THE RELATIONSHIP BETWEEN AIR AND SOIL TEMPERATURE AS A LOCAL INDICATOR OF CLIMATE CHANGE IN A SMALL AGRICULTURAL CATCHMENT

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ABSTRACT

Aim of the study

The aim of the study was to identify the trends in changes in air and soil temperature and their relationship, as well as to investigate if short data set can be an indicator of local climate change.

Material and methods

The study was based on the data of air and soil temperature collected between 2009 and 2015 at Czarna gauging station. It includes calculation of the average daily, monthly, semi-annual and annual air and soil temperature at particular depths of the soil profile. Monthly average values were used to determine the relationship between air and soil temperature. Based on the maximum air temperature, the number of frost, cold, cool, warm, hot and very hot days was calculated, according to the methodology provided by the Polish Climate Atlas. The basic statistical measures, trends in temperature change and linear regression were determined, as well as the statistical significance of equation coefficients using the Student's t-test.

Results and conclusions

The study shows a statistically significant increasing trend in average air temperature in summer. The annual average and winter average air temperature demonstrate an statistically insignificant increasing trend. The number of frost days shows a decreasing trend, contrary to the number of cold and very hot days. The average soil temperature appears to be increasing for the surface layer. The monthly distribution of average soil temperature corresponds with the monthly distribution of average air temperature. There is a strong relationship between air temperature and soil temperature.

Keywords: small catchment, air temperature, soil temperature, trends in air and soil temperature

INTRODUCTION

Recently, climate changes have not only affected air temperature, but also other factors such as soil temperature and precipitation (Barman et al., 2017). Air temperature is one of the most important climatic fac-

tors affecting soil temperature. In the winter season, depending on the intensity of snowfall and its fluctuations as well as the duration of snow cover, which acts as an isolator between air and soil, the reaction of soil temperature to climate change can differ significantly from the reaction of air temperature (Jungqvist

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et al., 2014). Soil temperature is connected to many processes such as dissolution of organic substances, soil mineralization or degradation, nutrient assimilation by plants, as well as forest productivity and the length of the vegetative season (Jungqvist et al., 2014). Changes in soil temperature are most distinct up to a depth of about 20 cm, while their amplitude decreases as the depth increases (Bryś, 2008; Szyga-Pluta, 2018). Soil temperature is shaped by factors such as: vegetation cover, periodic snow cover (Biernacka, 2010), soil water content and physiographic conditions (Kruk et al., 2018). However, according to Wojtkowski and Skowery (2017), radiation balance is the main factor of thermal conditions. Soil without cover shows much higher temperature amplitudes (Mularz and Wróbel, 2003). When air temperature drops and there is minimum insolation (i.e. at night), the temperature of soil without cover falls faster than that of soil covered by vegetation. In the evening, the temperature of soil covered with vegetation is also lower the air temperature, but higher by few degrees during the day.

In the first decade of the 21st century, an increase in air temperature was observed in spring and summer (Żmudzka, 2010; Michalska, 2009). Climate warming in Europe is also the cause of rising winter temperatures (Lorenc, 2000; Trepińska, 2001; Michalska 2011), which consequently affect the formation, duration and thickness of snow cover. Soil thermal and moisture conditions directly translate into plant growth and development, and have an impact on the length of growing season. In the years 2001–2009, the growing season in Poland was 8 days longer compared to 1971–2000, thus at the current rate of climate change by 2030 it may extend up to 14 days (Nieróbca et al., 2013). Long-term changes in the course of air and soil temperature by changing the duration of growing season may in the future affect the structure of crops and, as a result, the land use.

The main purpose of this analysis was to identify trends in air temperature and soil temperature and their interrelationships, as well as to examine whether short series of measurement data can serve as an indicator of local climate change. The study used measurement data from a hydro-metrological station located in the village of Czarna, belonging to the Faculty of Civil and Environmental Engineering, Department of Water Engineering and Applied Geology, SGGW. This station has been used since the 1960s to monitor hydrological and metrological changes.

RESEARCH AREA

The catchment area at Czarna station (51º25'37 "N 21º26'27" E) is 23.4 km². The location of the research catchment is presented in Fig. 1. Hydrological tests covered the upper part of the catchment area that is situated in the Radom Plain. In the catchment, a monitoring system has been installed in two measuring stations: Płachty Stare and Czarna. It is a flat, locally undulating land. The average precipitation in the catchment area in the years 1963–2011 amounted to 612 mm and the outflow was 107 mm (Banasik et al., 2013). The lowest annual precipitation was reported in 1991 (414 mm), while the lowest annual outflow was recorded in 1992 (52 mm). The most important watercourses have an average slope ranging from 2.5 ‰ to 3.5 ‰, with shallow and narrow valleys (Byczkowski et al., 2001; Hejduk et al., 2015). The catchment area of the Zagożdżonka river is mainly used for agriculture. The land use till Czarna ganging station 70% of the area is arable land, 20% forests, 9.4% pasture and 0.6% hardened areas (Hejduk and Hejduk, 2014). Grasslands dominate in the watercourse valleys. Grains (rye, oats and triticale), potatoes and papilionaceous plants were grown in this area (Banasik, 1994).

The monitoring system in the Zagożdżonka catchment consists of sensors installed in the measurement section of the river and in the weather station (Hejduk et al., 2010; Banasik and Hejduk, 2013). Along with the beginning of research on winter floods (snowmelt and snowmelt-rainfall), four ground thermometers were installed in the weather station at depths of 0 cm, 5 cm, 10 cm and 20 cm deep in the soil profile. All thermometers are placed in sandy soil and in the aeration zone.
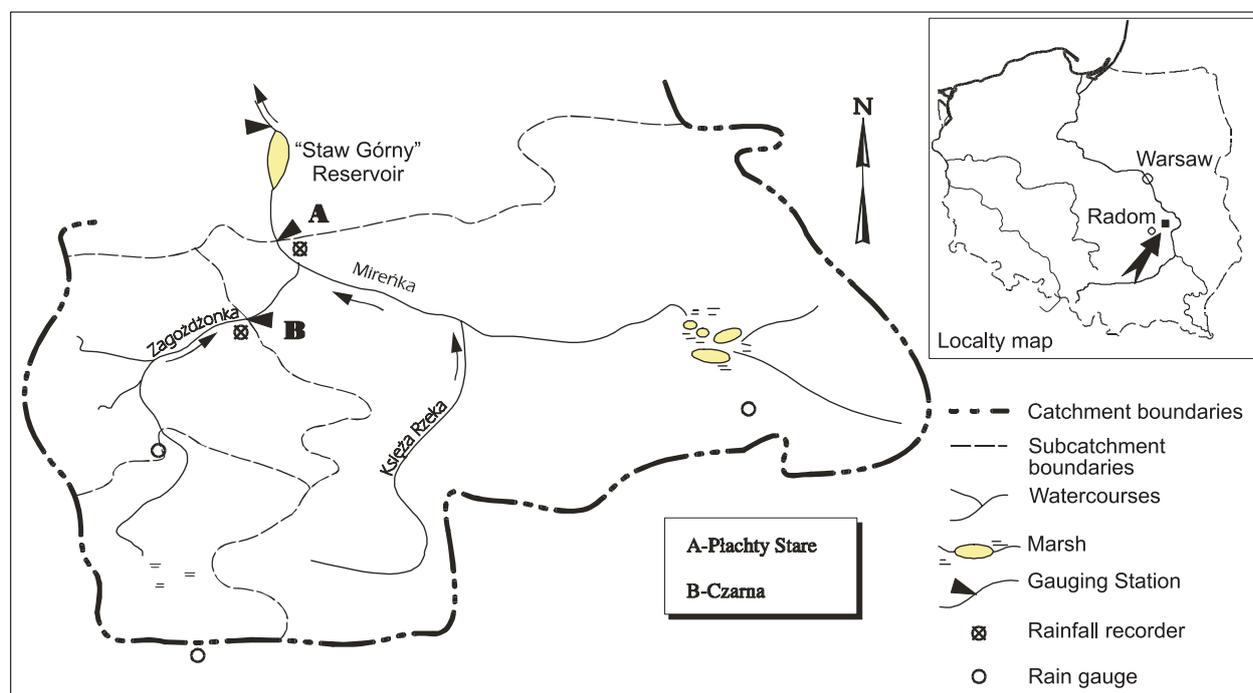
Fig. 1. Location of the research area

MATERIALS AND METHODS

Measurements of air and soil temperature, collected in the years 2009–2015 at the station in Czarna are the basis for the following calculations. The measurement of both air and soil temperature was taken automatically with a ten-minute time step. Occurring deficiencies in data were supplemented on the basis of equations determining the relationship between the temperature value at the measuring station in Czarna and the nearby weather station IMGW in Kozienice (Jóźwik, 2019). Using the available data, the minimum, maximum and average daily air and soil temperature were calculated at individual depths of the soil profile. On this basis, the monthly average, semi-annual average (separately for winter and summer half-years) and annual temperature were determined. Monthly average values also allowed determining the relationship between air and soil temperature at individual depths.

In order to characterize the thermal conditions in the studied area, the number of frosty, cold, cool, warm, hot and very hot days was calculated on the basis of the maximum air temperature, in accordance with the methodology given in the Polish Climate Atlas (Lorenz, 2005). If the maximum temperature (t_{max}) does not exceed 0ºC during the day, we consider it a frost day; when temperature $t_{max} \leq 10$ºC – it is a cold day; when t_{max} is in the range from 10.1ºC to 15.0ºC, we consider the day to be cool; t_{max} in the range between 18.1ºC and 23.0ºC defines a warm day; t_{max} taking values from 25.1ºC to 30.0ºC indicates a hot day, and when the maximum temperature exceeds 30.0ºC a day is considered very hot.

The trends of temperature changes as well as linear regression (the relationship between soil temperature at different depths and air temperature) were determined on the measured data. The statistical significance of equation coefficients was checked for both trends and linear regression equations using the t-Student's test. Basic statistical measures, i.e. mean values (mean), standard deviation (SD), coefficient of variation (ratio of standard deviation to mean value – V_t), range i.e. the difference between the maximum and minimum val-

ues (R_o) and the medium-term rate of change (geometric mean of individual chain indexes – T) expressed in percentages (Pralińska, Praliński 2003).

RESULTS

Air temperature variation

The average air temperature for the period 2009–2015 at the station in Czarna was 8.6ºC, ranging from 7.7ºC in 2013 to 9.4ºC in 2014 and 2015. The average monthly temperature ranged from –2.3ºC in January to 19.5ºC in July. The variation of the average annual air temperature and the average temperature of the winter and summer half-years is shown in Fig. 2

The trend line equations of changes in the average annual air temperature and the average air temperature of the winter and the summer half-years along with selected measures of variation are presented in Tab. 1. Both in annual and semi-annual terms, the average air temperature is showing a rising trend. It is respectively

0.19ºC per year, 0.14ºC in the summer half-year and 0.23ºC in the winter half-year. However, only in the summer half-year the trend line equation coefficients were statistically significant at the level p = 0.1. The standard deviation, temperature coefficient of variation and range were much larger in the winter half-year. This indicates that air temperature in the winter period is characterized by much greater variation and diversity than in the summer period. This is also evidenced by the medium-term rate of change, demonstrating the percentage increase in temperature from year to year, which was the largest for the winter half-year and amounted to 6.59%.

Given the average monthly temperature, the coldest months were respectively January, February and December (see: Fig. 3). Positive average temperature values were recorded in November, March and April. March is characterized by variable weather, snowfall, negative and positive air temperatures may occur. Similarly, November can be warm, with typical autumn
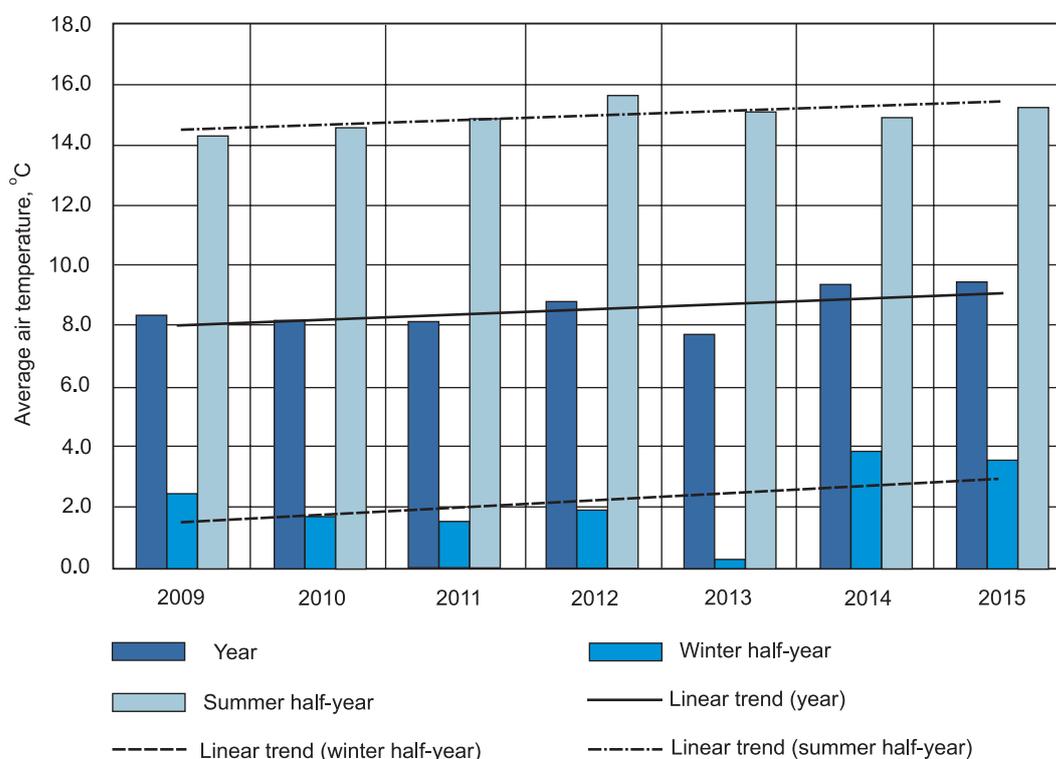
Fig. 2. Average air temperature for individual years and both the summer and the winter half-years of the period 2009–2015 in Czarna

Table 1. Summary of trend line equations and selected variation characteristics for the average temperature on an annual and semi-annual basis

Period	Equation	R^2	Average (°C)	SD (°C)	V_t (%)	R_O (°C)	T (%)	Statistics t	Significance at p
summer half-year	$Y = 0.143 \cdot X - 274.08$	0,44	14,9	0,47	3	1,4	1,13	1,975	0,105
winter half-year	$Y = 0.232 \cdot X - 465.57$	0,16	2,2	1,4	57	3,6	6,59	0,993	0,366
year	$Y = 0.188 \cdot X - 369.82$	0,39	8,6	0,65	8	1,7	2,02	1,782	0,134

given that Y – average air temperature, X – years
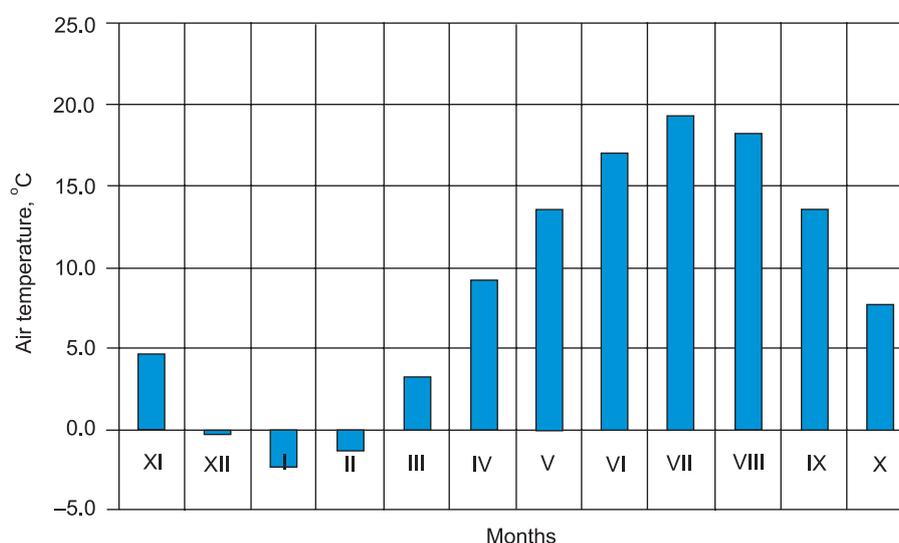
Fig. 3. Monthly distribution of average air temperature over the years 2009–2015 at the measurement station in Czarna

weather, or cool. At the station in Czarna, the first snow cover often appears at the end of November, but the average temperature of this month is positive (Hejduk and Hejduk, 2014). In the studied period, the warmest months were July, August and June, respectively. The average temperature in May and September was similar.

Analysing the variation of air temperature for individual months (see: Table 2), defined as the difference between the maximum and minimum average temperature of a given month, the highest dynamics were recorded in the winter months, i.e. January and March. The average January temperature ranged from –8.1°C in 2010 to 2.3°C in 2015. In March, the lowest average temperature (–1.9°C) was registered in 2013, and the highest a year later (6.0°C). The smallest variation of the average monthly air temperature in the studied pe-

riod was noted in April (from 8.1°C in 2015 to 10.1°C in 2011). In the remaining months, the difference between the lowest and the highest average monthly air temperature was 4.5°C on average. In seasonal terms, smaller temperature differences were recorded for the summer half-year (average 3.4°C).

Based on the maximum daily air temperature, the number of frost, cold, cool, warm, hot and very hot days (see: Fig. 4) was calculated. Trend line equations for the analysed days are summarized in Tab. 3, and their statistical characteristics are presented in Tab. 4. In the examined period, a total of 212 frost days were recorded, in which the maximum temperature did not exceed 0°C. The least frost days occurred in 2014––2015. In 2014, there were 16, and in 2015 only 15. Analysis of individual types of days in the analysed

Table 2. The range of average monthly air temperature in the years 2009–2015 at the measurement station in Czarna

Month	Range	The warmest in year	The coldest in year
November	2.3 – 6.2ºC	2011	2012
December	–5,5 – 2,4ºC	2012	2011
January	–8,1ºC – 2,3ºC	2015	2010
February	–6,2ºC – 1,9ºC	2014	2012
March	–1,9ºC – 6.0ºC	2014	2013
April	–8,1ºC – 10,1ºC	2011	2015
May	12,7ºC – 15,0ºC	2012	2009, 2015
June	15,5ºC – 18,2ºC	2011	2014
July	17,5ºC – 21,2ºC	2010	2011
August	17,3ºC – 21,3ºC	2015	2009
September	11,3ºC – 14,8ºC	2015	2013
October	–1.9ºC – 6.0ºC	2013	2010

period indicates a downward trend for frost days (see: Fig. 4). On a monthly basis, the largest number of frost days was recorded for January (95 days in total), February (55 days) and December (43 days).

In the summer period, in the years 2009–2015, 77 very hot days were registered with a maximum temperature exceeding 30ºC, with the most, as many as 22 days, in 2015. The frequency of very hot days in the studied period shows an upward trend. A total of 81 hot days were recorded, with a maximum temperature ranging from 25.1ºC to 30.0ºC. In the years 2009–2015 hot days were typical for July. On a monthly basis, the most very hot days ($t_{max} > 30$ºC) in the studied period were registered in August, (34 days) and in July (33 days), and occasionally appeared in June (5 days) and in September (3 days). On average, there were 30 frost days, 112 cold days, 52 cool days, 67 warm days, 38 hot days and 11 very hot days.
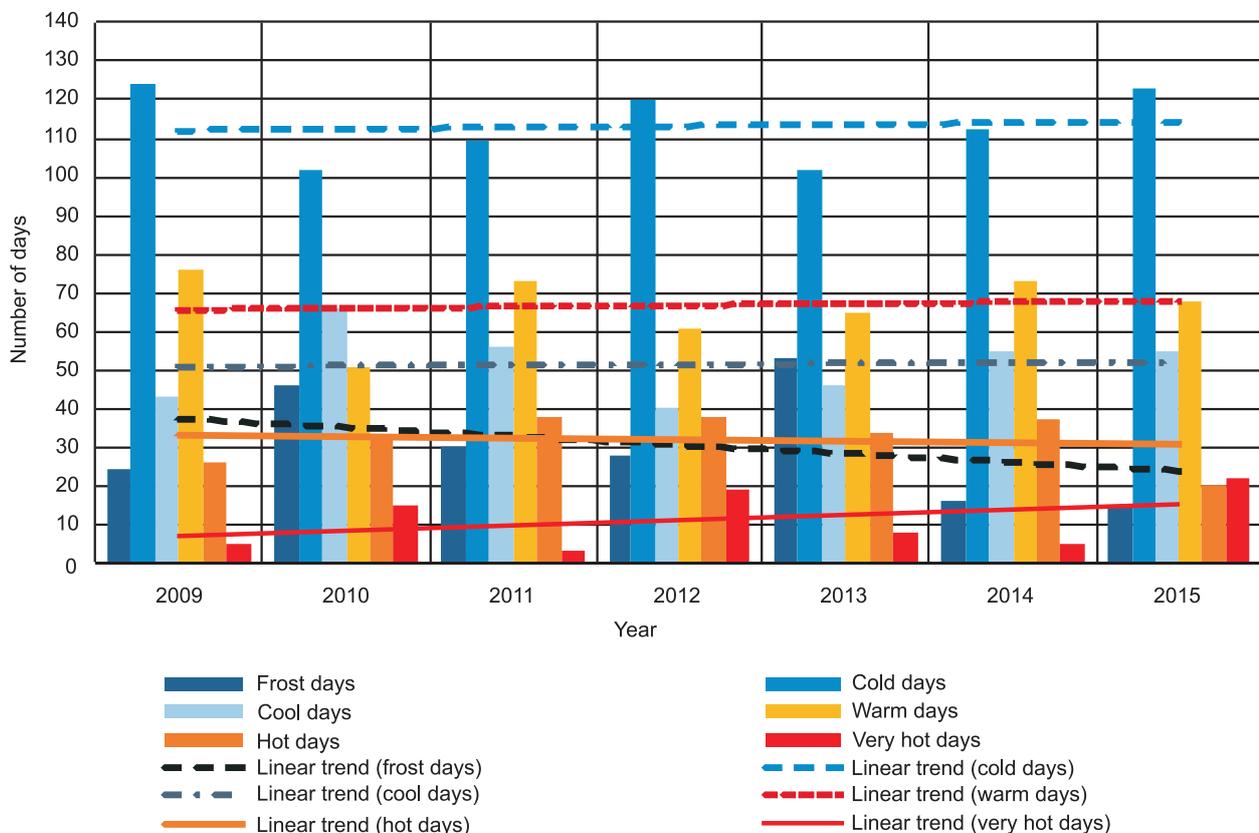
Fig. 4. Number of frost, cold, cool, warm, hot and very hot days occurring in the years 2009–2015 at the station in Czarna

Table 3. Trend line equations for calculated frost, cold, cool, warm, hot and very hot days.

Trend for:	Equation	R^2	Statistics t	Significance at p
number of frost days	$Y = -2.285 \cdot X + 4629.14$	0,12	0,815	0,451
number of cold days	$Y = 0.392 \cdot X - 677.00$	0,008	0,204	0,845
number of cool days	$Y = 0.143 \cdot X - 274.08$	0,001	0,076	0,942
number of warm days	$Y = 0.428 \cdot X - 795.57$	0,01	0,240	0,819
number of hot days	$Y = 0.428 \cdot X - 894.42$	0,02	0,305	0,772
number of very hot days	$Y = 1.29 \cdot X - 2575.86$	0,13	0,878	0,419

given that Y – number of days, X – year

Table 4. Comparing the selected coefficients of variation for calculated very hot, hot, warm, cool, cold and frost days.

Parameter	Unit	Days					
		Very hot	Hot	Warm	Cool	Cold	Frost
Average	(days)	11,0	32,1	66,7	51,6	113,4	30,3
SD	(days)	7,59	6,84	8,65	9,03	9,31	14,41
V_t	(%)	69	21	13	18	8	48
R_o	(days)	19	18	25	26	22	38
T	(%)	28,01	–4,28	–1,84	4,19	–0,13	–7,53

The number of frost and hot days (see: Fig. 4) showed values decreasing by 2 and 3 days per year respectively, however, statistical analysis (see: Table 3) showed no significance of regression. In other cases, i.e. for the number of cool, cold, warm and very hot days, an upward trend was proven. For very hot days it was 1.3 days a year, while in other cases from 0.14 through 0.39 to 0.43 days a year. In all cases, statistical analysis (see: Table 3) showed no significance of regression.

The standard deviation (see: Table 4) was greatest for the number of frost days (14.41) and similar for cool and cold days (9 and 9.3). The smallest recorded value of the standard deviation was for the number of hot days. The largest variation coefficients were recorded for the number of very hot days (69%) and frost days (48%), with the largest range measured for the number of frost days (38). The medium-term rate of change was positive only for the number of very hot and cool days. In other cases, the values of this indicator were negative. This means that the number of days increased from year to year only for very hot and cool days.

Soil temperature variation

For the examined period and individual depths of the soil profile, the average, minimum and maximum soil temperature was calculated on an annual, semi-annual and monthly basis (see: Fig. 5). The average soil temperature at a depth of 0 cm (i.e. right next to the ground) in the years 2009–2015 was 10.8ºC. It fluctuated from 10.1ºC in 2013 to 11.3ºC in 2014. In seasonal terms, the average soil temperature at a depth of 0 cm in the winter half-year was 4.6ºC. Its lowest value was recorded in 2013 (3.4ºC) and the highest in 2014 (5.7ºC). The average soil temperature at a depth of 0 cm in the summer half-year was 17.0ºC and ranged from 16.7ºC in 2009 to 17.6ºC in 2012. The average soil temperature at a depth of 5 cm was 10.9ºC. Its lowest value was registered in 2013 (10.2ºC) and the highest (11.2ºC) in
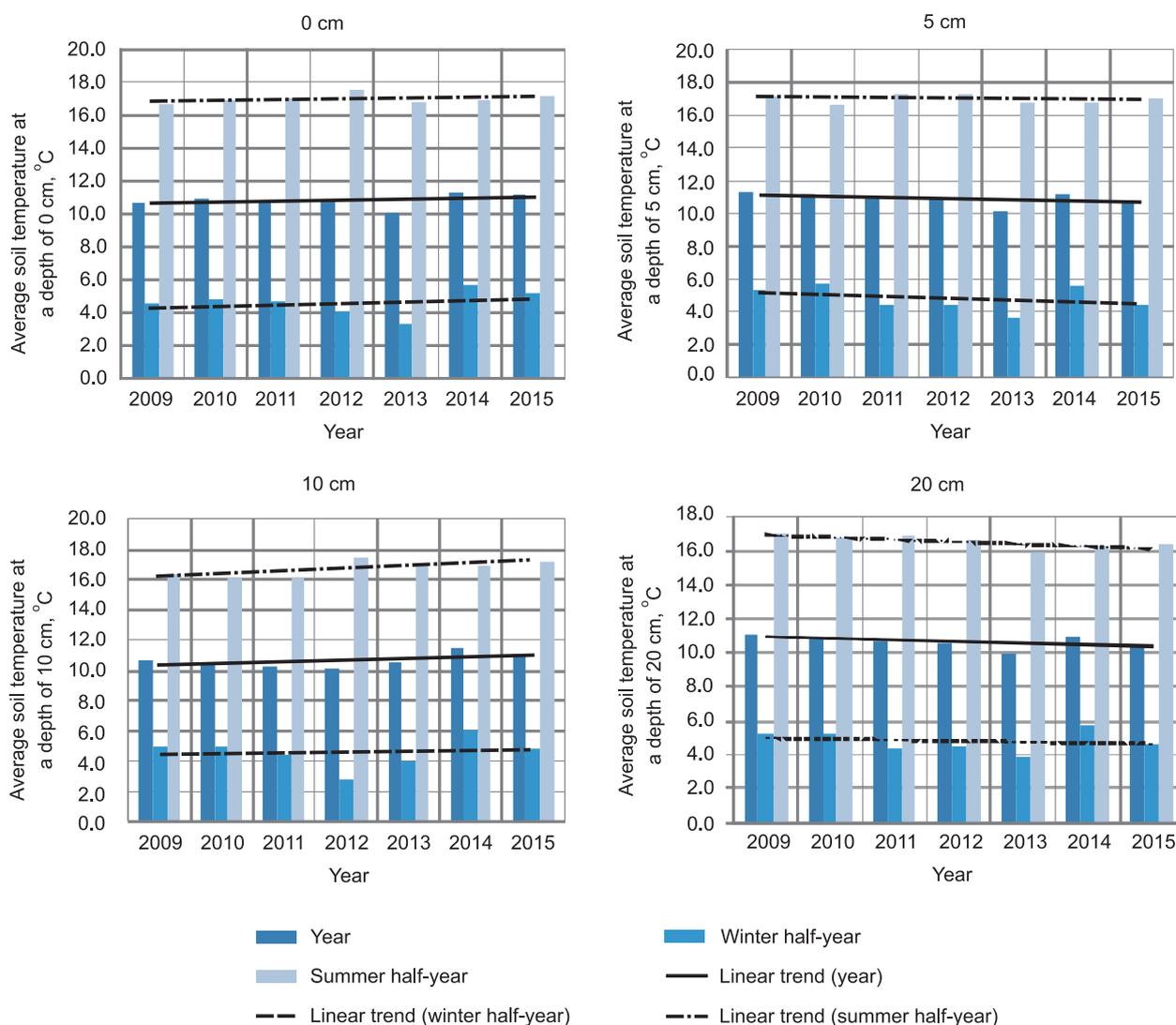
Fig. 5. Average soil temperature at a depth of 0 cm, 5 cm, 10 cm, 20 cm for individual years and the summer and winter half-years of the 2009–2015 period

2009 and 2010. On a seasonal basis, the average soil temperature at a depth of 5 cm in the winter for the 2009–2015 period was 4.8°C, varying between 3.6°C in 2013 and 5.7°C in 2010. In the summer half-year it was 17.0°C and oscillated between 16.7°C in 2010 and 2014 to 17.4°C in 2012. The average soil temperature at a depth of 10 cm in the 2009–2015 period at the station in Czarna was 10.7°C. The coldest year turned out to be 2012 (10.1°C), while the warmest was 2014 with an average of 11.5°C. In seasonal terms, the average soil temperature at a depth of 10 cm in the winter half-year was

4.6°C and ranged from 2.8°C (2012) to 6.1°C (2014). In summer, the average temperature at the level of 10 cm was 16.8°C. The coolest summer half-year was recorded in 2010 and 2011 (16.2°C), and the warmest in 2012 (17.5°C). The average soil temperature at a depth of 20 cm in the 2009–2015 period was 10.7°C. The coldest year was 2013 (9.9°C), the warmest – 2009 (11.1°C). The average soil temperature at a depth of 20 cm for the winter half-year was 4.8°C, varying between 3.9°C in 2013 and 5.8°C in 2014. In the summer period, the average soil temperature at a depth of 20 cm was 16.6°C.

Table 5. Trend line equations for the average temperature at individual depths of the soil profile

Soil profile depth	Trend line equation		
	Year	Summer half-year	Winter half-year
0 cm	$Y_0 = 0.065 \cdot X_0 - 120.66$	$Y_0 = 0.041 \cdot X_0 - 65.35$	$Y_0 = 0.089 \cdot X_0 - 175.97$
5 cm	$Y_5 = -0.077 \cdot X_5 + 167.09$	$Y_5 = -0.027 \cdot X_5 + 70.88$	$Y_5 = -0.128 \cdot X_5 + 263.31$
10 cm	$Y_{10} = 0.111 \cdot X_{10} - 213.51$	$Y_{10} = 0.168 \cdot X_{10} - 321.75$	$Y_{10} = 0.05 \cdot 4X_{10} - 105.28$
20 cm	$Y_{20} = -0.095 \cdot X_{20} + 202.99$	$Y_{20} = -0,143 \cdot X_{20} + 304.53$	$Y_{20} = -0.048 \cdot X_{20} + 101.46$

given that Y_{index} – soil temperature at an individual depth, X_{index} – years

Table 6. Comparison of selected statistical characteristics

Soil profile depth	Year			Summer half-year			Winter half-year		
	R^2	Statistics t	Significance at p	R^2	Statistics t	Significance at p	R^2	Statistics t	Significance at p
0 cm	0.13	0.874	0.421	0.10	0.764	0.479	0.07	0.609	0.569
5 cm	0.20	1.132	0.308	0.04	0.472	0.656	0.13	0.873	0.422
10 cm	0.26	1.324	0.242	0.52	2.337	0.066	0.01	0.262	0.803
20 cm	0.24	1.257	0.264	0.64	2.978	0.031	0.03	0.364	0.730

The coolest summer occurred in 2013 (16.0ºC), and the warmest in 2009 (17.0ºC). Trend line equations for the average temperature at individual depths of the soil profile are summarized in Tab. 5, and in Tab. 6 their selected characteristics. Table 7 presents a summary of selected coefficients of variation for the average temperature at individual depths of the soil profile.

The trend line equation coefficients presented in Tab. 5 are significant at the significance level p = 0.05 only for the trend of soil temperature variation at a depth of 20 cm for the summer half-year (see: Table 6), and are significant at the significance level p = 0.1 only for the trend of soil temperature variation at a depth of 10 cm for the summer half-year.

The trend line equations presented in Tab. 5, selected statistical characteristics (see: Table 6) and measures of variation (see: Table 7) suggest an upward trend in average temperature at 0 cm and 10 cm depths and a downward trend at 5 cm and 20 cm depths. The directional coefficients of trend line equations for all soil profile depths were close to zero. The highest standard deviation was recorded for the average soil temperature in the winter half-year. This applied to all depths of the soil profile. The standard deviation of the average annual soil temperature and the average summer period temperature were at a similar level. The average soil temperature at all depth levels showed the highest values of the coefficient of variation in the winter period. The medium-term rate of change was positive only for the average temperature at a depth of 0 cm both in an annual and semi-annual scale.

The monthly distribution of average soil temperature at individual depths of the soil profile is shown in Fig. 6.

Considering the average monthly soil temperature measured at a depth of 5 cm, the coolest month was February (1.4ºC), and the warmest was July (20.7ºC). At a depth of 10 cm, the average soil temperature ranged from 1.6ºC in February to 20.2ºC in July. At a depth of 20 cm, the lowest average temperature was also recorded in February (1.7ºC), the highest in July (19.9ºC). At all analysed depths of the soil profile, the average temperature decreased from August to February, while it increased from March to July.

Table 7. Comparison of selected coefficients of variation for the average temperature at individual depths of the soil profile.

	Unit	Average temperature		
		Annual	Winter half-year	Summer half-year
For 0 (cm):				
mean	(°C)	10.8	4.6	17.0
SD	(°C)	0.39	0.74	0.27
V_t	(%)	4	16	2
R_o	(°C)	1.2	2.3	0.8
T	(%)	0.84	2.36	0.41
For 5 (cm):				
mean	(°C)	10.9	4.8	17.0
SD	(°C)	0.37	0.76	0.28
V_t	(%)	3	16	2
R_o	(°C)	1.1	2.1	0.6
T	(%)	−0.70	−2.89	−0.06
For 10 (cm):				
mean	(°C)	10.7	4.6	16.8
SD	(°C)	0.47	1.01	0.50
V_t	(%)	4	22	3
R_o	(°C)	1.4	3.3	1.3
T	(%)	0.50	−0.61	0.83
For 20 (cm):				
mean	(°C)	10.7	4.80	16.56
SD	(°C)	0.42	0.65	0.39
V_t	(%)	4	13	2
R_o	(°C)	1.19	1.87	1.07
T	(%)	−0.98	−2.15	−0.64
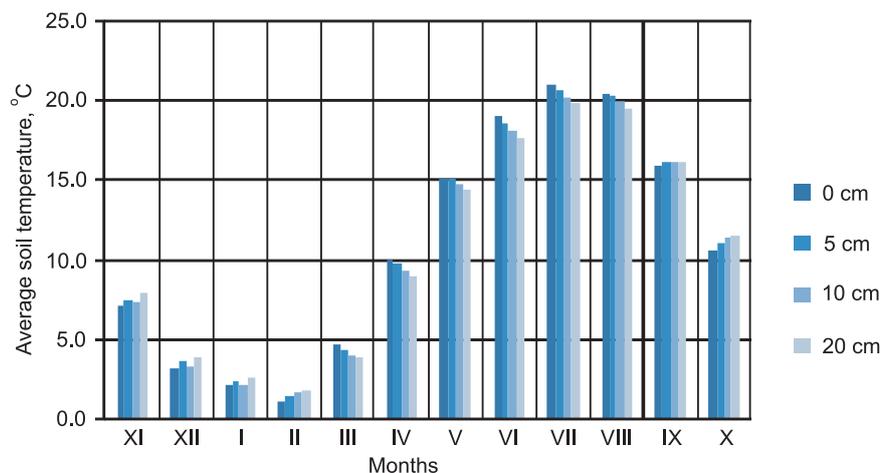
Fig. 6. Monthly distribution of average soil temperature at individual depths of the soil profile in 2009–2015 at the station in Czarna

Relationship between average monthly soil temperature and average monthly air temperature
The relationship between the average monthly soil temperature and the average monthly air temperature was determined using linear regression equations. Equations and correlation coefficients are summarized in Tab. 8. At all analysed depths of the soil profile, a strong relationship between soil temperature and air temperature was indicated. The correlation coefficient (R) was above 0.96 in all cases, and the directional coefficients of the equations were close to 1. The strongest relationship occurs in the relationship between soil temperature and air temperature at the ground surface. Both linear regression equation coefficients and correlation coefficients are statistically significant at a significance level of $p = 0.05$.

RESULTS DISCUSSION

The presented analysis of variation of annual and seasonal average air and soil temperature at the station in Czarna covers a relatively short period (2009–2015). However, the obtained results, responding to climate change, are consistent with global and national reports on changes in trends in the average air temperature. A statistically significant trend of increasing average air temperature in the summer half-year was demonstrated for the station in Czarna. The trend in average air temperature in winter and annually is analogous, i.e. it also shows an upward trend, but in both cases it is not statistically significant.

Climate change is manifested in, among others, increase in average air temperature on a global and local scale. Temperature trends in the subsequent decades of the period 1951–2005 in Poland indicate a systematic

increase since the 1980s, and this trend is particularly intensified in the early spring and spring (Michalska, 2011). The average air temperature in Poland increases by about 0.2°C per decade (Marosz et al., 2011; Michalska, 2011). At the beginning of the 21st century, extremely warm months were recorded in winter in Poland, mostly in November and April (Polish Climate Monitoring Bulletin, 2015). The warmest winter was recorded in 2015. The months from November 2014 to April 2015 were between slightly warm and abnormally warm. The thermal classification of year periods for reference meteorological stations (standard period 1971–2000, according to the H. Lorenc classification) clearly shows that after 2000 warm and even abnormally warm summers appear more often, while the years 2014 and 2015 were classified at some stations as extremely warm (PSHM Bulletin, 2015). In light of the report of the World Meteorological Organization (WMO), 2018 was recognized as the fourth warmest year in history (WMO, 2018). The average global temperature in the first ten months of 2018 exceeded by 0.98°C the level from 1850–1900. The years of 2015–2018 period is regarded as the four warmest in measurements history.

Undoubtedly, air temperature is a factor determining the formation and retention of snow cover. Czarnecka (2012) studying the temporal and spatial variation of snow cover in Poland from November to March in the winter seasons 1960/61–2009/10 of 40 IMGW meteorological stations, found that the incidence and thickness of snow cover showed a downward trend, with no statistical significance for most stations. A statistically significant downward trend in the number of days with snow cover was recorded in December and January. Czarnecka also states that in the second half of

Table 8. The relationship between the average monthly air temperature and the average monthly soil temperature at individual depths of the soil profile

Temperature at depth:	Equation	Correlation coefficient (R)	Statistics t	Significance at p
0 cm	Y = 0.9058 · X + 3.0171	R = 0.98	47.349	$2.51 \cdot 10^{-61}$
5 cm	Y = 0.8712 · X + 3.3901	R = 0.97	36.812	$9.23 \cdot 10^{-53}$
10 cm	Y = 0.8521 · X + 3.3257	R = 0.96	32.133	$3.12 \cdot 10^{-48}$
20 cm	Y = 0.8175 · X + 3.6387	R = 0.96	31.383	$1.88 \cdot 10^{-47}$

given that Y – soil temperature, X – air temperature

the studied period, winter seasons were generally less snowy than in the sixties or eighties.

Subsequent studies on the variation of dates of the beginning and end of thermal winter and the winter period conducted in 1960–2015 did not show statistically significant changes (Czarnecka and Niedzgorska-Lencewicz, 2017). However, the authors found a slight tendency of shortening of thermal winter and the number of winter days (the actual number of days with a negative daily air temperature). Earlier studies conducted in the Zagożdżonka River catchment of the profile in Czarna also showed that according to the Paczosa classification, in the period 2003–2013 moderately cold winters with extremely low snow precipitation dominated in the research area (Hejduk and Hejduk, 2014). The 2014–2018 period had predominantly mild winters with extremely low snow precipitation. Snow cover appears later and lasts shorter. There has been virtually no thick cover (> 20 cm) in recent years.

Analysis of the incidence of frost, cold, cool, warm, hot and very hot days at the station in Czarna in 2009–2015 indicated an increase in the incidence of very hot and cold days and a decrease in the incidence of hot and frost days, as well as a stable remaining at a similar level the incidence of cool and warm days. An increase in the frequency of very hot days and a decrease in the frequency of frost days are a response to an increase in average air temperature. Similar results were obtained by other authors. Cebulak and Limanówka (2007) by analysing only the days with extreme (minimum and maximum) air temperature from 19 selected stations evenly distributed throughout the country in the 1951–2005 period showed an increasing tendency of very hot days and a decreasing tendency of frost days in a large area of Poland . The authors pointed to a decrease in the number of frost days, especially after 1972, except for the 1985–1987 period. After 1987, for 16 years there were no frosts reaching –30ºC. At the same time, days with a maximum temperature exceeding 35ºC were noted, and according to Kossowska-Cezak (2010) this phenomenon intensifies after 1990. Koźmiński and Michalak (2011) analysing the data from April-September from 38 IMGW first order stations for the years 1986–2009 found a statistically significant positive trend in the number of hot days, without clear changes in the number of warm and very hot days. The number of cold days in northern and central Poland showed a highly significant negative trend, while in the south-eastern part it was only significant. The number of cool days, however, decreased significantly in the southern and western regions of Poland.

The increase in air temperature, and consequently warmer winters and earlier dates of recent frosts extend the vegetation period (earlier beginning and later end), what has been reported both globally and in Poland over the last few years by Peano et al. (2019), Linderholm (2006), Tomczyk and Szyga-Pluta (2016), Nieróbca et al. (2013), Bochenek and Marczewski (2013). As a consequence, this change has an impact not only on agrotechnical measures and the proper selection of cultivated plants, but also on the species of fauna and flora. In Poland, the forests are dominated by trees such as pine, beech, oak, spruce, birch and alder. An increase in air temperature causes a change in the range of some of these species (e.g. pine). New plant species – but also insects and fungal pathogens (polypore, honey fungus) – may appear in areas where they did not occur so far. As for the research catchment, which is mainly used for agriculture, and forests cover only 20% of area, the growing season duration has not been studied, however in the light of increasing air temperature, changes in this area can be expected.

Depending on the depth of soil and its coverage, soil temperature is connected to basic meteorological elements, such as: air temperature, solar radiation intensity and precipitation (Oni et al, 2017; Fang et al., 2019, Bryś, 2008; Wojtkowski and Skower, 2017, Szyga-Pluta, 2018). The average soil temperature at the Czarna station varies depending on the depth of the soil profile. The average temperature at the ground surface (0 cm) in the 2009–2015 period showed an upward trend. At other depths this tendency was not evident. When measuring at a depth of 20 cm, a slight, decreasing trend in changes of average temperature as well as in average summer and winter temperatures was observed.

The monthly distribution of average soil temperature at individual depths of the soil profile coincided with the monthly distribution of average air temperature. In both cases, the highest average temperature was recorded in July and the lowest in February. On a monthly basis, the average soil temperature at all examined depths of the soil profile was positive. Similar

results were presented by Wojtkowski and Skowera (2017), also pointing out the seasonal variation of the relationship between soil temperature and air temperature. By analysing data from the station in Ojców for the 1991–2006 period, the authors proved that the strongest relationship between air temperature and soil temperature occurs in spring and autumn. In other seasons it is much weaker. Szyga-Pluta (2018) came to similar conclusions when studying the temperature variation in the soil profile at the station in Jezior in 2002–2015. Plant cover and snow cover affect soil temperature throughout its profile. At the same time, rainfall weakens the relationship between soil temperature and air temperature. Dry soils have poor conductivity and low heat capacity, therefore they heat up faster and have a higher temperature than moist soils (Rojek and Usowicz, 2018).

CONCLUSIONS

The following conclusions are to be drawn from the results of the air and soil temperature analysis at the Czarna station in 2009–2015:

1. The average air temperature for the 2009–2015 period at the Czarna station was 8.6°C, showing an upward trend both annually and seasonally.

2. The distribution of average air temperature in individual months indicated that the coldest months were January, February and December, respectively. Positive average air temperature values were recorded in November, March and April. The warmest months were July, August and June. The average temperature in May and September was similar.

3. During the studied period, there was a decreasing tendency in the number of frost days, in contrast to cold and very hot days. The number of hot days in 2009–2015 remained at a similar level. The number of frost days showed the largest standard deviation (14.41), while the number of hot days – the smallest. The highest coefficients of variation were recorded for the number of very hot (69%) and frost (48%) days.

4. The average soil temperature showed an upward trend for the surface layer. The average soil temperature at all depth levels demonstrated the highest values of coefficients of variation in the

winter period. The medium-term rate of change was positive only for the average temperature at a depth of 0 cm both annually and semi-annually.

5. The monthly distribution of average soil temperature at individual depths of the soil profile coincided with the monthly distribution of average air temperature. At all analysed depths of the soil profile, the average temperature decreased from August to February, while it increased from March to July.

6. The relationship between air temperature and the temperature of the top soil layers was noted. It was the strongest just above the ground (correlation coefficient R = 0.98). The deeper the soil profile level, the lower the correlation coefficient, although it still remained at R = 0.90. At a depth of 20 cm, the impact of air temperature on soil temperature was still strong (R = 0.96).

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RELACJE POMIĘDZY TEMPERATURĄ POWIETRZA I GLEBY JAKO LOKALNY WSKAŹNIK ZMIAN KLIMATU W MAŁEJ ZLEWNI ROLNICZEJ

ABSTRAKT

Cel pracy

Celem pracy było rozpoznanie trendów zmian temperatury powietrza i temperatury gleby oraz ich wzajemnych zależności, jak również sprawdzenie, czy krótkie ciągi danych pomiarowych mogą być wskaźnikiem lokalnych zmian klimatu.

Materiały i metody

Podstawę obliczeń stanowiły dane pomiarowe temperatury powietrza oraz gleby na czterech głębokościach profilu glebowego, gromadzone z dziesięciominutowym krokiem czasowym na stacji w Czarnej w latach 2009–2015. Na podstawie posiadanych danych obliczono minimalną, maksymalną i średnią dobową temperaturę powietrza oraz gruntu na poszczególnych głębokościach profilu glebowego w ujęciu dobowym, miesięcznym, półrocznym i rocznym. Wartości średnie miesięczne posłużyły do wyznaczenia zależności pomiędzy temperaturą powietrza i gleby na poszczególnych głębokościach. W oparciu o temperaturę maksymalną powietrza obliczono liczbę dni mroźnych, zimnych, chłodnych, ciepłych, gorących i upalnych, zgodnie z metodyką podaną w Atlasie Klimatu Polski. Wyznaczono trendy zmian temperatury i regresję liniową. Zarówno w przypadku trendów jak i równań regresji liniowej sprawdzono istotność statystyczną współczynników równań przy zastosowaniu testu t–Studenta. Wyznaczono też podstawowe miary statystyczne.

Wyniki i wnioski

Wykazano istnienie statystycznie istotnego trendu rosnącego średniej temperatury powietrza w półroczu letnim. Średnia temperatura powietrza w zimie oraz w ujęciu rocznym również wykazuje tendencję wzrostową, lecz trend nie jest istotny statystycznie. Liczba dni mroźnych wykazuje tendencję malejącą, w przeciwieństwie do liczby dni zimnych i upalnych. Liczba dni gorących w badanym okresie pozostawała na podobnym poziomie. Średnia temperatura gleby wykazuje tendencję wzrostową dla w warstwy powierzchniowej, natomiast w warstwach głębszych zmienność temperatury jest bardziej zróżnicowana. Miesięczny rozkład średniej temperatury gleby jest zbieżny z miesięcznym rozkładem średniej temperatury powietrza. Wykazano związek pomiędzy temperaturą powietrza, a temperaturą wierzchnich warstw gleby.

Słowa kluczowe: mała zlewnia rolnicza, temperatura powietrza, temperatura gleby, tendencje zmian temperatury powietrza i gleby