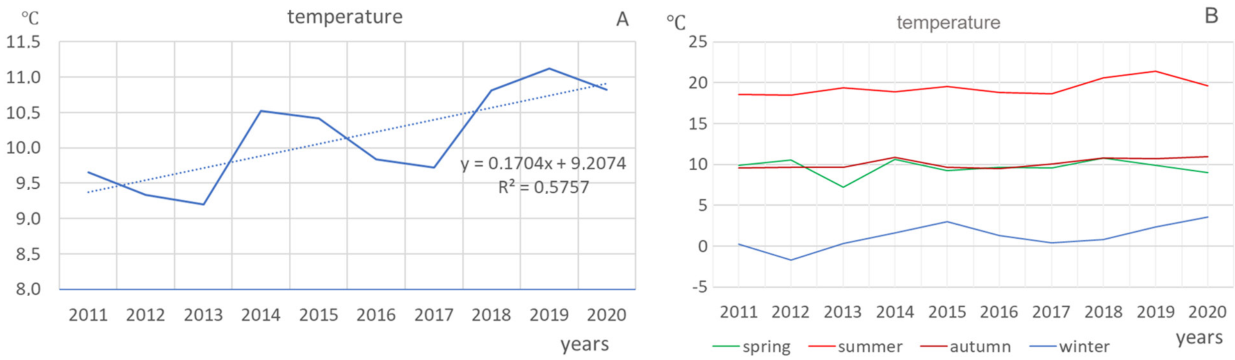

Fig. 1. The course of the average annual – (A) and seasonal – (B) values of air temperature in Poznań in years 2011–2020 with the annual trend line.

1.2°C. The lowest air temperature in winter occurred in 2012 (−1.7°C), and the highest in 2020 (3.6°C). In all seasons, except spring, there is a statistically significant ($\alpha > 0.001$) increase in temperature in the analysed period.

The values of mean annual and seasonal temperature were much higher compared to the average in the period 1951–2000 in Poznań, when the mean annual temperature was 8.3°C, and seasonal: in spring 8.0°C, in summer 17.5°C, in autumn 8.5°C and in winter −0.8°C (Woś 2010).

The mean cloudiness in the research period in Poznań was 65% and it was similar to the average value of 64% for the years 1951–2000 (Woś 2010). It varied from 60% in 2011 and 2018 to 71% in 2017 (Table 1). The annual sum of precipitation ranged from 373 mm (2018) to 668 mm (2017), averaging 526 mm a year. The average for the second half of the 20th century was 517 mm (Woś 2010). The amplitude of snow cover thickness was very high. The sum of snow cover depth was mostly very low in the study period. The highest snow cover of 632 cm occurred in 2013 and while it did not occur at all in 2020. Winters in Poznań are highly variable and differentiated, and negative trends were observed in relation to days with snow cover, total snow cover depth, winter snowiness coefficient and winter severity index in Poznań for the years 1966–2020 (Szyga-Pluta 2022). The relative humidity varied from 71% (2018) to 79% (2012). The average value was 75% in the last 10 years and earlier it was 78% (Woś 2010). The water vapour deficit changed from 9.1 hPa in 2015 to 10.2 hPa in 2014.

Ground temperature

Annual soil temperature

The mean annual ground temperature in the study period at a depth of 10 cm was the highest and reached 11.9°C (Table 2). The temperature there varied from 0.7°C in January to 23.2°C in July. At a depth of 20 cm, the mean annual temperature was somewhat lower at −11.5°C. Mean monthly ground temperature was the highest in August (22.5°C) and lowest in February (0.9°C).

Table 1. The average annual values of chosen meteorological elements in Poznań in years 2011–2020.

Year	Cloudiness [%]	Precipitation [mm]	Snow cover [cm]	Insolation [h]	Relative humidity [%]	Vapour pressure deficit [hPa]
2011	60	475	6	2030	76	9.6
2012	65	664	174	1900	79	10.0
2013	68	595	632	1721	78	9.7
2014	66	558	28	1962	77	10.2
2015	63	438	19	2036	72	9.1
2016	67	608	47	1823	76	9.7
2017	71	668	41	1739	77	9.8
2018	60	373	34	2225	71	9.6
2019	65	393	26	2040	73	9.9
2020	65	492	0	1518	73	9.7
Mean	65	526	101	1613	75	9.7

Table 2. Average monthly, seasonal and annual soil temperature [°C] at various depths in Poznań in 2011–2020.

Months	Depth [cm]				
	5	10	20	50	100
I	0.3	0.7	1.0	1.7	3.0
II	0.6	0.9	0.9	1.2	2.2
III	4.3	4.8	4.4	3.9	3.8
IV	10.8	11.5	10.6	9.3	8.1
V	16.7	17.6	16.6	14.9	13.1
VI	21.3	22.1	21.1	19.4	17.5
VII	22.3	23.2	22.3	20.9	19.4
VIII	22.2	23.1	22.5	21.4	20.4
IX	16.5	17.4	17.2	17.1	17.4
X	10.4	11.1	11.1	11.6	12.7
XI	5.4	5.8	6.1	6.9	8.4
XII	2.2	2.5	2.8	3.4	4.8
Spring	10.6	11.3	10.5	9.3	8.3
Summer	21.9	22.8	22.0	20.6	19.1
Autumn	11.0	11.6	11.7	12.1	13.0
Winter	1.0	1.4	1.5	2.1	3.3
Mean	11.2	11.9	11.5	11.1	11.0

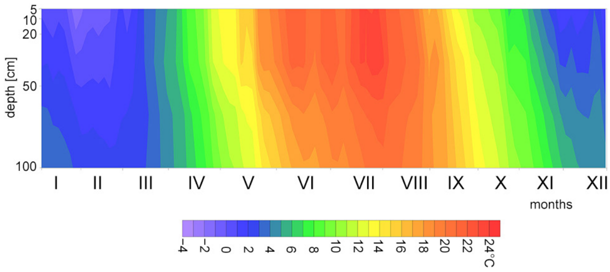

Fig. 2. Annual distribution of soil temperature at different depths in Poznań in the years 2011–2020.

Similar values were recorded at a depth of 5 cm. The mean annual soil temperature at that depth was 11.2°C, with the highest temperature reaching 22.3°C (July) and the lowest 0.3°C (January). Soil temperature at a depth of 50 cm showed a mean value of 11.1°C. In the warmest month, the mean temperature was 21.4°C (August) and in the coldest −1.2°C (February). The mean annual soil temperature at a depth of 100 cm was 11.0°C, with the highest value of 20.4°C in August and the lowest 2.2°C in February. As described by Wojkowski and Skowera (2017), in Ojców, the mean ground temperature in the years 1991–2006 at a depth of 5 cm was the highest and reached 10.8°C. The results of Hejduk et al. (2019) were similar. The highest mean monthly soil temperature occurred in Poznań in July at a depth of 10 cm (23.2°C) and the lowest in January at a depth of 5 cm (0.3°C). The publication by Ciaranek (2013) also describes July as the warmest month, with the highest value at a depth of 5 cm in Kraków, whereas January is the coolest, at a level of 50 cm.

The greatest differences in ground temperature at different depths occurred from April to August, and from November till January. The lowest amplitude concerned months of the transitional seasons, when the isothermy occurred almost throughout the ground profile.

On the monthly scale, the ground temperature decreased with depth from March to September (Fig. 2). In October and November, a decrease followed by an increase was observed at 50 cm, and then a decrease down to 100 cm. In December, the temperature decreased down to 10 cm, increased at a depth of 20–50 cm and then decreased in the deepest layer. In January, the ground temperature increased in profile 5–50 cm and decreased in the deepest layer. In February, the ground temperature decreased down the profile to 50 cm and then increased in the deeper layer.

In the study period, the mean monthly temperature values varied from 0.3°C in January at a depth of 5 cm to 23.2°C in July at a depth of 10 cm. Down to a depth of 10 cm, the highest values occurred in July. Profile 20–100 cm shows a month's delay of maximum ground temperature values with growing depth, which is in accordance with Fourier's third law. The lowest values occurred in January down to 10 cm and deeper in February. The difference in temperature between the shallowest and deepest layer was the highest in June (4.6°C) and May (4.5°C), and the lowest in September (0.9°C). The highest mean annual amplitude of temperature value was 22.4°C at a depth of 10 cm. The amplitude was lower at the depth of 5 cm (22.0°C) and decreased with growing depth. At a level of 20 cm, it was 21.6°C, at 50 cm 20.2°C and at 100 cm 18.1°C. This observation is in accordance with Fourier's second law stating that soil temperature amplitude decreases with depth. The conformity to Fourier's third law is also observed, i.e., the times of occurrence of the maximum temperature values were delayed with increasing depth (Molga 1983). This dependency is also described by Ciaranek (2013) based on data from Kraków. A delay of maximum ground temperature values with growing depth is also evident. Maximum values at a level of 50–100 cm occur 6 h later than in the layer located above. In Jeziory (Szyga-Pluta 2018), the greatest differences in ground temperature throughout the profile occur from May to August and in the winter period. It is also consistent with the previous research by Koźmiński and Michalska (2000). Jakusik and Owczarek (2008) point to the highest differences in temperature in the soil profile from April to August.

At the seasonal scale, the change in temperature with growing depth was differentiated (Table 2). The highest variability of ground temperature occurred in the warmest season, namely summer, with a range reaching 3.7°C. In spring, the range had a value of 3.0°C, in winter 2.3°C and in autumn 2.0°C. In the cold season, the temperature increased with depth in the whole profile. Therefore, the heat stream is directed towards the shallower layers. In the summer season and in spring, the heat stream is directed down the soil from the level of 10 cm. On average, in the shallower layer, the temperature increases with the depth in all seasons. From March to September, in the studied station, a decrease in ground temperature occurred with growing depth. In the winter months, the heat stream was reversed towards the shallower layers, as also confirmed by Ciaranek (2013). This dependency is confirmed by earlier studies conducted in Ojców in the period 1991–2006 (Wojkowski, Skowera 2017). These reversals are important biological triggers to soil animals and insects (Oke 1987). In the spring, they may come out of hibernation and/or move upwards towards the warmer surface layers. In the autumn, they retreat to depths where soil warmth is more equable.

Table 3. The standard deviation of monthly average soil temperature [°C] at various depths in Poznań in 2011–2020.

Months	Depth [cm]				
	5	10	20	50	100
I	2.8	2.4	2.0	1.4	1.0
II	3.7	3.2	2.7	2.0	1.3
III	4.7	4.1	3.3	2.5	1.9
IV	6.1	5.3	4.2	3.0	2.3
V	6.2	5.3	4.1	2.8	2.0
VI	6.3	5.1	3.8	2.2	1.7
VII	5.7	4.7	3.5	2.0	1.3
VIII	5.9	4.8	3.5	2.0	1.4
IX	5.4	4.6	3.5	2.4	1.7
X	4.3	3.8	3.0	2.2	1.7
XI	3.2	2.9	2.5	1.9	1.5
XII	2.6	2.3	1.9	1.3	1.0

The turn of spring and summer is characterised by the greatest variability in soil temperature, especially just below the ground surface. This is evidenced by the value of the standard deviation, the highest values of which occurred from April to June at the layers down to 20 cm (Table 3). The greatest changes in deeper levels appear earlier, i.e., from March to May and also later in autumn. Apart from the type and species of soil, the water regime prevailing in it is an important factor influencing thermal relations (Koźmiński, Michalska 1979).

In the soil of a forest clearing, spring showed the lowest variability (Szyga-Pluta 2018). The publication by Michalska and Nidzgorska-Lencewicz (2010) points to the greatest variability of soil temperature in spring, and summer was characterised by relatively low variability of ground temperature. According to analyses by Ciaranek (2013), in Kraków, spring is characterised also by the highest variability of ground temperature. Mild changes are observed from autumn to winter, during which time the soil heat storage still dominates the soil temperature variations in the United States; however, significant warming is found in the winter and spring season (Hu, Feng 2003).

The thermal activity of individual layers varies with the seasons of the year (Table 4). The greatest changes occurred in the shallowest layer of 5–10 cm, where the thermal gradient changes from 0.18°C $\cdot$ cm^{-1} in summer to 0.07°C $\cdot$ cm^{-1} in winter (Table 4). In profile 10–20 cm, the mean gradient value was lower, reaching 0.004°C $\cdot$ cm^{-1} in autumn to 0.02°C $\cdot$ cm^{-1} in winter. In a deeper profile (20–50 cm), the mean soil temperature gradient value was −0.05 °C $\cdot$ cm^{-1} in summer and the lowest in winter, i.e., 0.02°C $\cdot$ cm^{-1}. The greatest changes in the level 50–100 cm occurred in summer (−0.03°C $\cdot$ cm^{-1}). In autumn and winter in the whole profile, the soil temperature gradient was positive, i.e., the heat flows downwards, and in spring and summer in layer 10–100 cm it was negative, i.e., the heat flows upwards.

One of the elements of visible climate change is the nature and extent of the occurrence of land freezing, which is important from the point of view of vegetation and architecture, i.e., construction. The depth to which the ground freezing

Table 4. Average monthly, seasonal and annual values of the thermal gradient [°C · cm^{-1}] in Poznań in 2011–2020.

Months	Soil level [cm]			
	5–10	10–20	20–50	50–100
I	0.08↓	0.03↓	0.03↓	0.03↓
II	0.07↓	0.00↓	0.01↓	0.02↓
III	0.10↓	−0.04↑	−0.02↑	0.00↓
IV	0.14↓	−0.08↑	−0.05↑	−0.02↑
V	0.17↓	−0.10↑	−0.06↑	−0.04↑
VI	0.16↓	−0.10↑	−0.06↑	−0.04↑
VII	0.18↓	−0.08↑	−0.05↑	−0.03↑
VIII	0.19↓	−0.06↑	−0.04↑	−0.02↑
IX	0.18↓	−0.02↑	0.00↓	0.01↓
X	0.13↓	0.01↓	0.02↓	0.02↓
XI	0.09↓	0.02↓	0.03↓	0.03↓
XII	0.07↓	0.02↓	0.02↓	0.03↓
Spring	0.14↓	−0.07↑	−0.04↑	−0.02↑
Summer	0.18↓	−0.08↑	−0.05↑	−0.03↑
Autumn	0.13↓	0.004↓	0.01↓	0.02↓
Winter	0.07↓	0.02↓	0.02↓	0.02↓
Mean	0.13↓	−0.03↑	−0.01↑	0.003↓

reaches is most often equated with the location of the zero isotherm in the ground. In addition to external factors – i.e., negative air temperature and precipitation (including the extent and nature of snow cover) – freezing also depends on the type of soil, water content, etc. Therefore, the depth of freezing is not always the same as the position of the zero isotherm. Since weather stations measure the ground temperature and on this basis determine the position of the zero isotherm, it is considered to be the frost depth.

The mean position of the zero isotherm in the last decade in Poznań covers a short time from January to March (Fig. 2, Table 5). The linear extrapolation for the winter months shows that the depth of soil freezing may reach ca. 30 cm then. The depth is much lower in the analysed period than the average for the western zone of freezing in Poland, i.e., 0.8 m (PN-81/B-03020, Eurokod7).

Table 5. Values of the 1st empirical percentile of daily mean soil temperature (°C) at various depths in Poznań during the period November–March (2011–2020).

Months	Depth [cm]				
	5	10	20	50	100
I	−1.7	−0.9	−0.3	0.7	2.1
II	−0.6	−0.3	−0.1	0.7	2.0
III	1.5	2.0	1.8	1.8	2.4
XI	1.8	2.3	2.9	4.3	6.3
XII	0.6	1.0	1.5	2.6	4.2

Table 6. Mean annual number of days with soil temperature <0°C and >5°C at various depths in Poznań (2011–2020).

Temperature [°C]	Depth [cm]				
	5	10	20	50	100
≤0	19	7	5	0	0
≥5	243	246	246	249	258

In the years 1981–2005 on the Polish coast, it varied from 58 cm in Hel to ca. 100 cm in Świnoujście (Jakusik, Owczarek 2008). In the layer up to ca. 30 cm, approximately 80% of the root mass of the main crops is found and the most intense physicochemical and biological changes take place there; therefore, it is important for agriculture.

The number of days with the ground temperature above certain thermal thresholds is important information when we consider not only the soil freezing (0°C) but also plant development benefits (5°C). In the depth of 5 cm, the number of days below the freezing threshold was merely 19 days a year in the study period (Table 6). It is decreasing rapidly with depth to 7 days and 5 days, respectively, at 10 cm and 20 cm. The values are very low compared to the period of 1961–1980, when the average length of the period with temperature below 0°C was above 40 days in Poznań (Koźmiński, Michalska 1987). At the shallowest layer, the number of days with favourable thermal conditions for vegetation is 243 days a year and is increasing with depth to 258 days at 100 cm under the surface. The length of the periods was lower on the Polish coast (Jakusik, Owczarek 2008).

In the years 2011–2020 in Poznań, the thawing period was the shortest at the depth of 5 cm and lasted 341 days, and it did not apply to layers below the level ca. 30 cm, where the temperature did not fall below zero (Table 7). Its length increased in lower layers, which was also the case with the length of all other agricultural periods. The beginning of the agriculture activation period at the depth of 5 cm was on March 3rd and the growing season – on March 18th and respectively at the depth of 100 cm – on February 2nd, and March 3rd, which reflects the reversal of heat flow in the soil at this time of the year. The period beneficial for plants with relatively low thermal requirements (>6°C) shows the least diversified dates of commencement. The intense plant growth and development is possible on

Table 7. Average start and end dates and the length of the particular periods with temperature thresholds at various depths in Poznań (2011–2020).

Temperature threshold [°C]	Depth [cm]														
	5			10			20			50			100		
	Start date	End date	Length (days)	Start date	End date	Length (days)	Start date	End date	Length (days)	Start date	End date	Length (days)	Start date	End date	Length (days)
>0	14.02	20.01	341	27.01	21.01	360	27.01	22.01	361	–	–	365	–	–	365
>2.5	3.03	11.12	279	27.02	14.12	286	1.03	18.12	286	1.03	31.12	295	2.02	13.01	345
>5	19.03	18.11	245	17.03	21.11	250	19.03	23.11	250	22.03	30.11	254	25.03	13.12	264
>6	24.03	9.11	231	21.03	12.11	237	24.03	16.11	238	28.03	22.11	240	1.04	4.12	248
>8	2.04	28.10	210	30.03	1.11	217	2.04	2.11	215	8.04	6.11	213	15.04	18.11	218
>10	11.04	17.10	190	8.04	20.10	196	12.04	21.10	193	20.04	24.10	188	28.04	2.11	189
>12	22.04	6.10	168	19.04	10.10	175	23.04	10.10	171	1.05	12.10	165	9.05	19.10	164
>15	7.05	21.09	138	3.05	25.09	146	8.05	25.09	141	17.05	26.09	133	29.05	29.09	124

average from May 7th considering the surface layer. Deeper into the soil, this date is shifted to May 29th. The end of the periods with specified temperature thresholds was less diversified in the soil profile. The lowest shift of end dates with the depth applies to the periods with thresholds above 10°C and the highest above 6°C.

The thawing period in the analysed years was much longer than the one indicated in the area of Poznań, e.g., for the soil depth of 10 cm and 20 cm (by Koźmiński, Michalska 1979, 1984). The remaining periods began later and ended earlier than, e.g., those in 1961–1980 (Koźmiński, Michalska 1979, 1984), which indicates the general increase of air and soil temperature. It is worth noting that the characterised start and end dates as well as the duration of periods with different threshold soil temperature values, as average values, often blur the actual picture of the temporal changes of this element in individual years, which is interesting for cultivation practice (Koźmiński, Michalska 1979).

The thermal requirements of many crops are expressed in terms of the sum of temperatures; hence, they were calculated for the threshold values >5°C, >6°C, >8°C, >10°C, >12°C and >15°C for all ground depths and for the air temperature of the growing period (>5°C). In the period 2011–2020 in Poznań, the average sum of air temperatures during the growing season (>5°C) was 3641°C (Table 8). The value was much higher than the average sum of 2979°C in Poland in a longer period of 1966–2015; however, the warmest season recorded was associated with a larger temperature then in 2014, with an average sum of 3429°C (Tomczyk, Szyga-Pluta 2019). In the vicinity of Poznań, in Greater Poland (Wielkopolska), in the warmest growing season of 2014, the sum exceeded 3600°C.

In the ground, the highest values were recorded at the level of 10 cm, where they exceeded 4000°C during the period >5°C. It was also the soil level with the highest temperature values. The values for the depth of 5 cm were lower, which can be explained by the greater thermal activity and the greatest changing meteorological elements' impact. Apart from that, the reduction of the sum of temperatures was similar along

Table 8. The sum of air temperature and soil temperatures (°C) at various depths in Poznań in years 2011–2020.

Temperature threshold [°C]	Height 200 cm a.g.l.	Depth [cm]				
		5	10	20	50	100
>5	3641	3852	4069	3933	3736	3595
>6	3482	3792	4019	3860	3653	3551
>8	3400	3644	3849	3724	3532	3370
>10	3281	3469	3694	3528	3322	3161
>12	3026	3229	3426	3293	3041	2864
>15	2812	2773	3024	2836	2537	2371

with the depth, in the case of all thermal thresholds. According to the research of Koźmiński and Michalska (1979, 1984), these values at the depth of 10 cm in the years 1961–1975 and at the depth of 20 cm in the years 1961–1980 were also much lower in the vicinity of Poznań, considering all the thresholds. Regardless of that, these were areas designated as regions with favourable thermal soil conditions.

Ground temperature during the day

Measurement of ground temperature at 00:00 UTC was read out once a day at a depth of 5 cm. Measurements at 100 cm were read out at 12:00 UTC (Table 9). Mean hourly ground temperature values throughout the profile were calculated for the research period. The mean ground temperature during the day in Poznań was 11.4°C. The lowest mean ground temperature value was recorded at 00:00 UTC – 8.7°C, and the highest at 12:00 UTC – 15.6°C. At 06:00 UTC it was 8.9°C, and at 18:00 UTC 11.7°C. The data from Table 9 suggest that the highest mean temperature value during the day occurred at 12:00 UTC in profile 5–10 cm, and at 18:00 UTC at a depth of 20–50 cm. The data from Table 9 show certain constant dependencies. At 06:00 UTC, the heat stream was directed towards shallower layers, and at 12:00 UTC, the thermal profile in the ground was reversed, with the highest temperature at a depth of 5 cm. In the last measurement term (18:00 UTC), an increase was followed by a decrease at a depth of 50 cm. Intensive heat exchange in the surface area of the layer occurs during the day as a result of the effective radiation, while the higher temperature is maintained deeper (Olecki 1969). During the day, the high activity of the subsurface layers of the soil is strongly dependent on the intensity of solar radiation (Kossowski 2007).

Table 9. Average values of soil temperature [°C] during the day at various depths in Poznań in 2011–2020.

Depth [cm]	Hours			
	0 UTC	6 UTC	12 UTC	18 UTC
5	8.7	8.9	15.6	11.7
10	NA	9.1	14.0	12.5
20	NA	9.8	12.1	12.7
50	NA	11.1	10.9	11.4
100	NA	NA	11.0	NA

NA – not available.

Absolute extreme values

A more detailed analysis involved the determination of values of absolute extremes of ground temperature (Table 10). The absolute temperature minimum occurred on 6 February 2012 at 06:00 UTC (−12.2°C) at a depth of 5 cm. The weather on days before that date changed from cloudless to scattered clouds. On the day of absolute minimum, no snow or rainfall occurred. Also, no persisting snow cover was observed. Cloudiness was moderate (5/8) at the night before – *Altocumulus translucidus* formed and faded out in the morning. The absolute maximum had a value of 44.0°C at a depth of 5 cm on 26 June 2019 at 12:00 UTC. On days before that date, the cloudiness decreased. The light wind blew from the southern sector. The relative humidity ranged from 34% to 74%. No precipitation was recorded on 26 June 2019 either, and the isolation was intense. The sky was covered only by *Cumulus humilis* and *Cirrus fibratus* clouds.

Table 10. Values of absolute ground temperature extremes [°C] at various depths and dates of their occurrence in Poznań in 2011–2020.

Depth [cm]	6 UTC		12 UTC		18 UTC	
	MIN	MAX	MIN	MAX	MIN	MAX
5	−12.2	28.6	−8.2	44.0	−10.4	34.8
	6.12.2012	12.6.2019	7.2.2012	26.6.2019	6.2.12	26.6.2019
10	−11.0	26.1	−8.4	36.0	−9.4	33.6
	6.12.2012	10.8.2018	6.2.2012	1.8.2018	6.2.12	26.6.2019
20	−9.4	27.1	−8.6	30.5	−7.8	32.2
	6.12.2012	10.8.2018	6.2.2012	1.8.2018	6.2.12	1.8.2018
50	−5.2	26.8	−5.5	26.3	−5.1	26.9
	7.12.2012	10.8.2018	7.2.2012	10.8.2018	7.2.12	3.8.2018
100	NA	NA	0.0	23.9	NA	NA
			12.2.2012	10.8.2018		

Maximum daily amplitudes of ground temperature were also found at particular depths. The highest amplitude concerned months of the summer season, and the lowest the winter season. At a level of 5 cm, the daily amplitude was the highest in summer (28.9°C; 8 June 2018). It was a day with very high air temperature and a mainly cloudless sky, with a few *Cu hum* at noon, and light southeast wind (2–4 m · s^{-1}). That day was preceded by a period of typical radiation cloudless weather. In deeper layers, the daily amplitude of ground temperature decreased proportionately to depth (Molga 1983), in accordance with Fourier's second law. The highest amplitude at a level of 10 cm occurred on 24 July 2020 (15.2°C). The highest amplitude at a level of 20 cm also occurred on 24 July 2020 (9.7°C). The day was hot and the cloudiness most of the day was none or low, and it was preceded by a long period of similar weather with convective cloud development. In the afternoon the *Cumulonimbus* cloud developed and the temperature decreased after the precipitation, which probably caused the decrease of the temperature of the upper layer. At a level of 50 cm, the highest daily temperature amplitude was observed on 23 August 2015. The great temperature difference at this level is the result of long-term, cloudless, sunny weather.

The conducted analysis shows that the highest daily amplitude of ground temperature occurred in the months of the summer season and the lowest in winter. At a depth of 5 cm, daily ground temperature amplitude was the highest in summer. In accordance with Fourier's second law, the daily amplitude of ground temperature decreased in proportion to depth. Similar findings were also presented in papers by Michalska and Nidzgorska-Lencewicz (2010), Wojkowski and Skowera (2017) and Szyga-Pluta (2018).

There is a statistically significant increase in the air temperature in Poznań in the study period (Fig. 1A); however, the rise of the soil temperature is not so obvious – the trends determined for daily temperature values are positive in the whole soil profile, although not statistically significant (Fig. 3), which is due to the very short period. Hejduk et al. (2019) observed that the average soil temperature for the years 2009–2015 shows an increasing tendency for the surface layer, while in deeper layers the temperature variation is more varied. The results of Hu and Feng (2003) show

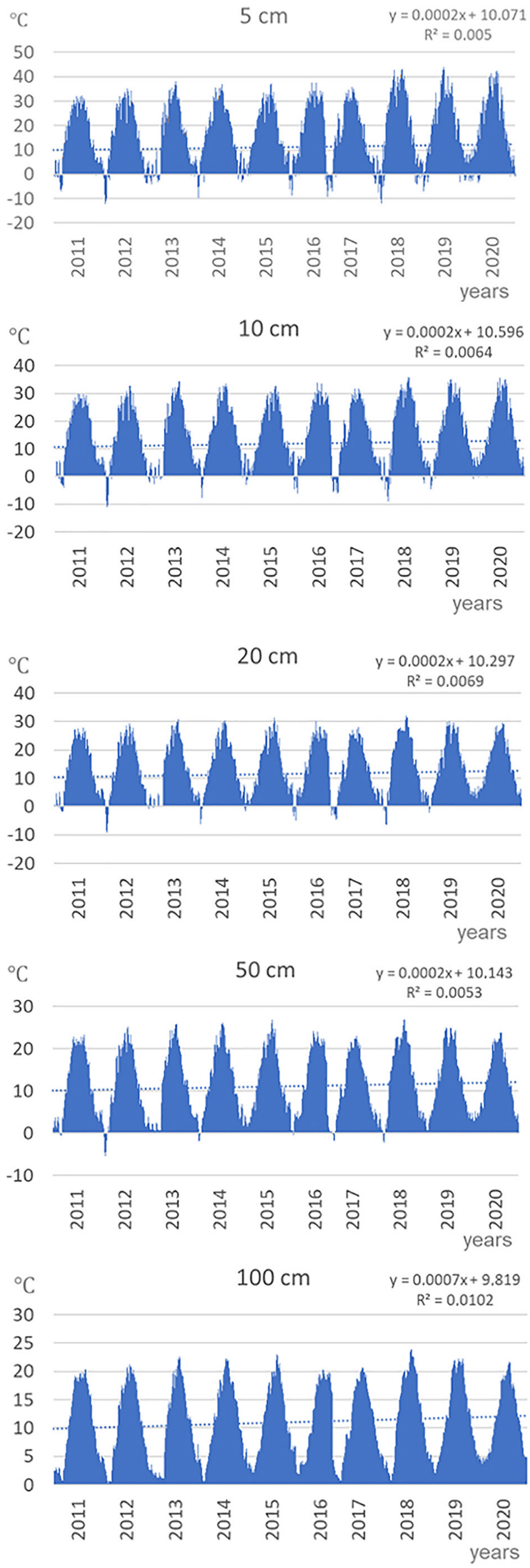

Fig. 3. The course of the temperature for individual soil levels in Poznań in the years 2011–2020 with the trend line.

the soil at 10 cm depth had been warming with an average rate of 0.31°C ·10 a^{-1} in the United States in the years 1967–2002. Garcia-Suarez and Butler (2006) analysed soil temperature trends at depths of 30 cm and 100 cm at three sites in Northern Ireland and the Republic of Ireland. They found that soil temperatures increased within a range of 0.04–0.25°C a decade, depending on location, depth and season. Zhang et al. (2005) detected an increase in the annual mean soil temperature of 0.6°C in the last century averaged over the whole of Canada, which was less than the increase in the annual mean air temperature (1.0°C). Isard et al. (2007) reported no temporal trends in mean annual air temperatures, but decreasing trends in mean annual soil temperatures at a depth of 50 cm in the Great Lakes Region of the United States over the period 1951–2000.

Relationship of ground temperature and selected meteorological elements

In Poznań in the years 2011–2020, air temperature, insolation, precipitation and water vapour pressure are positively correlated with the ground temperature. In the case of cloudiness, snow cover and humidity there is a negative correlation (Table 11).

Air temperatures had a clear and significant effect on soil temperatures at all depths with strong positive correlations between them. A direct influence of air temperature was highlighted the best in the 0–10 cm layer, which showed changes compatible with fluctuations in air temperature. The obtained results show a very strong correlation between air and ground temperature in the upper layers (Table 11). A strong correlation was observed for depths of 5–50 cm. It was the strongest at the level of 5 cm and decreases with depth. As also shown by results obtained earlier (Przybylak et al. 2010, Wojkowski, Skowera 2017, Szyga-Pluta 2018), ground temperature in Poznań is statistically significantly determined by air temperature, where *r* varied from 0.42 for 100 cm to 0.96 at a level of 5 cm. The correlation coefficient decreased with growing depth. This is confirmed by the previous results obtained for various types of soils in the warm half-year (Konopko, Kasperska 2002). Yeşilırmak (2014) noticed that this relationship was stronger in winter and spring than in summer and autumn, and that the effect of air temperature on soil temperatures in the upper layers was stronger than in the deeper layers, as expected and as is evident from the decreasing correlation coefficients from upper to deeper layers. Similarly, Garcia-Suarez and Butler (2006) found the strongest correlation between air temperatures and soil temperatures in winter. Helama et al. (2011) reported highly positive correlations between soil and air temperatures in all months at six stations in Finland, with the highest correlations in summer and early autumn.

Table 11. The correlation coefficient of the soil temperature at particular depths and selected meteorological elements in Poznań in 2011–2020.

Meteorological element	Depth [cm]				
	5	10	20	50	100
Air temperature (2 m a.g.l.)	0.96	0.81	0.78	0.73	0.42
Cloudiness	−0.17	−0.08	−0.08	−0.06	0.03
Insolation	0.54	0.60	0.56	0.52	0.44
Snow cover	−0.12	−0.10	−0.09	−0.08	−0.04
Humidity	−0.60	−0.62	−0.56	−0.47	−0.45
Precipitation	0.02	0.01	0.01	0.03	−0.004
Vapor pressure deficit	0.79	0.77	0.71	0.62	0.53

The dependence between snow cover and soil temperature in Poznań in the study period was weak (Table 11). Considering the low height of snow cover in most of the winter seasons of the research period, under the influence of air temperature rise/drop, the surface layer was also warming/cooling down. Changes in deeper soil layers were delayed and thus the correlation is lower. The lowest correlation was in the lowest layer, at the depth of 100 cm. Similar results were obtained by Ciaranek (2013), additionally stating variation in correlation throughout the day. Wojkowski and Skowera (2017) found that the strongest relationships between air temperature and soil temperature occur in spring and autumn; they are weaker in summer and mainly down to the depth of 20 cm, and in winter, snow cover plays an important role in weakening this relationship. The thickness of snow cover above soil may have a significant effect on the response of soil temperature change to air temperature change due to the insulation effect of snow cover and albedo change (Zhang et al. 2001). Isard et al. (2007) reported a decrease in the soil temperatures at a depth of 50 cm in the Great Lakes Region of the United States over the period 1951–2000, contrary to increasing air temperatures in winter. They attributed this to the thinning of the snow cover due to the air temperature increase and, thereby, to a lessening of the thermo insulation effect of the snow cover over the soil.

The results obtained for Poznań (Table 11) do not confirm the strong influence of cloud cover on soil temperature demonstrated earlier by Olecki (1969). The effects of clouds on the diurnal soil temperature pattern are fairly obvious: with overcast skies, absolute temperatures are lower by day but warmer at night, and the wave amplitude is smaller; variable cloudiness induces an irregular pattern upon the diurnal wave. However, according to Oke (1987), frequent changes in cloudiness cause temperature changes in a very shallow layer of soil. On cloudy days, the downwelling long-wave atmospheric radiation may reduce the surface long-wave radiation loss enough to keep the soil temperature slightly higher.

Soil temperature changes are primarily governed by solar radiation and latent and sensible heat exchange at the soil surface, and also by heat transfer in the soil in a vertical direction (Hu, Feng 2003). Thus, strong dependence is found between insolation and the ground temperature in Poznań (Table 11), which confirms the results of Ciaranek (2013). Similarly, studies in the literature, e.g., Tabari et al. (2011), detected significant positive correlations between soil temperature and solar radiation in the arid province of Isfahan in Iran. Moreover, Kossowski (2007) showed that the reaction of the soil to the inflow of solar radiation is delayed in the morning hours, and that the evening cooling of the soil occurs in advance of sunset. Sunshine duration and soil temperature are negatively correlated in winter but positively correlated in other seasons, noticed Yeşilırmak (2014). Bryś (2004) and Kossowski (2005) state that the relationship of daily soil temperature amplitudes with daily amplitudes of air temperature turns out to be stronger than with any meteorological element (considered individually), and the significance of the inflow of solar radiation in the daily amplitudes of soil temperature changes has the greatest impact.

There was no correlation between soil temperature in Poznań and precipitation in the study period (Table 11). The relationships between soil temperature and daily rainfall at all depths analysed by Michalska and Nidzgorska-Lencewicz (2010) proved to be statistically insignificant. There was also almost no such correlation on an annual scale according to Yeşilırmak (2014) in Turkey, where the correlation coefficients between rainfall and soil temperature were close to each other at 5 cm, 10 cm and 20 cm, but distinctly greater than those at 50 cm and 100 cm in all seasons. The increase in precipitation in spring and autumn weakened the relationship between air temperature and soil temperature according to Wojkowski and Skowera (2017). Moreover, the research of Michalska and Nidzgorska-Lencewicz (2010) showed that the precipitation the day before the measurement caused a significant change in the diurnal amplitude in the shallower soil layers and its total disappearance at a depth of 50 cm. Daily changes of water content in only the surface soil layer were affected by the soil water status on a rainy day, stated Biniak-Pieróg et al. (2012). Both the temperature values and the dynamics of their changes were much lower during the wet weather days, when the global solar radiation was reduced (Bednorz, Kolendowicz 2010). The efficiency of precipitation influencing soil moisture depends on the soil surface maintaining system and its intensity (Żyromski 1990, Klamkowski et al. 2011). Garcia-Suarez and Butler (2006) reported that decreasing rainfall between 1904 and 2002 at Armagh Observatory (Northern Ireland) resulted in declining soil moisture and, thus, created a soil temperature increase which was larger than the air temperature increase.

The rate of water loss as a result of evaporation depends, among other things, on air humidity and vapour pressure deficit gradient in the atmosphere. High values achieve correlation coefficients with both the vapour pressure deficit (negative) and relative humidity (positive) in Poznań (Table 11) contributed by surface evaporative cooling. Moisture deficiency affects the intensity of evaporation from the ground, which causes changes in the ground temperature. The maximum relationship falls on the near-surface layer, and the minimum, similar to the air temperature with which it is very closely related, is at the level of 100 cm, and this finding is also confirmed by the results of Bryś (2004). Similar results were obtained by Michalska and Nidzgorska-Lencewicz (2005), noticing that the strongest positive relationship with the soil temperature showed vapour pressure deficit and the negative one relative humidity. According to Koźmiński et al. (2003) the temperature of soil showed the closest relation to the temperature of air at 200 cm above the ground, then there was insufficiency of humidity and then indicative evaporation from the Wild evapometer.

In Canada, three mechanisms were investigated to explain this differentiation: air temperature change, which altered the thickness and duration of snow cover, thereby altering the response of soil temperature; seasonal differences in changes of air temperature; and changes in precipitation (Zhang et al. 2005). The first two mechanisms generally buffer the response of soil temperature to changes in air temperature, while the effect of precipitation is significant and varies with time and space. This complex response of soil temperature to changes in air temperature and precipitation would have significant implications for the impacts of climate change.

Conclusions

The high thermal activity of the soil in the shallowest layers up to 20 cm results in the smallest temperature differences between the layers near the surface of the ground. The greatest heat exchange with the environment takes place in these layers, and since the most heat is stored in the innermost layers, the layers close to the surface are characterised by a quick responsiveness to changes in the thermal conditions of the environment. The greatest temperature differences were between the levels 50 cm and 100 cm throughout the year. Only the direction of the flow changed the heat in the transitional seasons. The isothermal profile was clearly visible in March and September. The overlying layer was characterised by, however, a large accumulation of heat in the warm half of the year – then occurred the greatest differences between the levels of 20 cm and 50 cm.

The analysis of the annual and daily course of ground temperature in station Poznań in the years 2011–2020 suggests that values of mean annual and seasonal ground temperature decreased with a growing depth of the measurement profile starting from the level of 10 cm. Mean annual values of ground temperature gradient decreased with depth.

The highest variability of ground temperature occurred in summer and the lowest in winter. From March to September, the temperature decreased with depth, and in the months of the winter season, the heat stream was reversed towards shallower layers. In layer 50–100 cm, a month's delay of maximum values of ground temperature with growing depth was evident. The highest daily amplitude occurred in the months of the summer season, and the lowest in winter. The daily amplitude of ground temperature decreased with an increase in depth.

In the years 2011–2020 in Poznań, the thawing period was the shortest at the depth of 5 cm and lasted 341 days, and it did not apply to layers below the level ca. 30 cm, where the temperature did not fall below zero. Its length increased in lower layers, which was also the case for the length of all other agricultural periods.

In the ground, the highest sums of temperature were recorded at the level of 10 cm, as well as the highest temperature values. Apart from that, the reduction of the sum of temperatures was similar with increasing depth, in case of all thermal thresholds.

Ground temperature is closely correlated with air temperature, insolation, precipitation and water vapour deficit are positively correlated with the ground temperature. Negative correlation occurred in the case of humidity, cloudiness and snow cover.

The interaction of soil thermals with radiation factors is the strongest in the shallowest layer; then they systematically decrease and undergo an inversion between 50 cm and 100 cm of soil depth.

Contemporary climate change is unquestionable and evident, among others, in the observed increase in mean global air temperature. Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 (0.84–1.10)°C higher than that during 1850–1900 (IPCC 2021). There is, of course, a close relationship between soil and air temperature. There is a statistical increase in the air temperature in Poznań in the study period; however, the rise of the soil temperature is not so obvious – the trends at the whole soil profile are positive although not statistically significant. Only persistent long-term (such as interannual and decadal-scale) anomalies in surface heat budget can propagate to deep soil layers and affect temperature variations in those layers (Lachenbruch, Marshall 1986, Beltrami, Harris 2001, Beltrami 2002). The developed soil temperature dataset can be used in studies that lead to an improved understanding of, for example, the thermodynamic process in soils and the relationship of soil temperature and surface heat flux variations. This information is valuable among others for agrometeorologists, biologists and soil scientists, but it is also of importance in construction and other aspects of practical life.

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