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Contemporary changes of thermal conditions in Poland, 1951-2015

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Abstract. The main subject of the research whose outcomes are presented in this paper is the spatial and temporal variability of thermal conditions in Poland during the period from 1951 to 2015. The analysis revealed the occurrence of symptoms indicating a systematic and sustained warming. Significant growth is observed in mean and extreme temperatures and their extreme percentiles, as well as in annual number of hot days, warm waves and their duration. In turn, downward trends are noted in series of the annual number of frost days, as well as in the number of cold waves and their duration. The results obtained confirm the thermal pattern determined for the whole region, especially for the southern part of the Baltic Sea Basin.

Key words:
mean and extreme air temperature, air temperature change indices, climate change, Poland

Introduction

Climate constitutes an important element of the geographical environment and is an essential factor of human activity. It significantly influences all processes occurring in the environment and the currently observed climate change is classified as one of the features that most significantly shape the present world. Because of its importance in many sectors (e.g. energy production, agriculture, health care and human well-being) it is not only a subject of research, but also a social and political issue. Extreme events, including those related to air temperature, particularly influence numerous aspects of human life.

According to the definition established by the IPCC, the term “climate change” refers to a change in the state of the climate which can be identified by changes in the mean – and/or the variability – of its properties and which persists for an extended period, typically decades or longer (IPCC 2013). Changes in thermal conditions, manifested by a change in average as well as extreme values of air temperature, are among the most meaningful changes. Paleoclimatic reconstructions of air surface temperature for Europe going back to 1500 show the late-20th- and early-21st-century continent is warmer than that of any time during the past 500 years (Luterbacher et al. 2004). Compared with the 20th century, annual mean temperatures in Europe during the period 1500–1900 were lower by approximately 0.25°C, and winter average temperatures by 0.5°C. Casty et al. (2007) noted that seasonal European temperatures were showing a positive trend, mainly over the period 1961–2000, with the absolute highest values since 1766. After 1900 a strong increase in winter temperature was detected. Until 1900 a cooling had been observed in spring, which then increased again to warmer than average temperatures after 1900. When compared to a reference period of 1901–2000, a slight cold phase in summer temperatures was observed during the period 1966–1984 and recent temperature anomalies again are positive. In turn, autumn temperatures decreased to lower than average values during 1967–1980, and nowadays are significantly increasing. According to Reports of the EEA (2012) and the IPCC (2014), the average temperature for the European land area for the decade 2002–2011 is 1.3°C above the pre-industrial level (1850–1899 average).

A clear increase in surface air temperature in the Baltic Sea basin has also been observed since the beginning of the observational record in 1871. Linear trends in the annual mean temperature anomalies from 1871 to 2011 were 0.08°C per decade south of 60°N in the Baltic Sea Basin. This is higher than the trend recorded for the global mean temperature, which is about 0.06°C per decade for 1861–2005 (von Storch et al. 2015). Likewise, all seasonal trends in the mean temperature anomalies are positive and statistically significant in this region. South of 60°N in the Baltic Sea Basin, the largest trends are observed in winter and spring (0.1°C per decade); in autumn it is 0.07°C per decade and the smallest trend is in summer (0.04°C per decade).

Climate research has also shown some long-term changes in indices of daily temperature in Europe. The 1946–1999 trend in the average annual number of days with minimum temperature below 0°C was -1.7 per decade, which means that in late 90s of the 20th century it was already about 9 days fewer than in half of 40s. On the other hand, the trend in the average annual number days with maximum temperature above 25°C (0.8 per decade) indicates an average decrease by 4 days over the analysed period (Klein Tank and Können 2003).

An explicit increase was detected in extreme thermal conditions in summer (June–August) in various countries in western Europe. Over the period 1880–2005 the length of summer heat waves over western Europe doubled and the frequency of hot days almost tripled (Della-Marta et al. 2007; EEA 2012).

Climate models broadly confirm all emission scenarios for Europe, predicting the strongest warming in Southern Europe in summer, and in Northern Europe in winter. Land temperature in Europe is projected to increase between 2.4°C and 4.1°C, depending on the particular RCP (Respective Concentration Pathway, IPCC 2013), by 2071–2100 compared to the period 1971–2000 (Jacob et al. 2013). According to the IPCC Atlas of Global and Regional Climate Projections (IPCC 2013), the warming is projected to be greatest in north-eastern Europe and Scandinavia. Climate projections also show an evident increase in high temperature extremes (IPCC 2012). Particularly, the heat waves are projected to become more frequent and last longer across Europe over the 21st century (EEA 2012).

Data and methods

In order to prepare the analysis of air temperature in Poland, data series recorded at 18 stations for the period 1951–2015 were used (Fig. 1). The stations represent different geographical regions of the country. The above-mentioned series were obtained from a certified, adjusted-for-inhomogeneity database of the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB). Only two series were incomplete (Rzeszów covers the years 1952–2015, the data of Kasprowy Wierch Mt. in the Tatra Mountains are available for the period from 1961).

On the basis of the daily mean, maximum and minimum temperatures series (Tmean, Tmax and

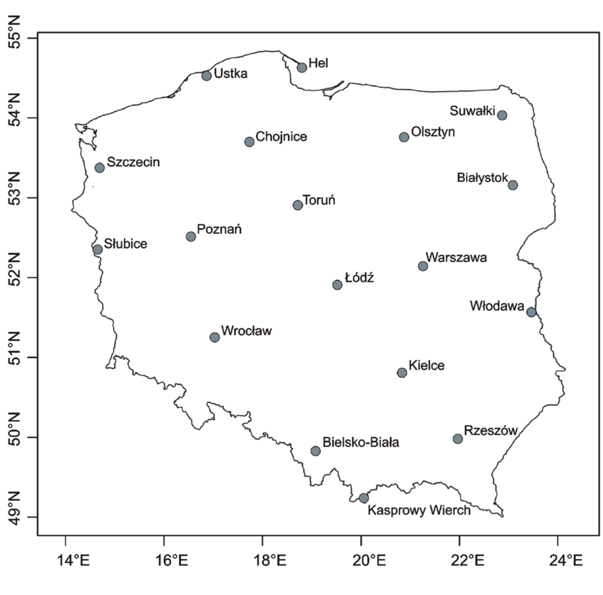

Fig. 1. Location of stations from which data has been used

Tmin, respectively), annual and seasonal (December–February, March–May, June–August and September–November) means were calculated. The same characteristics were also calculated for the difference between daily maxima and minima (DTR – Daily Temperature Range). Additionally, the relation between extreme temperatures and their percentiles – 5% for the minimum temperature and 95% for the maximum – were estimated.

What is more, the annual number of days meeting the determined criteria, known as "thermally specific days" has been established. For the purpose of this study they have been defined as follows:

— "ice" and "very ice" days – days with maximum air temperature lower than 0°C and days with particularly low air temperature, when maximum air temperature is below -10°C, respectively;

— "frost" days – days with maximum air temperature exceeding 0°C and daily minima lower than 0°C, which means that the threshold 0°C was crossed;

— "hot" days – days when maximum air temperature exceeds 25°C;

— "sweltering" days – days with maximum air temperature equaling at least 30°C.

Additionally, the annual number and duration of spells of a particularly high, or particularly low, air temperature, defined as a "warm wave" and a "cold wave", were also counted. The definition of the waves was formulated depending on climatic conditions, on the basis of the works of Morawska-Horawska (1991), Miętus and Filipiak (2001), Owczarek (2012). A warm wave has been defined as at least 4 consecutive days with daily maximum temperature exceeding its long-term average (1971–2000) by more than one standard deviation. A cold wave has been defined similarly to the above-mentioned – as at least 4 consecutive days with daily minimum temperature lower than its long-term average by more than one standard deviation.

All analysed series follow a normal distribution. Complying with the principles expressed by Wibig (1990), the authors tried to search for features in their simplest form (linear regression), because, for a complicated equation, it is difficult to find an appropriate physical interpretation. The statistical significance of the trends was examined using the F-Snedecor test at the significance level $1-\alpha=0.95$. This test allows a range of changes of a given variance to be assessed (explained by the trend equation) and to verify if its value increases significantly when transiting to a higher order (Wibig 1990). The F-Snedecor test was also widely used in the previous climatological analyses (Sneyers 1990; Miętus and Filipiak 2001; von Storch and Zwiers 2001) and that is why the authors decided to apply it in order to estimate linear regression.

Spatial diversity of air temperature in Poland

The mean annual air temperature in Poland (Table 1) varies between 6.4°C (Suwałki, north-eastern Poland) and 8.9°C (Słubice, western Poland). Generally, the western part of the country is warmer than the east. However, the decrease in mean annual air temperature from west to east is most considerable in northern Poland, within the Lakeland belt. To some extent, the thermal activity of the Baltic Sea, especially the deepest areas of the Gulf of Gdańsk, plays a role in the thermal regime of the seaside stations. Thus, the mean annual air temperature recorded by the seaside stations is not lower than 8°C. Submountain areas and valleys located in southern Poland are also among the warmest regions of the country, with the mean annual air temperature at about 8°C or more. The most elevated regions of the country (the Tatra Mts., southern Poland) are much colder – the value of the element does not exceed 0°C (-0.5°C at Mt. Kasprowy Wierch, 1986 m a.s.l.).

The range of average maximum annual air temperature in Poland is about 3°C (Table 1), and varies from the highest values observed at stations situated in the interior (13.6°C in Słubice, 13.5°C in Wrocław) to 11°C and even less recorded in the lakelands and lowland areas of north-eastern Poland (10.5°C in Suwałki, 11.4°C in Białystok). In the seaside region, the maximum annual air temperature slightly exceeds 11°C (11.2°C in Ustka and Hel). The lakelands in northern Poland also have a relatively low value of this parameter (11.3°C in Chojnice, 11.4°C in Olsztyn). In central and southern Poland the maximum annual air temperature exceeds 12°C. In the Tatra Mts., it scarcely exceeds 2°C.

The seaside stations usually record the highest values of average minimum annual air temperature, which is usually higher than 5°C (Table 1). North-eastern Poland, where the average minimum annual air temperature does not exceed 2.5°C, is the coldest region of the country (except for the mountains). Eastern Poland, and the lakelands (located in northern Poland) are also relatively cold regions. In some cases, a particular station's local conditions can influence minimum temperature readings, e.g. in Kielce (3.0°C) where the station is located in the vicinity of the Świętokrzyskie Mts. (the culmination of Małopolska Upland in southern Poland). Besides this, the minimum temperature fluctuates around the value of 4°C, except in the Tatra Mts., where it equals –3°C.

The mean annual value of the DTR varies between 6°C and 9°C (Table 1). Only locally does it exceed 9°C (Wrocław, in south-western Poland – 9.4°C; Słubice, in western Poland and Kielce, in southern Poland – 9.3°C). Much lower values of DTR are only typical for the coast (6°C) and the highest mountains (5.4°C).

In spring, the coastal region is the coldest in Poland, as the value of the mean seasonal air temperature is at least 1.5°C less there than in the interior. In Ustka it is 6.3°C; in Hel, located on a narrow peninsula, it is only 6°C. Western Poland remains the warmest part of the country, whereas the eastern part is colder than the centre and south. The spatial diversity of the mean maximum temperature is similar to the spatial diversity of the mean temperature. The lowest values are recorded on the coast (below 10°C), and the lakelands in north-eastern Poland (less than 11°C). In western Poland the mean value of maximum seasonal temperature rises to 13.5° and more, while in southern Poland it also exceeds 13°C. The diversity of the minimum air temperature is rather small, the values range between 2°C and approximately 3.5°C. Only the values recorded in north-eastern Poland do not exceed 2°C (e.g., Suwałki – 1.4°C). The DTR is the smallest at the seaside stations (about 7°C), while its highest values, exceeding 10°C, characterise the interior.

In summer (June–August) the mean seasonal temperature rises above 17.5°C in central and southern Poland (Warszawa – 17.9°C, Poznań and Wrocław – 17.8°C, Toruń and Włodawa – 17.7°C). The lakelands and the coast are among the coldest regions in the country; there, the mean temperature does not exceed 17°C and occasionally falls below 16.5°C (the lakeland stations, Chojnice and Suwałki; the seaside station, Ustka). The average maximum seasonal temperature varies between 20°C (Ustka) and 23.6°C (Rzeszów and Wrocław). The southern and central parts of Poland are the warmest parts of the country. On the other hand, the average minimum temperature recorded in the seaside stations reaches 12.7°C and more, whereas in the interior this parameter's value varies between 11 and 12°C, with the exception of the largest cities. In Warszawa, Poznań, Wrocław and Łódź the average minimum seasonal temperature exceeds 12°C. The lowest values of DTR are typical for the coast (below 8°C) and are about 2.5–3°C lower than in the remaining area.

Autumn is usually warmer than spring in Poland; however, the difference between the air temperature readings for these two seasons in some locations is very small. Both seasons differ considerably in terms of spatial variability of air temperature. In autumn, the northern and western parts of the country are the warmest. The mean temperature exceeds 8.5°C (western Poland) or even 9°C (the coast), whereas in the remaining area of Poland it is rather below 8°C, or even less (6.8°C in Suwałki). As for the maximum air temperature in autumn, the thermal preference of the seaside region is not observed. The values noted there, fluctuating around 12°C, are comparable with the readings obtained in the interior. Two regions are visibly warmer: the most westward areas of Poland and the Silesian Lowland (respectively, in Słubice – 13.6°C and in Wrocław – 13.6°C). The previously-mentioned privilege of the coast is clearly visible when analysing the spatial diversity of the minimum seasonal air temperature. The coast is 2–3°C warmer than the rest of the territory of the country. Hel has a remarkably high value, at 7.2°C. The minimum air temperature in the interior varies between 3.5°C and 5°C, and the western part of the country is slightly warmer than regions located in eastern and southern parts of Poland. The mean daily temperature range in autumn varies, from 5–5.5°C in the coastal region to 7°C in the lakelands (Suwałki, Chojnice, Olsztyn), 8°C in central Poland (Warszawa, Łódź, Toruń, Poznań), and even 8.5–9°C in certain areas of western (Wrocław, Słubice) and south-eastern Poland (Rzeszów).

The longitudinal decrease in air temperature is the most characteristic feature of winter. The mean seasonal air temperature varies from positive values in western Poland (Słubice – 0.2°C and Szczecin – 0.3°C) and the seaside stations (Ustka and Hel – 0.3°C), to -3.0°C in Białystok and -3.6°C in Suwałki in eastern Poland. In the coastal region, the sea exerts a strong influence on temperature as its values decrease gradually with increased distance from the coastline. The values of the maximum seasonal temperature are negative only in north-eastern Poland (-0.4°C in Białystok and -1.2°C in Suwałki), whereas in the western part of the country they reach more than 3°C (Słubice). The average minimum temperature in winter across the whole area of the country is below 0°C, the coast is the warmest region in Poland with the temperature value above -2°C. The values vary in western Poland between -2°C and -3°C, and in central Poland between -3°C and -4°C, while in eastern Poland the minimum air temperature does not exceed -5°C. The lakelands are even colder, with increasing geographical longitude as well as distance from the Atlantic Ocean, the minimum temperature values decrease from about -4°C (Chojnice) to less than -6°C (Suwałki). The mean seasonal DTR values in winter are the lowest at the seaside stations (Hel – 3.5°C and Ustka 4.3°C); however, they are not considerably higher in the interior, since at the majority of stations they do not exceed 5.5°C. In certain stations in western and southern Poland, DTR equals or exceeds 6°C (Wrocław, Słubice, Kielce, Rzeszów and Bielsko-Biała).

In the mountains, the values of T_{mean}, T_{max} and T_{min} are considerably lower in comparison with the remaining part of the country. The value of DTR in particular seasons fluctuates around 5–6°C throughout the year.

Long-term variability of air temperature in Poland

The annual mean temperature and both extreme temperatures have increased significantly since 1951 in Poland. As for the mean annual temperature, no specific regional regularity can be found in the spatial diversity of the rate of growth, besides a slower increase in air temperature at stations in eastern and north-eastern Poland (Włodawa, Białystok and Suwałki) (Table 2, Fig. 2). The rate of growth varies between 0.18 and 0.34°C per decade, which indicates that the mean annual air temperature in Poland has grown by 1.1–2.2°C since 1951. The rate of increase of maximum annual temperature is less diversified than in the case of mean temperature. The slowest increase, at 0.19°C per decade, was achieved in Hel (Fig. 2a) and Kielce, while the greatest increase was detected in Słubice (western Poland), and Rzeszów and Bielsko-Biała (southern Poland), with 0.34°C per decade. Generally, the rate of increase of the minimum annual temperature in Poland is slightly faster. At the seaside station in Ustka, during the analysed period, these values grew by scarcely 2°C in Włodawa by 1.8°C and in Hel and Rzeszów by 1.7°C (Fig. 2a, 2d). On the other hand, the increase in the daily minima in Suwałki (Fig. 2b) and Kielce scarcely exceeded 1°C, while in Białystok the rate of increase was even slower, and did not exceed 0.8°C.

Most of the considered stations detected an asymmetric trend in the air temperature range, which is caused by a more intense increase in the daily minima than in the maxima. In Ustka, Hel and Włodawa, the negative trends of DTR are statistically significant. A statistically significant upward trend also revealed itself in data series obtained at the station in Suwałki.

Spring is the season when the most dynamic changes occur. The increase in the mean and extreme temperatures is statistically significant within the whole Polish territory. In the case of the mean temperature, the rate of growth reaches 0.3–0.4°C per decade, while in the case of the maximum temperature it is even higher, and usually exceeds 0.4°C per decade; in Suwałki (north-eastern Poland), it equals 0.5°C per decade. The slowest rate of increase was detected in the coastal region. The mean value of the daily minima also increases significantly at all the stations. Its long-term change in the analysed period varies between 1.2°C in Białystok and Kasprowy Wierch Mt. and 2.7–2.8°C in Hel and Ustka, respectively. The daily maxima in spring are growing at a faster pace in comparison with the daily minima. It is worth noting that only in the coastal belt was the minimum temperature growing faster than the maximum temperature.

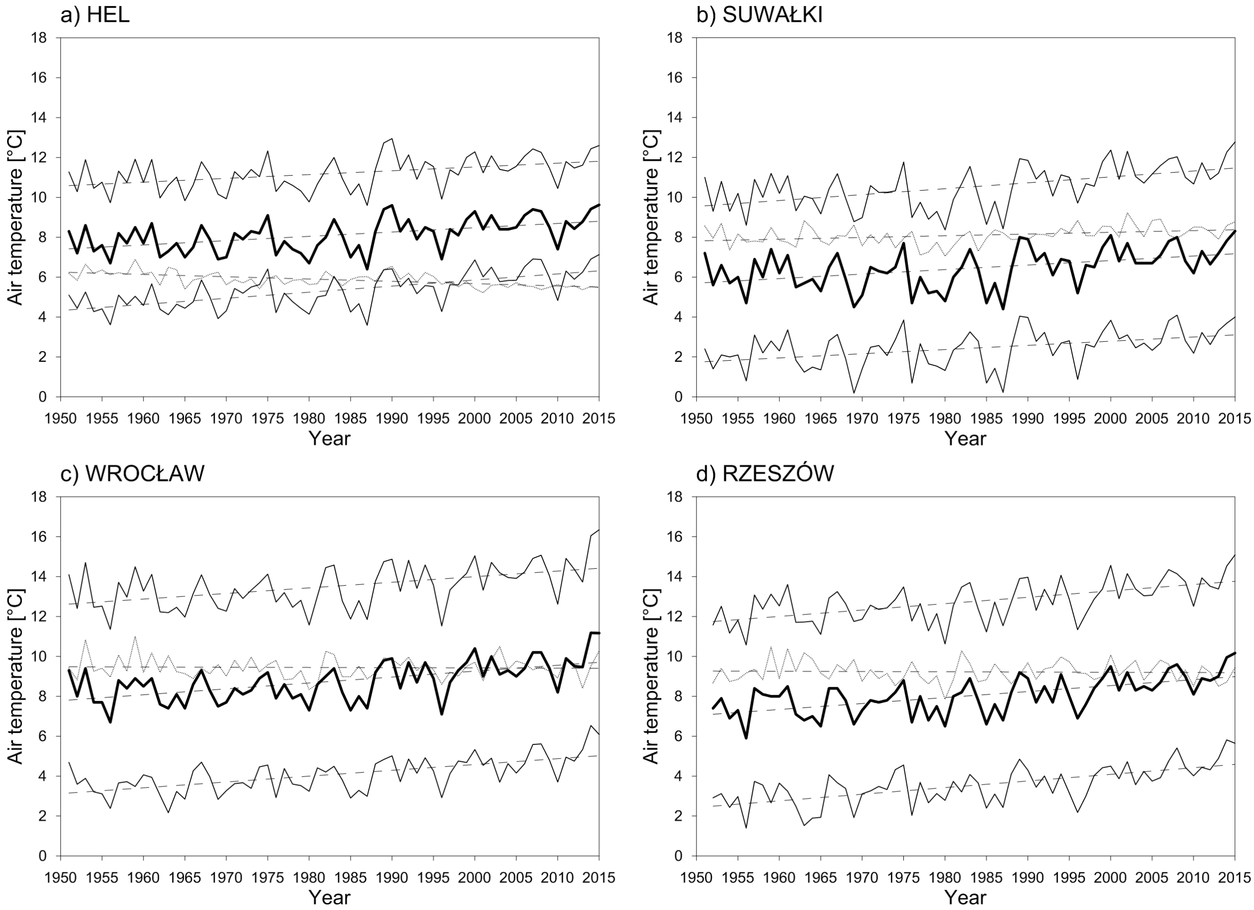

Fig. 2. Long-term variability of annual mean temperature (thick solid line), maximum temperature (upper thin solid line), minimum temperature (lower thin solid line) and daily temperature range (dotted line) at selected stations in Poland, 1951–2015. Dashed lines represent respective trends

The rate of the air temperature increase is slower in summer than in spring, with the exception of Kasprowy Wierch Mt. The trend is statistically significant for the majority of series. The mean seasonal temperature is rising at the fastest pace, equaling at least 0.3°C per decade at a few stations, located irregularly across the country's territory. The series of daily maxima, except that of Białystok (north-eastern Poland), show a significant positive trend whose rate varies between 0.13°C and 0.38°C per decade in Hel (coast) and Bielsko-Biała (southern Poland), respectively. At Kasprowy Wierch Mt. that value is considerably higher, and reaches 0.51°C. Nonetheless, the greatest increase in minimum temperature was detected (with a rate of 0.34°C per decade) on the coast. At three stations the revealed changes are not statistically significant (both stations in north-eastern Poland, and Kielce, located in the uplands of southern Poland). It can be stated that in the north-eastern part of Poland the temperature in summer has not changed since 1951.

The changes in air temperature in autumn are not as evident as in spring and summer. The mean seasonal temperature shows a positive trend only for a half of the analysed series and its rate does not exceed 0.2°C per decade. As for the minimum temperature, all the series show a statistically significant growth. There are no observed changes in the mean maximum temperature. In the whole of Poland, except the northeast, DTR is decreasing – statistically significantly in the case of a few stations.

A strong systematic increase in the extreme air temperatures is typical for winter, especially in the case of the daily minima. For some series the rate of increase exceeds 0.4°C per decade (Włodawa and Rzeszów, eastern and south-eastern Poland, respectively; and Toruń, Central Poland), which translates into a 3°C increase in the daily minima in the analysed period. In the case of the maximum temperatures it varies from 0.34°C per decade in Szczecin (north-western Poland) and Toruń (central Poland) to 0.2°C per decade in Hel (coast). A statistically significant increase in the mean temperature is also very common in winter in Poland, although in the case of four series (Białystok, north-eastern Poland; Bielsko-Biała, southern Poland; Włodawa, eastern Poland; and Kielce, southern Poland) the trend coefficients are not significant. As the daily minima increases faster than the daily maxima, a decrease in DTR in winter is common for numerous stations, and a statistically significant trend was observed for half of the series. The spatial diversity of the value of the trend coefficient is irregular.

Similarly to the annual maximum and minimum air temperatures, their extreme percentiles are also systematically increasing. In the case of the 95% percentile of maximum temperature, a statistically significant increase can be observed among all the series, with the exception of Białystok (north-eastern Poland) and Kielce (southern Poland). The value of the 5% percentile of minimum temperature also grew rapidly throughout the discussed period. The rate of increase is the lowest in Hel (coast), whereas the highest rates were observed in Rzeszów and Włodawa (south-eastern and eastern Poland, respectively).

The values of both analysed percentiles of extreme temperatures increase in spring and summer. A statistically significant growth is more common in the case of the 95% percentile of maximum temperature, as it concerns the majority of series. Some fast positive changes of this variable are particularly common in summer. Notwithstanding, in summer the value of the 5% percentile of minimum temperature decreased at the stations located in the north-east of the country. No long-term changes in the series of the analysed percentiles were observed in autumn. In the case of winter, the values of both percentiles increased; moreover, the 95% percentile of maximum temperature was growing at a fast rate (about 0.3–0.4°C per decade) in the whole country (except of Rzeszów, south-eastern Poland and Kasprowy Wierch Mt.). A statistically significant increase in the 5% percentile of minimum temperature in winter was observed only in a few of the selected locations.

The relationship between the minimum annual temperature and its 5% percentile is stronger than between the maximum annual temperature and its 95% percentile. A 1°C change in the minimum temperature would change the 5% percentile value by 2.5–3°C on average. In the case of the stations located in north-eastern and eastern Poland the 5% percentile would change by more than 3.5°C. A 1°C change in the daily maximum would change the equivalent by, at most, 1°C of its 95% percentile.

The scheme of relations described above is repeated in particular seasons. A 1°C change in the maximum seasonal temperature would change the 95% percentile value by 1°C in autumn and summer. In spring the range of the change of percentile responding to the change of minimum temperature is higher and varies between 0.5°C and 1.3°C. In winter the 95% percentile would change by less than 1°C. A 1°C change in the mean minimum temperature of particular season would change the 5% percentile value by more than 2°C in spring, 1°C in summer, nearly 2°C in autumn and 1.5°C in winter.

Variability of the number of thermally specific days

During the discussed period of time, in the western part of Poland and on the coast approximately 25 ice days were observed. Such days appear during the period from November to March, and occasionally in April and October. Only in the Tatra Mts. are ice days recorded throughout the year, and their number was also the highest there (on average 143 a year). In north-eastern and eastern Poland from 50 to 60 ice days were annually registered, whereas in the other regions it was less than 40 (Table 3). Very ice days can be identified in Poland only in winter (DJF) and very rarely in March and November (the mountains are the exception). Such days appear, on average, a few times a year: once on the seashore and in western Poland, twice or three times in the remaining areas, excluding the north-eastern part, where 4–5 such days are observed, and in the mountains, where the number is highest (18 days). The greatest number of such days was recorded during the winter season 1984/1985: 32 in the Tatra Mts. and 23 in Włodawa (eastern Poland). The number of both types of these spe-

Table 1. Average annual and seasonal air temperature (T_{mean}), maximum (T_{max}), minimum (T_{min}) and daily temperature range (DTR) in Poland [°C], 1951-2015

STATION	Year				Spring (MAM)				Summer (JJA)				Autumn (SON)				Winter (DJF)			
	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR
Białystok	7.0	11.4	2.7	8.7	6.8	11.9	1.8	10.2	17.0	22.7	11.2	11.5	7.2	11.3	3.6	7.7	-3.0	-0.4	-5.8	5.4
Bielsko-Biała	8.2	12.4	4.2	8.2	7.8	12.4	3.4	9.0	16.9	22.0	12.1	9.9	8.9	12.9	5.2	7.7	-0.9	2.2	-4.0	6.2
Chojnice	7.1	11.3	3.5	7.8	6.5	11.5	2.3	9.2	16.3	21.8	11.4	10.4	7.5	11.4	4.6	6.7	-1.9	0.6	-4.1	4.7
Hel	8.1	11.2	5.3	5.9	6.0	10.0	2.7	7.3	16.5	20.8	12.9	7.8	9.5	12.0	7.2	4.8	0.3	2.0	-1.5	3.5
Kielce	7.5	12.3	3.0	9.3	7.4	12.8	2.2	10.5	17.1	23.1	11.3	11.7	7.8	12.5	3.8	8.7	-2.2	0.9	-5.3	6.2
Łódź	8.0	12.4	4.0	8.4	7.8	12.7	3.2	9.5	17.5	23.1	12.1	11.0	8.3	12.6	4.8	7.8	-1.5	1.2	-4.2	5.4
Olsztyn	7.3	11.4	3.3	8.1	6.8	11.7	2.0	9.6	16.8	22.1	11.6	10.6	7.8	11.4	4.5	7.0	-2.2	0.3	-4.8	5.1
Poznań	8.6	12.9	4.4	8.5	8.2	13.3	3.4	9.9	17.8	23.5	12.4	11.1	8.8	12.9	5.1	7.8	-0.7	2.0	-3.4	5.4
Rzeszów	8.0	12.8	3.5	9.2	7.9	13.3	2.8	10.5	17.6	23.6	11.9	11.7	8.5	13.0	4.4	8.6	-1.9	1.0	-5.0	6.0
Słubice	8.9	13.6	4.3	9.3	8.5	13.9	3.2	10.7	17.6	23.5	11.8	11.8	9.1	13.6	5.1	8.5	0.2	3.3	-2.8	6.0
Suwałki	6.4	10.5	2.4	8.1	6.0	10.8	1.4	9.4	16.5	21.9	11.1	10.8	6.8	10.5	3.5	7.0	-3.6	-1.2	-6.3	5.1
Szczecin	8.8	12.9	4.9	8.1	8.2	13.1	3.5	9.6	17.4	22.7	12.4	10.3	9.2	13.0	5.8	7.2	0.3	2.8	-2.3	5.1
Toruń	8.0	12.6	3.8	8.8	7.6	12.9	2.6	10.3	17.7	23.4	11.9	11.5	8.3	12.6	4.7	7.9	-1.4	1.4	-4.1	5.5
Ustka	8.1	11.2	5.2	6.0	6.3	10.0	3.3	6.7	16.2	19.9	12.7	7.2	9.4	12.4	6.6	5.7	0.3	2.5	-1.8	4.3
Warszawa	8.2	12.4	4.1	8.4	8.0	12.9	3.3	9.6	17.9	23.3	12.6	10.8	8.3	12.4	4.7	7.7	-1.7	1.0	-4.4	5.4
Włodawa	7.6	12.0	3.2	8.8	7.5	12.5	2.6	9.8	17.7	23.4	11.9	11.5	7.9	12.2	3.9	8.2	-2.6	0.1	-5.6	5.7
Wrocław	8.8	13.5	4.1	9.4	8.5	13.8	3.2	10.5	17.8	23.6	12.1	11.5	9.0	13.8	4.7	9.0	-0.3	2.9	-3.7	6.6
Kasprowy W.	-0.5	2.4	-3.0	5.4	-2.1	0.8	-4.4	5.2	7.0	10.3	4.6	5.7	0.7	3.5	-1.7	5.2	-7.7	-4.9	-10.3	5.5

Table 2. Trend coefficients (°C · decade^{-1}) of average annual and seasonal air temperature (T_{mean}), maximum (T_{max}), minimum (T_{min}) and daily temperature range (DTR) in Poland [°C], 1951–2015.

STATION	Year				Spring (MAM)				Summer (JJA)				Autumn (SON)				Winter (DJF)			
	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR	T_{mean}	T_{max}	T_{min}	DTR
Białystok	**0.18**	**0.21**	**0.15**	0.05	**0.29**	**0.40**	**0.19**	**0.21**	0.04	0.10	0.03	0.08	0.05	0.04	0.03	0.01	0.30	**0.28**	**0.38**	-0.08
Bielsko-Biała	**0.27**	**0.32**	**0.28**	0.04	**0.37**	**0.46**	**0.34**	**0.12**	**0.31**	**0.38**	**0.29**	**0.09**	0.11	0.14	**0.15**	-0.01	0.29	**0.29**	**0.32**	-0.03
Chojnice	**0.34**	**0.28**	**0.26**	0.02	**0.47**	**0.45**	**0.30**	**0.15**	**0.31**	**0.23**	**0.21**	0.03	**0.20**	0.11	**0.14**	-0.02	**0.36**	**0.30**	**0.37**	-0.08
Hel	**0.22**	**0.19**	**0.31**	**-0.12**	**0.37**	**0.37**	**0.41**	-0.04	**0.18**	**0.13**	**0.34**	**-0.20**	0.08	0.02	**0.17**	**-0.16**	**0.23**	**0.22**	**0.29**	**-0.06**
Kielce	**0.20**	**0.23**	**0.21**	0.01	**0.31**	**0.38**	**0.28**	0.10	**0.18**	**0.21**	0.17	0.04	0.05	0.05	0.07	-0.01	0.24	**0.26**	**0.35**	-0.09
Łódź	**0.26**	**0.27**	**0.27**	0.00	**0.38**	**0.44**	**0.30**	**0.14**	**0.23**	**0.25**	**0.25**	0.00	0.11	0.07	**0.14**	-0.06	**0.31**	**0.29**	**0.40**	**-0.10**
Olsztyn	**0.25**	**0.26**	**0.30**	-0.03	**0.39**	**0.46**	**0.38**	0.08	**0.17**	**0.20**	**0.21**	-0.01	0.11	0.08	**0.15**	-0.07	**0.31**	**0.28**	**0.43**	**-0.15**
Poznań	**0.28**	**0.27**	**0.30**	-0.03	**0.40**	**0.43**	**0.35**	0.08	**0.23**	**0.24**	**0.25**	-0.01	**0.14**	0.09	**0.17**	-0.09	**0.34**	**0.32**	**0.43**	**-0.11**
Rzeszów	**0.30**	**0.32**	**0.33**	-0.01	**0.41**	**0.47**	**0.37**	0.10	**0.30**	**0.35**	**0.31**	0.04	**0.15**	0.13	**0.19**	-0.05	**0.34**	**0.31**	**0.47**	**-0.16**
Słubice	**0.26**	**0.32**	**0.30**	0.01	**0.36**	**0.46**	**0.34**	0.12	**0.25**	**0.35**	**0.25**	0.11	**0.12**	0.13	**0.21**	-0.08	**0.31**	**0.32**	**0.41**	**-0.09**
Suwałki	**0.23**	**0.30**	**0.21**	**0.09**	**0.35**	**0.50**	**0.26**	**0.24**	0.12	**0.21**	0.08	**0.14**	0.10	0.13	0.08	0.05	**0.31**	**0.31**	**0.40**	-0.09
Szczecin	**0.27**	**0.28**	**0.26**	0.02	**0.37**	**0.40**	**0.34**	0.07	**0.21**	**0.23**	**0.19**	0.04	**0.13**	0.13	**0.13**	0.00	**0.35**	**0.34**	**0.37**	-0.03
Toruń	**0.28**	**0.30**	**0.33**	-0.03	**0.41**	**0.49**	**0.35**	**0.14**	**0.21**	**0.25**	**0.29**	-0.04	**0.15**	0.12	**0.22**	-0.10	**0.35**	**0.34**	**0.45**	**-0.11**
Ustka	**0.31**	**0.27**	**0.34**	**-0.07**	**0.39**	**0.36**	**0.43**	-0.07	**0.30**	**0.28**	**0.34**	-0.06	**0.19**	**0.14**	**0.23**	**-0.09**	**0.32**	**0.28**	**0.35**	**-0.07**
Warszawa	**0.26**	**0.28**	**0.30**	-0.02	**0.39**	**0.47**	**0.35**	**0.13**	**0.23**	**0.25**	**0.28**	-0.03	**0.12**	0.08	**0.19**	**-0.11**	**0.31**	**0.31**	**0.38**	**-0.07**
Włodawa	**0.20**	**0.24**	**0.33**	**-0.09**	**0.33**	**0.41**	**0.39**	0.03	**0.13**	**0.19**	**0.25**	-0.06	0.07	0.06	**0.20**	**-0.14**	0.29	**0.28**	**0.50**	**-0.22**
Wrocław	**0.30**	**0.28**	**0.29**	-0.01	**0.37**	**0.40**	**0.31**	0.10	**0.30**	**0.30**	**0.30**	0.00	**0.16**	0.09	**0.17**	-0.08	**0.35**	**0.31**	**0.39**	-0.07
Kasprowy W.	**0.27**	**0.29**	**0.27**	0.02	**0.23**	**0.26**	**0.21**	0.06	**0.45**	**0.51**	**0.42**	**0.09**	0.11	0.10	0.13	-0.02	**0.29**	**0.28**	**0.31**	-0.02

Statistically significant (at 0.05 level) values are in bold cific days with low temperature increases gradually from west to east. A statistically significant decrease in the amount of very ice days was observed only in Słubice (western Poland). As for ice days, a statistically significant decrease, from 2 to 4 days per decade, was registered at 10 stations.

The annual number of frost days (when the 0°C threshold is crossed) shows an irregular spatial distribution. The minimum number of such days occurs on the coast – about 53 (Table 3). The greatest amount is registered in the lowlands in western Poland and in the high-elevation areas of the country where the frost days can be observed about 80 and more times a year. In the remaining area, on average, from 60 to 76 frost days can be recorded during the year. A statistically significant negative trend in the annual number of frost days is very common for the analysed series and, thus, the number of such days was decreasing by 2–3 per decade on average. The strongest trend can be indicated for the series obtained in Włodawa (eastern Poland), Ustka and Hel (coast) (Fig. 3), where the number of such days decreased by 4 over the period of 10 years.

In the case of days with a particularly high air temperature, it can be stated that the hot days occur from April to October throughout Poland, with the exception of the Tatra Mts. On average, during the considered years from 10 to 14 hot days were recorded on the coast and about 30–40 in central Poland (Table 3). The largest number of such days, exceeding 40 cases, was observed in south-western and south-eastern Poland. Extremely hot days, classified as sweltering days, can be observed during the period from May to September and occasionally in April and October, except the high mountains. Sweltering days are most frequent in western-eastern Poland (8 days a year, on average). On the coast and in north-eastern Poland such cases occur very rarely, only once or twice a year. In the remaining area such days are recorded 4 to 7 times a year, on average. However, in some years, the number of sweltering days exceeded 20. There were 26 such

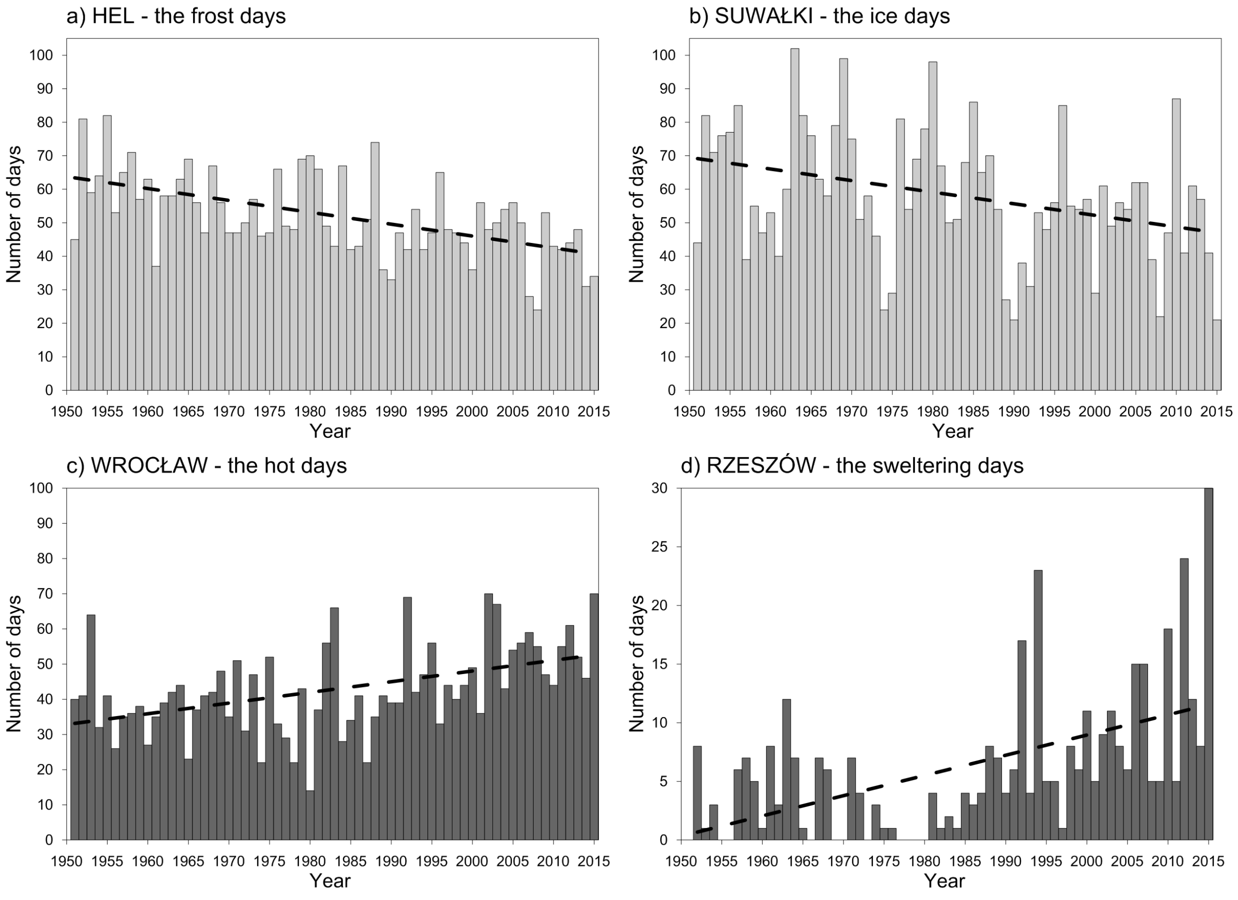

Fig. 3. Long-term variability of annual number of thermally specific days at selected stations in Poland, 1951–2015. Dashed lines represent respective trends

days in Poznań in 2006. A lot of sweltering days were also observed in 2015 in Wrocław (32 days) and in Rzeszów (30 days).

The annual number of hot and sweltering days in Poland is systematically increasing. Since the mid-20th century this increase has ranged from 4 to 23. At most stations, a statistically significant growth in the number of hot days – at a pace from 2 to 4 per decade – can be observed. In the case of sweltering days, the values of the coefficient of the linear trend are about 1 day per decade.

Variability of warm waves and cold waves

In Poland, warm waves appear, on average, from four times a year on the coast and in north-eastern Poland (Suwałki) to six times a year in the remaining area. On average, from 27 to 41 days classified as belonging to warm waves were recorded during the analysed years (Table 4). At the coastal stations (Ustka and Hel) and in Suwałki, the heat waves appear less frequently than in other areas, and their length is also the shortest. Less than 30 days of warm waves appear there yearly. The longest total duration of warm waves occurs in Włodawa and Rzeszów, with an average of 41 and 40 days a year, respectively.

Warm waves can be noticed throughout the year, but most frequently occur at particular stations in July, September, June and November. The highest number of warm waves – and of days with warm waves – was recorded in July (stations in north-eastern Poland; Słubice, western Poland; and Kielce, southern Poland), in September (Coast; Szczecin, north-western Poland; Łodź, Central Poland; and Bielsko-Biała, southern Poland) and in June (Chojnice, northern Poland and Poznań, western Poland). On average, one can observe up to 5 days with warm waves during each of these months. In the remaining months, days classified as warm waves

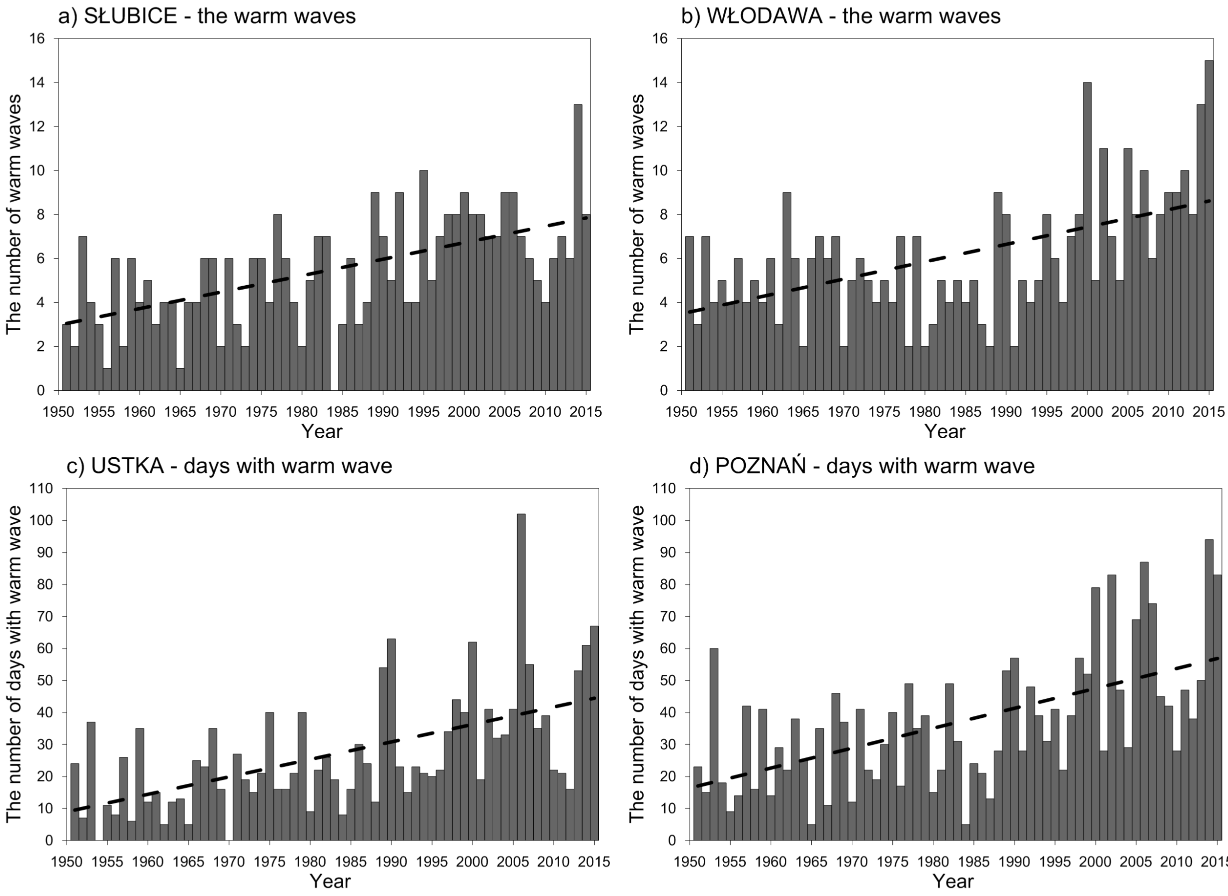

Fig. 4. Long-term variability of the annual number of warm waves and the annual number of days with the warm wave at selected stations in Poland, 1951–2015. Dashed lines represent respective trends

Table 3. Mean annual number of days (mean) and trend coefficients (trend, day·decade^{-1}) of the thermally specific days in Poland, 1951–2015

STATION	Very ice days		Ice days		Frost days		Hot days		Sweltering days	
	mean	trend	mean	trend	mean	trend	mean	trend	mean	trend
Białystok	4	-0.2	50	**-2.4**	76	0.1	32	0.7	4	0.4
Bielsko-Biała	2	-0.3	36	-1.4	67	**-1.8**	27	**3.6**	3	**1.1**
Chojnice	2	-0.0	42	**-2.9**	69	**-1.8**	25	**1.6**	3	**0.5**
Hel	0	-0.0	26	-1.7	52	**-3.6**	10	0.6	0	0.0
Kielce	2	-0.3	41	-2.0	83	-0.6	38	1.3	6	0.6
Łódź	2	-0.2	38	-1.7	69	**-2.5**	38	**2.3**	6	**0.9**
Olsztyn	3	-0.1	44	**-2.4**	71	**-3.0**	28	**1.6**	4	**0.6**
Poznań	1	-0.2	31	**-2.1**	68	**-3.2**	40	**2.4**	7	**1.1**
Rzeszów	3	-0.4	40	**-2.2**	73	**-1.6**	42	**3.3**	8	**1.7**
Słubice	1	**-0.2**	23	-1.4	72	**-3.2**	41	**3.7**	6	**1.5**
Suwałki	5	-0.3	58	**-3.5**	70	0.1	25	1.4	3	**0.6**
Szczecin	1	-0.1	24	**-1.9**	61	**-2.3**	31	**2.4**	5	**0.8**
Toruń	2	-0.1	35	**-2.8**	74	**-2.8**	40	**2.6**	7	**1.1**
Ustka	0	-0.0	24	**-1.9**	54	**-3.9**	14	**1.2**	2	0.2
Warszawa	2	-0.1	39	-2.0	68	**-2.5**	39	**2.4**	6	**1.0**
Włodawa	3	-0.3	47	-2.1	75	**-3.8**	39	**1.6**	6	**1.0**
Wrocław	1	-0.2	25	-1.6	80	**-2.4**	43	**3.0**	7	**1.1**
Kasprowy W.	18	-0.5	143	**-4.1**	78	0.9	0	-	0	-

Statistically significant (at 0.05 level) values are in bold

Table 4. Mean annual number of warm/cold waves, their annual total duration (days) and trend coefficients (trend, case/day·decade^{-1}) in Poland, 1951–2015

STATION	The number of warm waves		Total duration of warm waves		The number of cold waves		Total duration of cold waves	
	mean	trend	mean	trend	mean	trend	mean	trend
Białystok	6	**6.6**	38	**4.9**	4	**-3.2**	27	**-2.4**
Bielsko-Biała	6	**6.7**	39	**6.0**	4	**-4.3**	28	**-3.6**
Chojnice	6	**6.5**	38	**6.5**	4	**-5.4**	30	**-4.3**
Hel	5	**4.9**	31	**4.1**	4	**-5.8**	27	**-3.6**
Kielce	6	**4.6**	39	**4.2**	4	**-4.6**	24	**-4.2**
Łódź	6	**6.2**	37	**5.3**	5	**-5.3**	32	**-4.2**
Olsztyn	6	**5.8**	37	**5.1**	4	**-2.3**	26	**-2.4**
Poznań	6	**7.6**	37	**6.2**	4	**-5.1**	29	**-4.2**
Rzeszów	6	**7.5**	40	**6.1**	3	**-4.4**	23	**-3.8**
Słubice	5	**7.5**	36	**6.4**	3	**-3.3**	24	**-3.3**
Suwałki	4	**6.8**	32	**5.9**	3	-2.0	26	-1.9
Szczecin	5	**8.8**	33	**7.0**	4	**-5.2**	26	**-3.9**
Toruń	5	**7.7**	36	**7.0**	5	**-6.1**	31	**-5.1**
Ustka	4	**5.6**	27	**5.5**	4	**-8.5**	29	**-6.2**
Warszawa	6	**7.0**	38	**5.8**	3	**-2.8**	25	**-2.8**
Włodawa	6	**7.9**	41	**5.6**	4	**-3.8**	27	**-3.5**
Wrocław	6	**5.9**	37	**5.4**	3	**-3.3**	23	**-3.1**
Kasprowy W.	6	**5.3**	36	**5.4**	6	**-5.3**	35	**-3.7**

Statistically significant (at 0.05 level) values are in bold are less frequent. The longest warm waves are observed in winter: in January and February, warm waves can last from 6 to 10 days. In the remaining months the longest warm waves last from 5 to 8 days on average.

From the beginning of the 50s of the 20th century there was a considerable growth in warm waves and the number of days with warm waves (Table 4, Fig. 4). The series for the number of heat waves show statistically significant positive trends. In western Poland the annual number of heat waves increased by 6 throughout the period under discussion; in most of the remaining stations it increased by 4. At the same time, one can observe a statistically significant, systematic growth in the annual number of warm wave days, at a rate from 4 to 7 days per decade (Table 4, Fig. 4). Since 1951, the number of warm wave days has considerably increased in the lakelands in the northwest of Poland (by 45 days in Szczecin and by 41 days in Chojnice) and in the west (by 41 days in Słubice).

Cold waves appear in Poland from three to six times a year on average (Table 4). The highest number of days classified as cold waves was observed in the mountains (35 times a year, on average), in Łódź and Toruń, Central Poland (32 and 31 days a year, respectively). In the remaining area, on average, 26 to 30 days with cold waves have been recorded in a year. In most parts of Poland, cold waves can be observed throughout the year. At some stations there were no cold waves in July and August (Wrocław, south-western Poland) or in summer (Warsaw, Central Poland). The highest number of cold waves, as well as days with cold waves, was recorded at particular stations in the period from December to March. The longest cold waves can occur in January and February, when they may last from 7 to 11 days. In the remaining months, the longest cold waves can take from 5 to 8 days. The number of cold waves and the number of days with cold waves underwent changes in the period discussed (Table 4). According to the linear trend equations for the discussed 65 years, the annual number of cold waves decreased, by between four and six, both on the coast and in north-western Poland. In the remaining area, there are 2 to 3 cold waves fewer. All series are characterised by a statistically significant negative trend (Table 4, Fig. 5), with the exception of Suwałki (north-eastern Poland). The number of days classified as cold waves is decreasing at a pace of from 2 to as much as 7 days (in Ustka) per decade. From 1951 to 2015 the number of days constituting a cold wave decreased by factors ranging from 13 days in north-eastern Poland, to 33 days (Toruń, Central Poland) and 40 days in the coast (Ustka).

Discussion and conclusions

The influence of the main factors determining climate in Poland (such as the radiant factor, thermal activity of the Atlantic Ocean and the Baltic Sea, land relief and elevation) was confirmed by the analysis of spatial diversity of thermal conditions. The analysis has revealed some symptoms of considerable changes in thermal conditions in Poland during the second half of the 20th century and the first fifteen years of the 21st century. The main characteristic feature of long-term air temperature variability in Poland during the analysed period is its systematic growth, confirmed by a statistically significant change in all the related analysed indicators.

A constant, statistically significant growth is observed throughout the analysed area in the case of mean annual temperature, as well as annual daily maxima and minima and their extreme percentiles. The rates of change of the mean annual temperature varies from 0.2 to 0.3°C per decade, and increased compared with the trend registered in the period 1951–2010.

According to the previous studies covering the years 1951–2010, the annual average temperature change exceeds 0.20°C per decade (Marosz et al. 2011; Wójcik and Miętus 2014). The largest increase was observed in the northern and western parts of Poland (Biernacik et al. 2010). When analysing the consecutive decades of the 20th century it becomes obvious that the average annual temperature was constantly growing, and during the period 2001–2010 was 1°C higher than in the 1970s (Wójcik and Miętus 2014).

The maximum and minimum temperatures grew by more than 0.3°C per decade during the analysed period. These trends are stronger (by about 0.01–0.05°C per year) when compared with the results for the shorter period of 1951–2010. As proven in

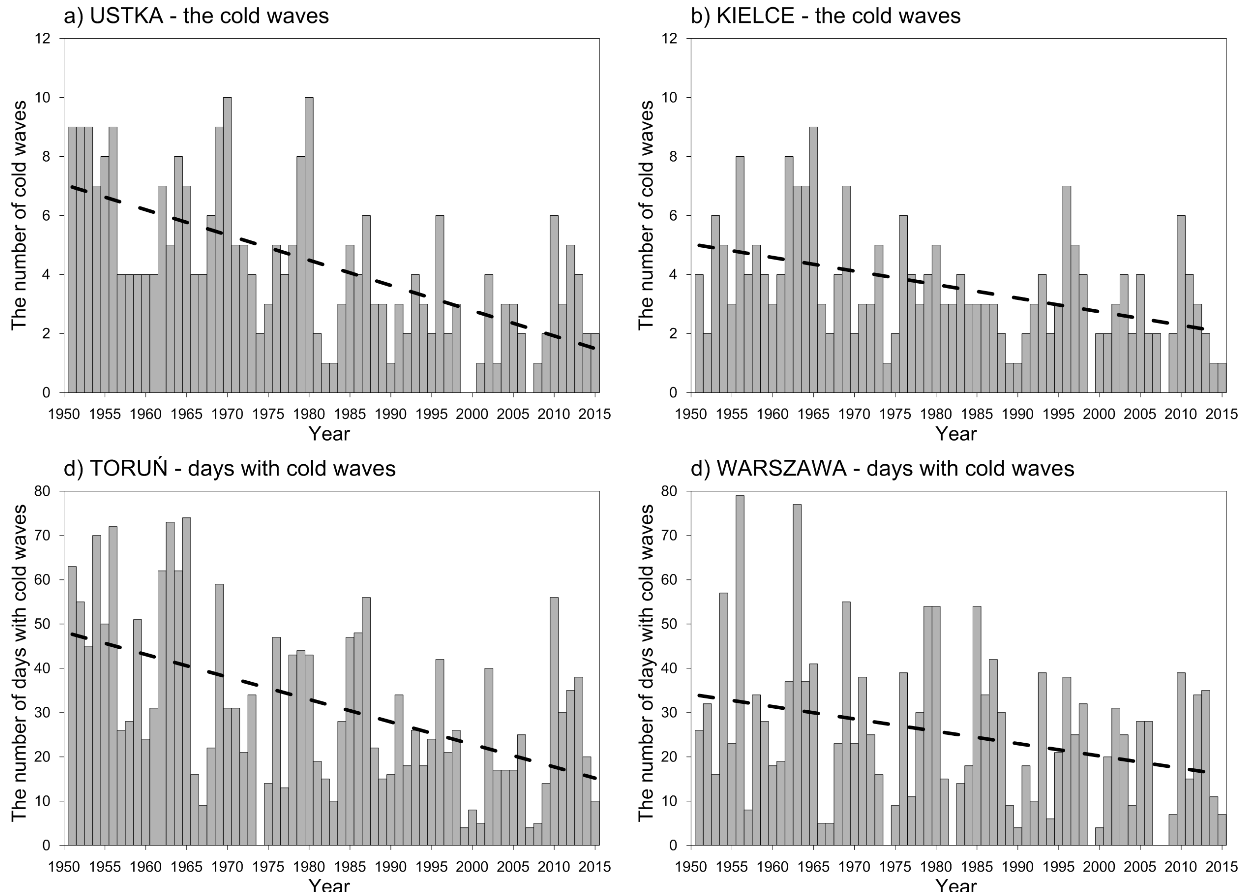

Fig. 5. Long-term variability of the annual number of cold waves and the annual number of days with the cold waves at selected stations in Poland, 1951–2015. Dashed lines represent respective trends

some previous publications, there were also many places in Central Europe in which the means for extreme daily temperatures have increased more than the mean daily values (Wibig and Głowicki 2002; Wibig et al. 2009a).

A noticeable change in the trend coefficient, resulting from supplementing data by series for 5 additional years, can be perceived as evidence of a systematically increasing rate of warming in the 21st century. The WMO report issued at the beginning of 2016 clearly states that the last pentad (2011–2015) was far and away the warmest 5-year period in the history of instrumental meteorological measurements. The analysis presented herein has also proven that this period was also abnormally warm in Poland, substantially influencing the values of positive trend coefficients regarding long-term changes in air temperature in this region.

Spring was the season when the most significant changes took place, particularly in the case of maximum temperature, which increased by 0.4–0.5°C per decade. In comparison with the period 1951–2010, the rate of growth did not change. Statistically significant upward trends were also observed at almost all the considered stations in summer and in winter. In autumn, at the majority of stations, positive trends in minimum temperature became statistically significant when compared with the shorter period 1951–2010. According to Wibig et al. (2009a) the strongest warming occurred in Poland in late winter and spring. However, some less apparent changes were observed in early winter and summer and described in previously published studies. A slightly higher rate of change was observed in winter and spring during the period 1951–2008 (Marosz et al. 2011) and 1951–2010 (Wójcik and Miętus 2014), which may have been caused by the abnormally cold winters of 2010 and 2011 and springs of 2010 and 2013.

In winter, a decrease in DTR is observed throughout the whole country, as the daily minimum temperature grows faster than the daily maximum temperature. Such a situation is not common for other seasons. The revealed negative trend coefficients which characterise the autumn series are not statistically significant.

Klein Tank and Können (2003) confirmed the existence of greater warming trends in the daily minimum nighttime temperatures than in the daily daytime maxima for the period of 1946–1999 in Europe as a whole, which confirms the observed negative trend in the mean diurnal temperature range of -0.04°C per decade. However, from 1976 to 1999 there was no significant trend in the mean diurnal temperature. A swifter rise in minimum temperatures than in maxima, which resulted in a decrease in the DTR, was thought to be a possible sign of intensified concentration of greenhouse gases in the atmosphere (Brázdil et al. 2009). According to Tuomenvirta (2000), a decrease of the Fennoscandian DTR during the 20th century is more dependent on the intensification of westerly circulation causing an increase in cloudiness.

Similar trends in temperature changes are also visible in neighbouring and near-situated countries, as well as in the whole Baltic Sea Basin. A decreasing tendency in the frequency of very low daily minima in winter surface temperatures has been present across most of Europe, including the Baltic Sea region, over the past 50 years (Rutgersson et al. 2015). An analysis of temperature trends from 1970 to 2008 in the Baltic Sea area showed a significant growth by 0.2 to 0.3°C per decade during spring and summer in the central and southern parts of the Baltic Sea area (von Storch et al. 2015). A warming trend in annual mean temperature (0.4°C or more per decade) was observed over the Baltic Sea during 1970–2008 (Lehmann et al. 2011). The most substantial change takes place in northern Baltic Sea in autumn and winter (from 0.5 to 0.6°C per decade).

Mean annual temperature in Sweden during 1981–1990 was 0.2°C higher than during 1961–2000; during the next decade it was 0.8°C higher, and even 1.2°C higher during 2001–2005 (Hellström and Lindström 2008). From 1958 to 2008, the annual mean temperature in Finland increased by about 1.5°C (Tietäväinen et al. 2010). The rate of warming was the fastest in winter and in spring (by about 3.5°C). The wintertime warming was even more pronounced: an increase in the mean temperature during 1979–2008 reached 4.28°C. During the same period the mean temperature in summer and autumn was increasing at a rate of about 0.5°C per decade.

Some warming symptoms were also discovered in the Russian part of the Baltic Sea Basin, where temperatures increased by 0.4°C per decade during 1976–2006 (Rutgersson et al. 2015). However, in other studies regarding north-eastern Europe, no significant long-term trends (1938–2008) for temperature were found in the annual average series (Svyashchennikov and Førland 2010).

Statistically significant increasing trends in maximum and minimum temperatures during the period 1951–2010 in the whole eastern Baltic region were detected for annual values, as well as for some winter, spring and summer months (Jaagus et al. 2014). Warming was slightly higher in Estonia compared to Lithuania and Latvia. The highest positive trend in the diurnal temperature range over the whole analysed area revealed itself in only two spring months (April and May), while in January and June a negative trend was detected. The annual temperature range did not change. Upward trends in the maximum and minimum temperatures, as well as in the mean temperature (at a rate of 0.3 per decade), were detected for annual values at Estonian stations (Jaagus 2006; Kont et al. 2011). In terms of seasonal change, statistically significant warming occurred in winter (by about 2.5°C), spring (by almost 3°C) and summer (by about 1.5°C), but not in autumn. Recent studies by Jaagus et al. (2014) confirmed these trends. Some notable increases in winter and spring air temperatures in Latvia since the 1970s have been also found (Klavinš and Rodinov 2010). The mean minimum temperature in Riga increased by 1.9°C during 1913–2006 (Avotniece et al. 2010). The mean maximum temperature increased by 1.7°C, most rapidly in two spring months (April and May) while the greatest growth of minimum temperature was observed in winter. Thus, the daily temperature range has decreased (Avotniece et al. 2010). Jaagus et al. (2014) noticed that warming in Latvia and Lithuania was slightly lower than in Estonia. The highest positive trend in DTR on the whole analysed area was observed in April and May, while in January and June a negative trend was detected. The minimum temperature grew much faster than the maximum temperature from 1950 until the 1990s.

According to the Met. Office Report (Huhne and Slingo eds. 2011), considerable warming in Germany was also confirmed. Regionally-averaged trends of seasonal temperature in Germany during the period 1960–2010 are 0.36°C per decade for summer and 0.32°C per decade for winter. Tomczyk and Bednorz (2014) reported a statistically significant increase in the mean annual air temperature during 1971–2010 within the German and the Polish coast of the Baltic Sea; specifically, the value of changes ranged between 0.25°C per decade in Kołobrzeg and 0.42°C per decade in Rostock.

General temperature increase is also a common feature in fluctuations of temperature characteristics in the Czech Republic, when analysed in the period 1961–2005 (Brázdil et al. 2009). This growth in the mean temperature revealed itself mainly on the annual scale, and in spring and summer. A significant trend towards warming is also evident for the mean and maximum temperatures in winter. A strong increase in the mean maximum temperature in two summer months (July and August) with a rate ranging from 0.40 to 0.63°C per decade was also detected (Kyselý 2010). The mean annual air temperature in the period beginning in 1988 was usually higher (with the exception of the year 1996) than the mean air temperature observed in the longer period 1961–1990.

In line with the global temperature rise, air temperatures in most European regions increased during the 20th century, with an extremely high rate of change observed in the last quarter of the century (Klein Tank and Können 2003). A consistent warming in countries located quite far from Poland was also determined. In both France and in the United Kingdom, there was a spatially consistent warming trend during 1960–2010 in summer, where the temperature increased by 0.35°C and 0.23°C per decade, respectively (Met. Office Report 2011). There has also been widespread warming over Italy, with greater warming in summer than winter, at a rate of 0.43°C. Furthermore, both minimum and maximum temperatures increased in the southern part of Italy, especially after 1971 (Piccarreta et al. 2014). Some initial symptoms of warming were also detected in Russia in summer. The average trend for the whole region is 0.35°C per decade in winter and 0.1°C per decade in summer. In Georgia (southern Caucasus) during 1981–2010, some significant positive changes regarding the annual minimum temperature were discovered – the temperature grew at a rate of 0.39°C per decade. The maximum temperature grew at a rate of 0.47°C per decade (Keggenhoff et al. 2015). The increase of the maximum temperature in summer since 1960 has also been detected in the Mediterranean Sea Basin (Kuglitsch et al. 2010). The value of the 95% percentile of maximum temperature, averaged over the whole eastern Mediterranean region area, has increased by about 0.4°C per decade. According to Tomczyk and Bednorz (2016), a significant increase was observed in the mean maximum summer air temperature from 1971 to 2010 in South Europe (e.g. 0.96°C per decade in Greece, 1.5°C in Serbia and 0.79°C per decade in Spain). According to the same authors, the warming rate in Central Europe equals 0.52°C per decade.

Warming in Poland is also visible when analysing indicators of positive and negative temperature extremes. A decrease in the occurrence of particularly cold days is observed in Poland, but some series show no statistically significant trends. More notable downward trends revealed themselves in series of annual numbers of frost days (especially in the eastern part of Poland and at the coastal stations), with the exception of several stations located at higher altitudes. On the other hand, warm days are observed more and more frequently in Poland: in the case of the annual number of hot days, the growth rate is 1 to 4 days per decade, and the annual number of sweltering days increases by 1 per decade. The observed acceleration of these changes is more pronounced when compared with the trend coefficients of shorter periods. According to Rutgersson et al. (2015), similar changes were described by Wibig (2008). The number of ice days and frost days decreased by 2 and 3 days per decade, respectively, while the frequency of hot days generally increased during 1951–2006. A downward trend in the annual number of days with maximum temperature below -10°C during the period 1951–2006 in Poland was demonstrated by Wibig et al. (2009b). It should also be mentioned that the annual number of cold days in central Poland has decreased since the 1930s at a rate of 0.87 days per decade (Wibig 2007). Some significant upward trends were also observed in the case of the number of hot days and of the annual number of days with temperature exceeding the 95 and 99 percentile (Wibig 2012). The value of the 95% percentile of maximum air temperature increased on average by 1.4˚C in the years 1966–2008, while a decrease was observed in the case of the 5% percentile of minimum air temperature (Miętus et al. 2012). Similar conclusions were obtained using NCEP/NCAR reanalysis data: values of maximum and minimum air temperature, the number of warm days and the number of hot days all increased during 1951–2005 (Kejna et al. 2009).

A significant growth in the annual number of heat waves, and a decrease in the annual number of cold waves, are observed. There are also some significant changes in their duration. However, the growth in the annual number of warm waves and their duration (4 to 7 days per decade) is larger than the rate of decline in cold waves (2 to 6 days per decade). There is also a significant increase in number of warm waves and their duration in Poland during 1966–2008 (Marosz et al. 2011). The analyses regarding Central Poland (Łódź) for the period 1931–2006 demonstrated that the duration of extremely mild periods increased significantly in winter, whereas the number of periods with extremely warm temperatures increased in summer and over the whole year (Wibig 2007). The long-term course for annual numbers of extreme warm days in Poland showed an upward trend during the period 1979–2006, which corresponds to the strong warming in Central Europe. At some stations the increase in the number of warm days was even higher than 8 days per decade (Wibig et al. 2009a).

The same changes in temperature extremes were recorded in other regions, especially in the neighbouring countries. Although different research methods were used, the results were usually similar. During the period 1946–1999 in Europe, the number of days with maximum temperature above 25° increased by 4.3 days (Klein Tank and Können 2003). A significant increase in the number of extreme warm days and a decrease in the number of extreme cold days during the period 1971–2010 on the southern coast of the Baltic Sea were revealed, for which the rates of change were, respectively, 2.3 days per decade and 1.2 days per decade. An increase in the frequency of heat waves was discovered in the Czech Republic in 1961–2006 (Kyselý 2010). In Germany, Poland and the Czech Republic as a whole, a statistically significant increase in the number of hot days (2.9 days per decade on average) during the study period of 1971–2010 was documented by Tomczyk and Bednorz (2016). A decreasing trend in the annual number of ice days and frost days was observed in Latvia, while an increasing trend was discovered in the annual number of days with daily maximum temperature higher than 25°C (Avotniece et al. 2010). The number of hot days increased also in Lithuania during 1961–2010, especially in July and August and after 1992 (Kažys et al. 2011). The research concerning the period 1951–2011 conducted in Ukraine revealed that the number of heat wave episodes was highest in the period 2001–2010 and most of the heat wave episodes occurred at stations located in the eastern part of the country (Shevchenko et al. 2013).

The tendencies observed in Poland are in accordance with the tendencies noted on a larger spatial scale (global, European). The detected trends and their significance resemble those discovered in the neighbouring countries, as well as in the whole Baltic Sea Basin. Although the mentioned changes do not show a distinct spatial differentiation, it is possible to distinguish several areas where the rate of warming is fastest, e.g. the coast, the western part of Poland and the south-eastern edge of the country. Local diversity in trend coefficient values can be observed at particular stations, which is most probably caused by some local factors e.g. urban heat islands (some of the stations are located in suburban areas of big agglomerations), land relief, local winds. The detected changes have turned out to be stronger than those detected during the period of 1951–2010. However, the revealed tendencies are still being strengthened. Therefore, although the study period analysed herein appears to be only about five years longer than in the previous studies, the results seem alarming. The changes in thermal conditions in Poland are continuous and undeniable. It can be stated that the consequences of climatic change will occur more often in the future, and their scale may be larger than that previously predicted, particularly in urban areas of large population centres. The results of the presented research should constitute an important component of the environmental monitoring system. Therefore, the problem of contemporary changes in thermal conditions should be taken into consideration when assessing potential threats and benefits resulting from the climate change taking place in Poland.

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