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ORIGINAL PAPER

Spatial diversity of air temperature changes in Poland in 1961–2018

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Abstract

The article comprises an analysis of the spatial distribution, and variability of air temperature in Poland in the years 1961–2018. It was found that the mean increase in air temperature was 0.33 °C/10 years. The most evident warming occurred in the west of the country and at the Baltic Sea (> 0.4 °C/10 years). The greatest increase in the temperature was observed in summer (July 0.48 °C/10 years), winter (January 0.46 °C/10 years) and spring (April 0.41 °C/10 years), whereas in autumn the warming was not statistically significant. The major role of atmospheric circulation in shaping air temperature in Poland was corroborated. The positive correlation with the NAO was confirmed, and Pearson's linear correlation coefficient (r) reached 0.81 in the north of Poland in January. An analysis of the variability of air temperature in Toruń (Central Poland) in 1991–2018 demonstrated that the increase in temperature was correlated with a solar irradiance ($r = 0.69$ in July). Moreover, the types of atmospheric circulation and incoming air masses are also significant. The type of baric centre was found to play a very important role that is opposite in winter to what it is in summer. In cyclonic situations, air temperature increased in winter ($r = 0.65$ in January) and decreased in the warm half of the year ($r = -0.47$ in September). An intensified flow of incoming air masses from the west caused air temperature to increase in winter ($r = 0.72$ in January) and to cool in summer ($r = -0.69$ in August). The role of meridional flow becomes particularly evident in autumn ($r = 0.49$ in October).

1 Introduction

The global increase in air temperature in the years 1880–2012 amounted to 0.85 °C (IPCC. Climate Change 2013) and kept increasing (Simmons et al. 2016). The rate of increase varies from one region of the world to another. It is an effect of regional factors, such as changes in atmospheric circulation, oceanic currents (ENSO) and sea-ice extent. In polar regions, there are feedbacks that increase warming, e.g. the Arctic amplification (Serreze and Barry 2011). Local changes are also significant, occurring around observational stations, where the urban heat island phenomenon often occurs (Stewart and Oke 2012).

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In Poland, like elsewhere in Europe (Luterbacher et al. 2004), substantial climate changes are taking place. The country is situated in Central Europe where the climate is intermediate (Woś 2010; Kożuchowski 2011). From the west to the east, oceanity becomes less influential, yielding to continental air masses from Eastern Europe (Gorczynski 1920; Marsz 1995). Any changes in the atmospheric circulation in this region result in considerable changeability of weather and climate conditions. That is why Poland may constitute a testing ground for studies of regional determinants of climate changes.

The history of research on climate change in Poland is long. The research relies on measurement data, both contemporary and historical (early-instrumental) (Przybylak et al. 2010a; Marsz and Styszyńska 2018). Moreover, valuable proxy data is used: historical sources (Przybylak et al. 2005), lake deposits, dendroclimatological methods (Koprowski and Zielski 2006), geophysical and others (Przybylak et al. 2010b). A number of works analysing climate changes—and air temperature in Poland in particular—have been published. The most recent include the following: Kożuchowski and Żmudzka (2001); Błażejczyk (2006); Biernacik et al. (2010); Marosz et al. (2011); Michalska (2011); Wójcik and Miętus (2014); Owczarek and Filipiak (2016); Wypych et al. (2017); Marsz and Styszyńska et al. (2019). The research demonstrated a spatial variability in the size of warming in Poland and various trends in individual seasons. The trends are reflected in observations from different weather stations in Poland, e.g. Gdańsk (Filipiak and Miętus 2010), Kraków (Trepińska and Kowanetz 1997), Łódź (Wibig et al. 2004), Poznań (Kolendowicz et al. 2019), Toruń (Pospieszyńska and Przybylak 2019), Warsaw (Lorenc 2000) and Wrocław (Bryś and Bryś 2010).

The main cause of global warming is believed to be an intensified greenhouse effect triggered by added anthropogenic concentration of greenhouse gases released into the atmosphere (IPCC. Climate Change 2013). Regional and seasonal variability of air temperature trends is, on the other hand, explained by the impact of other factors, such as atmospheric circulation. In Europe, the zonal activity of atmospheric circulation is essential, along with the flow of air masses from the west (Degirmendžič et al. 2004). A positive correlation was found between the North Atlantic Oscillation (NAO) and air temperature in Europe (Hurrell 1995), and was also observed in Poland, especially in winter (Przybylak et al. 2003; Marsz 2013; Bednorz et al. 2018; Kossowska-Cezak and Twardosz 2018; Marsz and Styszyńska 2019; Styszyńska et al. 2019).

The purpose of the present work was to analyse changes in the spatial distribution of air temperature in Poland and in the variability of the warming rate in the years 1961–2018. A case study was also done. Using the example of a weather station in Toruń (Central Poland), the influence of solar radiation and atmospheric circulation on the variability of air temperature was analysed.

2 Methodology and data

The supporting data regarding mean monthly values of air temperature at 55 meteorological stations (synoptic and climatological) in Poland was obtained from the database of the Institute of Meteorology and Water Management, National Research Institute (IMGW PIB) covering the years 1961–2018. The basic information is provided in Table 1 and the locations of the stations are shown in Fig. 1.

There were gaps in measurements in some of the stations, so the missing data was supplemented by referring to the principle of stability of temperature differences determined for each month individually. Because of climate changes, the calculation was based on temperatures for the 20 years around the gaps. In the case of Gdańsk, data from Świbno station was used, as the site has the longest series of observations, supplemented with data from Rębiechów airport station (with due allowances). In Elbląg, in 2013, the station was moved from its location at 40 m a.s.l. to the hilltop of Milejewska Góra (189 m a.s.l.). That caused a loss of homogeneity in its data series. The Elbląg data was therefore reconstructed for 2013–2018 considering its original location. In Płock, likewise, the relocation of the meteorological station from the valley of the Vistula River to the morainic plateau also called for a correction of values. If there was a longer break in measurements, the relevant station was not considered.

Ultimately, the analysis was based on data from 55 stations evenly distributed across the country, 48 of which were situated in lowlands below 300 m a.s.l. The mountainous regions were represented by Kłodzko (356 m a.s.l.), Jelenia Góra (398 m) and Mt. Śnieżka (1,603 m) in the Sudetes, and Bielsko-Biała (398 m), Lesko (420 m), Zakopane (855 m) and Mt. Kasprowy Wierch (1,991 m) in the Carpathians (Table 1).

The distribution of air temperature parameters was established using the kriging method (Childs 2004), a common geostatistical tool also used for climatic analysis (Ustrnul and Czekierda 2006). The spatial distribution analysis disregarded the impact of elevation; thus, the representation of the spatial distribution of air temperature in the mountains is a result of simple interpolation based on available station data.

Linear correlation was used to analyse the trends of air temperature. Most were expressed in °C 10 years^{-1}, and the statistical significance was determined using the Fisher–Snedecor test. It was assumed that the correlation was statistically significant at $\alpha \leq 0.05$. The influence of atmospheric circulation on the variability of air temperature was determined using relevant monthly values of the North Atlantic Oscillation Index found in the CRU database of the University of East England for the years 1961–2018.

In the case study, the 1991–2018 air temperature and solar irradiance data was sourced from the IMGW PIB station in Toruń (Central Poland)—Table 1 and Fig. 1. The station was founded in the residential district of Wrzosy, which is characterised by semi-detached houses. In 1981, the station was moved approximately 1 km (Ciesielski 2004), which did not affect the homogeneity of its series of observations (Pospieszyńska and Przybylak 2019). However, the surrounding area started to undergo development, which led to the formation of an urban heat island (UHI). The influence of the UHI in the city centre reaches 1 °C on average (Przybylak et al. 2017). Any missing radiation data from Toruń was supplemented with the information obtained from the Warsaw-Bielany station (1994 and 2002) and the Meteorological Observatory of the Nicolaus Copernicus University in Toruń (2017–2018). In addition, the relationship between air temperature in Toruń and the types of synoptic patterns occurring there in 1994–2018 was analysed. To that end, according to the methodology proposed by Niedźwiedź (1981), a calendar was developed on the basis of IMGW PIB weather charts for 12 UTC; it took into account the type of barometric pressure centre (anticyclone or cyclone) with advection direction (eight types). Other elements considered included anticyclone centre (Ca), cyclone centre (Cc), anticyclonic

Table 1 Meteorological stations in Poland used in this study and mean values of air temperature parameters in the years 1961–2018

Station	Acronym	Altitude m a.s.l.	Longitude	Latitude	Air temperature			
			E	N	Year	January	July	Amplitude
Białystok	BIA	148	23° 09′ 44″	53° 06′ 26″	7.1	− 3.9	17.8	23.9
Bielsko-Biała	BIE	398	19° 00′ 04″	49° 48′ 29″	8.3	− 1.6	17.7	21.5
Chojnice	CHO	164	17° 31′ 57″	53° 42′ 55″	7.4	− 2.4	17.2	21.7
Częstochowa	CZĘ	293	19° 05′ 33″	50° 48′ 45″	8.2	− 2.3	18.3	22.5
Elbląg	ELB	40	19° 32′ 37″	54° 13′ 23″	8.0	− 2.0	17.7	22.0
Gdańsk	GDA	135	18° 29′ 33″	54° 22′ 27″	7.9	− 1.7	17.7	21.4
Gorzów Wlkp.	GOR	72	15° 16′ 38″	52° 44′ 28″	8.8	− 1.0	18.5	21.6
Hel	HEL	1	18° 48′ 43″	54° 36′ 13″	8.2	− 0.3	17.5	19.4
Jelenia Góra	JEL	342	15° 47′ 20″	50° 54′ 01″	7.5	− 2.0	16.7	20.8
Kalisz	KAL	138	18° 04′ 55″	51° 46′ 55″	8.6	− 1.7	18.5	22.3
Kasprowy Wierch	KAS	1991	19° 58′ 55″	49° 13′ 57″	− 0.4	− 7.9	7.7	18.2
Katowice	KAT	284	19° 01′ 58″	50° 14′ 26″	8.4	− 2.0	18.2	22.1
Kętrzyn	KĘT	108	21° 22′ 10″	54° 04′ 06″	7.4	− 3.3	17.6	23.2
Kielce-Suków	KIE	260	20° 41′ 32″	50° 48′ 37″	7.6	− 3.2	17.9	22.9
Kłodzko	KŁO	356	16° 36′ 51″	50° 26′ 13″	7.7	− 2.2	17.0	21.2
Koło	KOŁ	116	18° 39′ 41″	52° 12′ 01″	8.5	− 1.9	18.5	22.6
Kołobrzeg	KŁB	3	15° 34′ 50″	54° 10′ 58″	8.3	− 0.2	17.3	19.3
Koszalin	KOS	32	16° 09′ 20″	54° 12′ 16″	8.2	− 0.7	17.2	19.8
Kraków	KRA	237	19° 48′ 07″	50° 04′ 49″	8.3	− 2.6	18.4	22.7
Legnica	LEG	122	16° 12′ 27″	51° 11′ 33″	9.0	− 0.7	18.6	21.4
Lesko	LES	420	22° 20′ 30″	49° 27′ 59″	7.6	− 2.8	17.2	22.0
Leszno	LSZ	91	16° 32′ 05″	51° 50′ 09″	8.6	− 1.3	18.4	21.8
Lębork	LĘB	38	17° 43′ 25″	54° 33′ 11″	8.0	− 1.0	17.3	20.3
Lublin	LUB	238	22° 23′ 37″	51° 13′ 01″	7.7	− 3.4	18.1	23.5
Łeba	ŁEB	2	17° 32′ 05″	54° 45′ 13″	7.9	− 0.6	16.9	19.3
Łódź	ŁÓD	187	19° 23′ 59″	51° 43′ 24″	8.2	− 2.3	18.3	22.7
Mikołajki	MIK	127	21° 35′ 19″	53° 47′ 22″	7.4	− 3.4	17.9	23.6
Mława	MŁA	147	20° 21′ 40″	53° 06′ 15″	7.5	− 3.2	17.9	23.4
Nowy Sącz	NOW	292	20° 41′ 21″	49° 37′ 38″	8.4	− 2.3	18.2	22.3
Olsztyn	OLS	133	20° 28′ 22″	53° 46′ 16″	7.4	− 3.0	17.6	22.8
Opole	OPO	165	17° 58′ 08″	50° 37′ 37″	9.0	− 1.3	18.8	22.0
Piła	PIŁ	72	16° 44′ 54″	53° 07′ 52″	8.1	− 1.7	18.1	21.9
Płock	PŁO	106	19° 43′ 33″	52° 35′ 18″	8.1	− 2.4	18.2	22.8
Poznań	POZ	83	16° 50′ 09″	52° 25′ 02″	8.7	− 1.3	18.7	22.2
Racibórz	RAC	205	18° 11′ 30″	50° 03′ 42″	8.7	− 1.6	18.3	21.9
Resko	RES	52	15° 24′ 53″	53° 46′ 18″	8.2	− 0.9	17.6	20.5
Rzeszów	RZE	200	22° 01′ 12″	50° 06′ 41″	8.2	− 2.9	18.5	23.3
Sandomierz	SAN	217	21° 42′ 57″	50° 41′ 48″	8.2	− 3.1	18.6	23.6
Siedlce	SIE	152	22° 14′ 41″	52° 10′ 52″	7.7	− 3.3	18.2	23.6
Słubice	SŁU	21	14° 37′ 10″	52° 20′ 56″	9.0	− 0.4	18.6	21.1
Sulejów	SUL	188	19° 51′ 52″	51° 21′ 10″	8.0	− 2.6	18.0	22.6
Suwałki	SUW	184	22° 56′ 56″	54° 07′ 51″	6.5	− 4.4	17.3	24.1
Szczecin	SZC	1	14° 37′ 22″	53° 23′ 43″	8.9	− 0.3	18.3	20.6
Śnieżka	ŚNI	1603	15° 44′ 22″	50° 44′ 10″	0.9	− 6.5	8.9	17.8
Świnoujście	ŚWI	6	14° 14′ 32″	53° 55′ 24″	8.6	0.0	17.6	19.4
Tarnów	TAR	209	20° 59′ 04″	50° 01′ 48″	8.8	− 1.9	18.7	22.6

Table 1 (continued)

Station	Acronym	Altitude m a.s.l.	Longitude	Latitude	Air temperature			
			E	N	Year	January	July	Amplitude
Terespol	TER	133	23° 37′ 17″	52° 04′ 42″	7.8	− 3.5	18.5	24.1
Toruń	TOR	69	18° 35′ 43″	53° 02′ 31″	8.3	− 2.1	18.5	22.8
Ustka	UST	6	16° 51′ 15″	54° 35′ 18″	8.2	− 0.2	17.1	19.2
Warszawa	WAR	106	20° 57′ 40″	52° 09′ 46″	8.3	− 2.5	18.8	23.4
Wieluń	WIE	200	18° 33′ 28″	51° 12′ 40″	8.5	− 1.9	18.3	22.2
Włodawa	WŁO	177	23° 31′ 46″	51° 33′ 12″	7.7	− 3.7	18.5	24.2
Wrocław	WRO	120	16° 54′ 00″	51° 06′ 12″	8.9	− 1.0	18.6	21.7
Zakopane	ZAK	855	19° 57′ 37″	49° 17′ 38″	5.5	− 3.9	14.7	20.5
Zielona Góra	ZIE	187	15° 31′ 28″	51° 55′ 49″	8.8	− 1.2	18.6	21.8

wedge (Ka), cyclonic trough (Bc) and other, unspecified situations (X). In order to aggregate the 21 synoptic situation types, monthly values of three atmospheric circulation indices were worked out: cyclonicity (C), zonality (W) and meridionality (S)—Niedźwiedź (2003, 2006). The scoring principles are shown in Table 2.

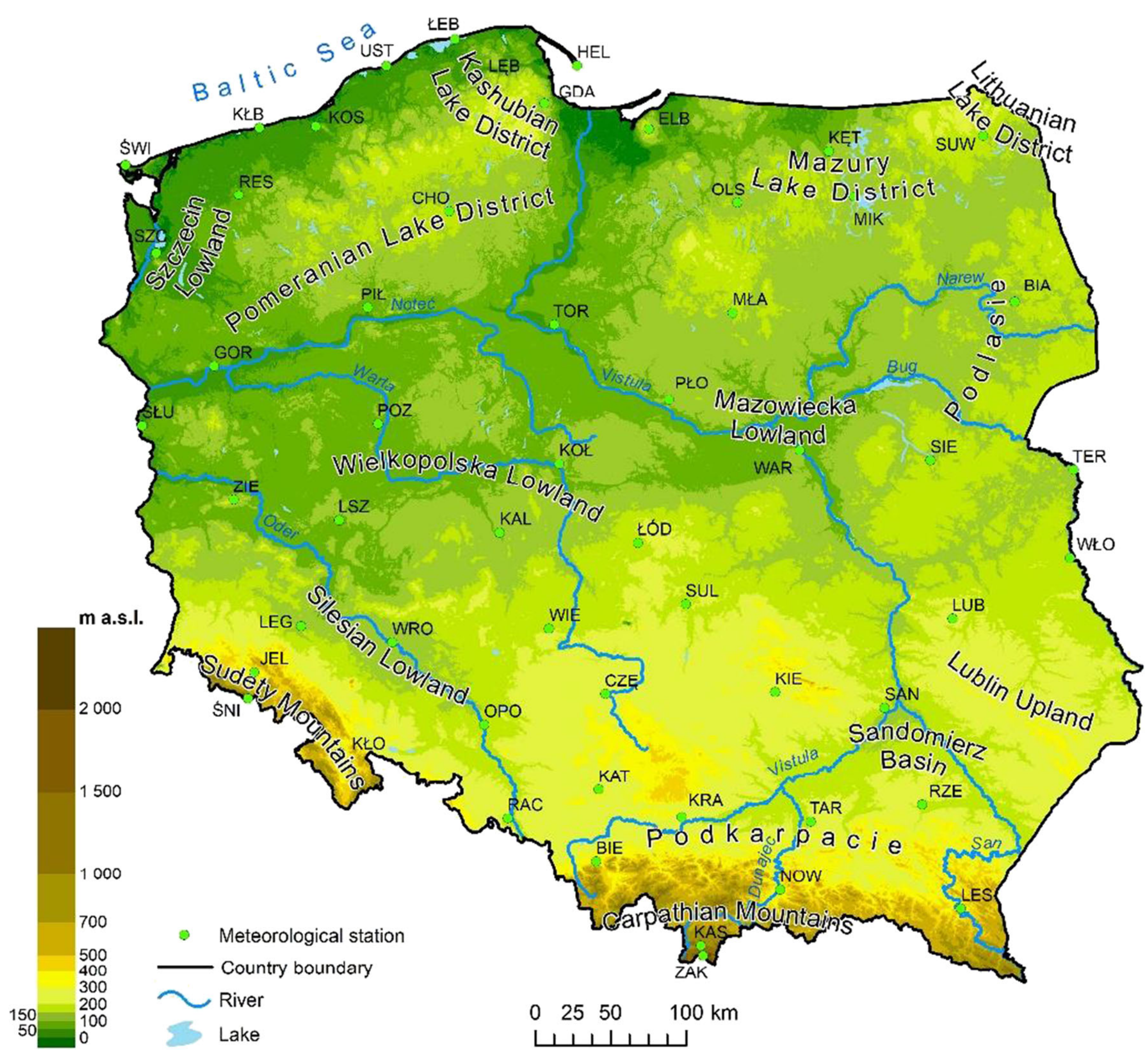

Fig. 1. Hypsometric map of Poland and locations of meteorological stations used in the article

Table 2 Points allocated to the different types of synoptic patterns for the indices of cyclonicity (C), zonality (W) and meridionality (S)

Anticyclonic types				Cyclonic types			
Types	C	W	S	Types	C	W	S
Na	− 1	0	− 2	Nc	1	0	− 2
NEa	− 1	− 1	− 1	NEc	1	− 1	− 1
Ea	− 1	− 2	0	Ec	1	− 2	0
SEa	− 1	− 1	1	SEc	1	− 1	1
Sa	− 1	0	2	Sc	1	0	2
SWa	− 1	1	1	SWc	1	1	1
Wa	− 1	2	0	Wc	1	2	0
NWa	− 1	1	− 1	NWa	1	1	− 1
Ca	− 2	0	0	Cc	2	0	0
Ka	− 2	0	0	Bc	2	0	0

For X C = 0, W = 0, S = 0

3 Results

3.1 Air temperature distribution in Poland

The distribution of air temperature in Poland has been the subject of numerous studies that used both data from observational stations (Paszyński and Niedźwiedź 1991; Kożuchowski and Żmudzka 2001; Lorenc 2005; Ustrnul and Czekierda 2009; Biernacik et al. 2010; Wójcik and Miętus 2014), and from reanalysis (Kejna et al. 2009) or models considering, for example, surface features (Miętus et al. 2008; Wypych et al. 2017).

The spatial distribution of mean air temperatures in Poland in 1961–2018 presented in Fig. 2 is a result of the effects of various factors: latitude affecting the amount of solar radiation reaching the ground, atmospheric circulation bringing in different air masses, the effect of temperature reduction as

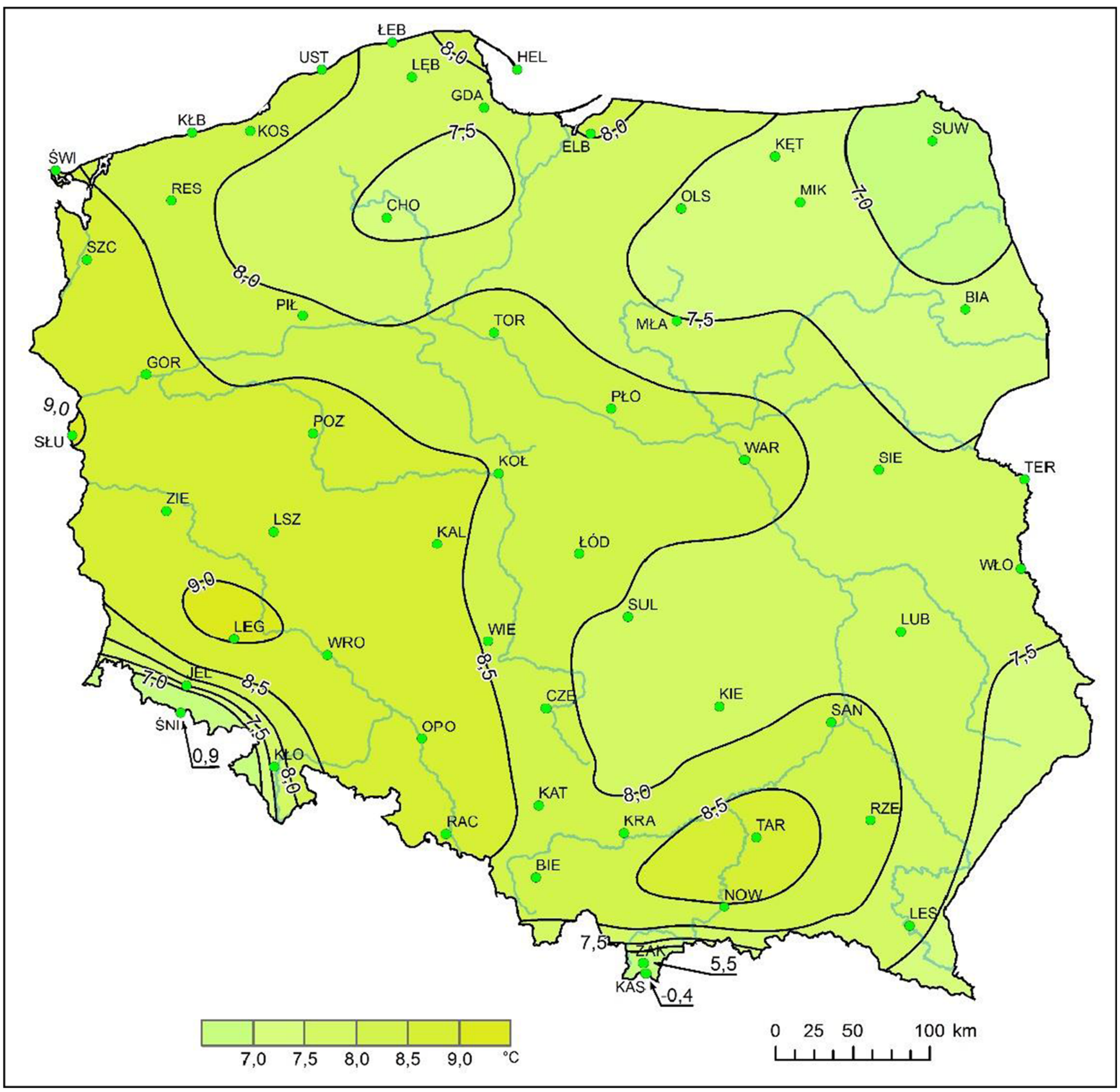

Fig. 2 Mean annual air temperature distribution in Poland in 1961–2018

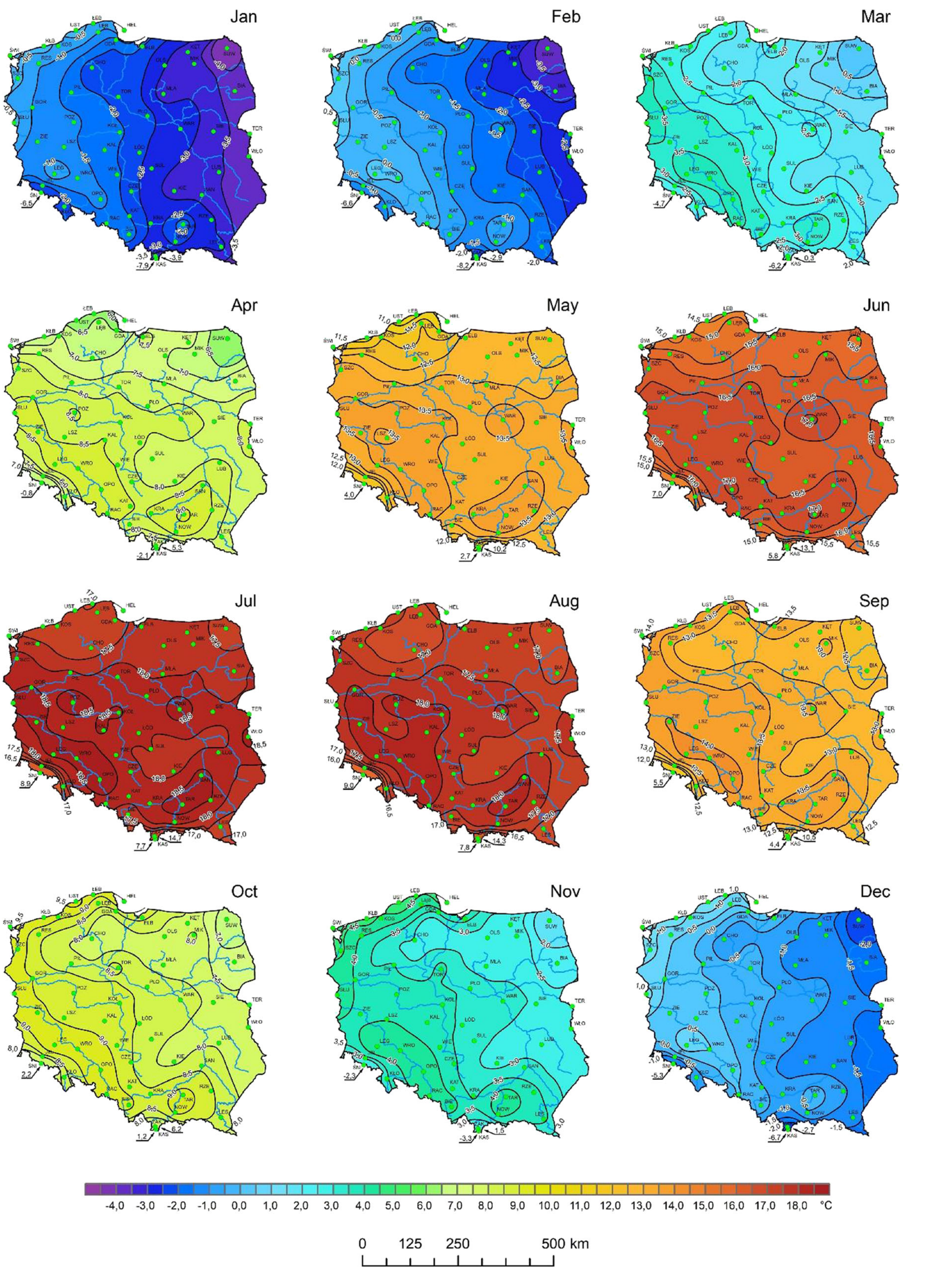

Fig. 3 Spatial distribution of air temperature in Poland by months in 1961–2018

absolute height increases and local factors. On the coast, the Baltic Sea is also observed to have an influence.

In 1961–2018, the greatest mean air temperature was noted in the west of Poland (the Szczecin Lowland, the Silesian Lowland and the western part of the Wielkopolska Lowland) and ranged from 8.5 °C to over 9 °C (9.1 °C in Legnica). A mean temperature exceeding 8.5 °C also occurred in the Sub-Carpathian region of the country (8.8 °C in Tarnów). The coldest region was south-eastern Poland, specifically the Lithuanian Lakeland (6.5 °C in Suwałki) and Podlasie (7.1 °C in Białystok). The isotherms of mean annual air temperature in Poland run NW to SE, but their pattern is disturbed by local factors. There is an influence of the Baltic Sea on the coast, where the temperature was higher than that in the interior (8.6 °C in Świnoujście). Absolute height also causes evidently lower temperatures in the Kashubian Lake District (8.0 °C in Lębork), in the highlands (7.6 °C in Kielce) and in the mountains in the south of Poland. The lowest air temperature was recorded on Mt. Kasprowy Wierch in the Carpathians (− 0.4 °C) and on Mt. Śnieżka in the Sudetes (0.9 °C).

During the year, the arrangement of isotherms in Poland undergoes a transformation from meridional in winter months to latitudinal in summer (Fig. 3). The lowest mean monthly air temperature was recorded in January when, except for mountain and seaside areas, the isotherms ran meridionally. The lowest air temperature in winter was observed in the north-east (4.4 °C in Suwałki), where cold continental air masses flow from the east more often (Więcław 2004). The warmest part of Poland was the west (− 0.7 °C in Legnica), where oceanity is more evident (Marsz and Styszyńska 2000), and on the Baltic coast (0.0 °C in Świnoujście). A similar arrangement of isotherms occurred in February.

In March and April, a greater amount of incoming solar radiation transformed the isotherm pattern to latitudinal. As a result of the cooling effect of the Baltic Sea waters, the lowest air temperature in April was not recorded in the north-eastern Poland (6.4 °C in Suwałki), but on the coast (6.1 °C in Łeba). At that time, it was the warmest in the south of the country (9.1 °C in Tarnów).

In summer, the latitudinal arrangement of isotherms was fully developed. In July, the warmest part of Poland was the south (18.7 °C in Tarnów and 18.6 °C in Legnica, Słubice and Wrocław). As a matter of fact, a higher temperature was observed in Warsaw (18.8 °C) but that was partly attributed to the effect of the urban heat island (Kuchcik et al. 2014). The north was the coldest (16.9 °C in Łeba, 17.3 °C in Suwałki). In autumn, the isotherms gradually changed back to the meridional pattern, with a clear warming influence of the Baltic Sea in the north.

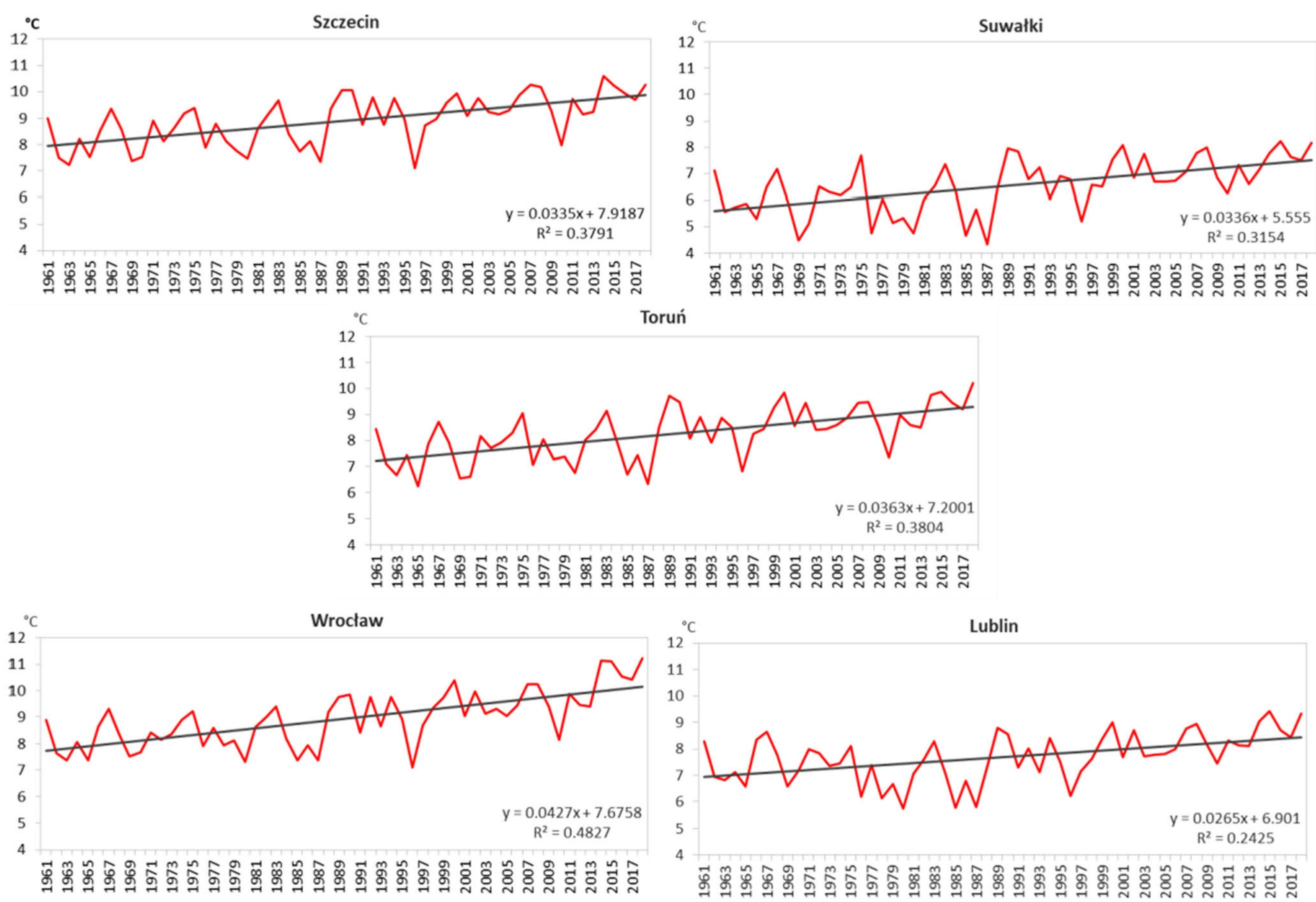

Fig. 4 Air temperature variability and trend in Szczecin, Suwałki, Toruń, Wrocław and Lublin in 1961–2018

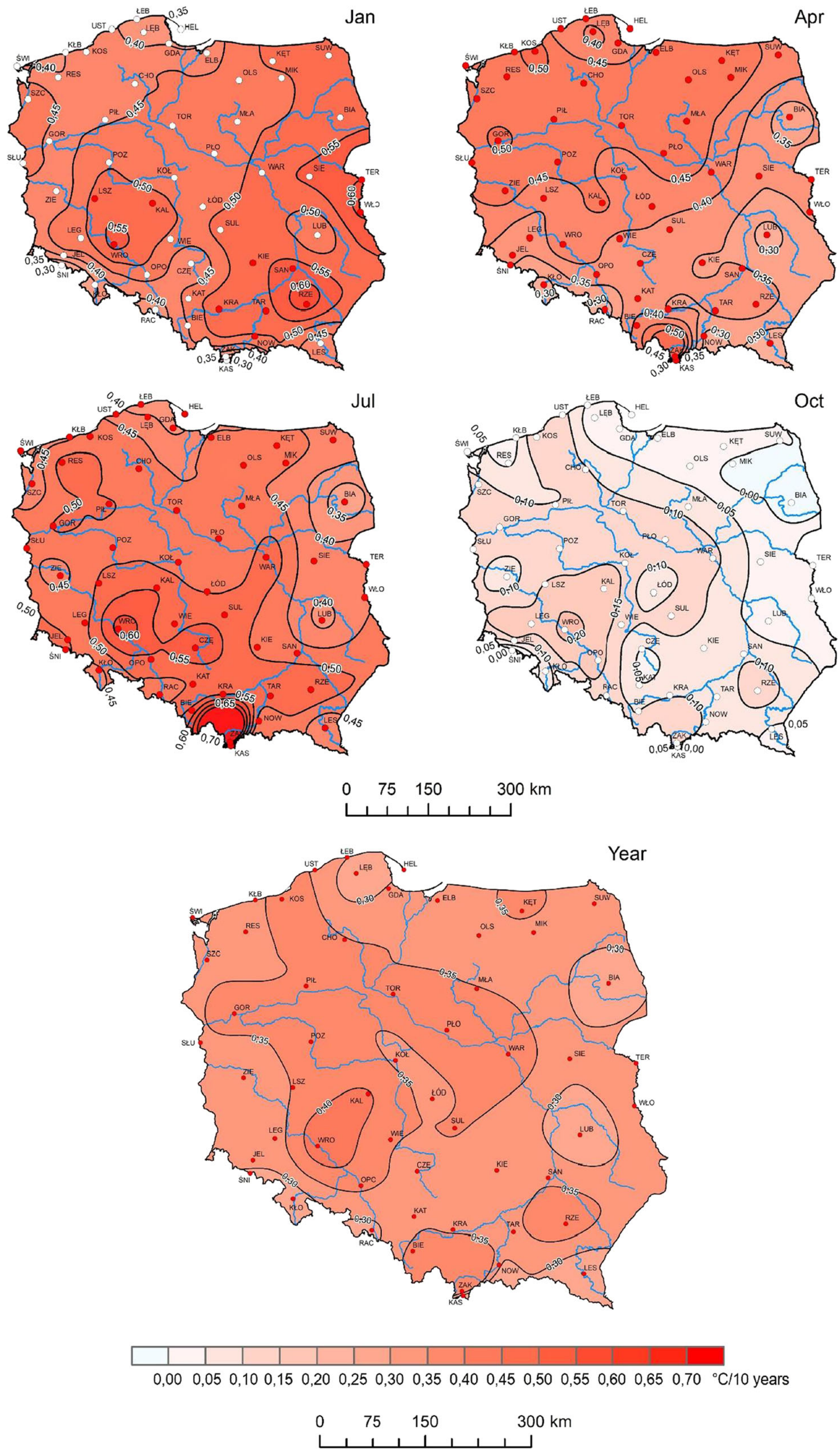

Fig. 5 Air temperature trends in Poland in January, April, July and October, and the whole year in 1961–2018

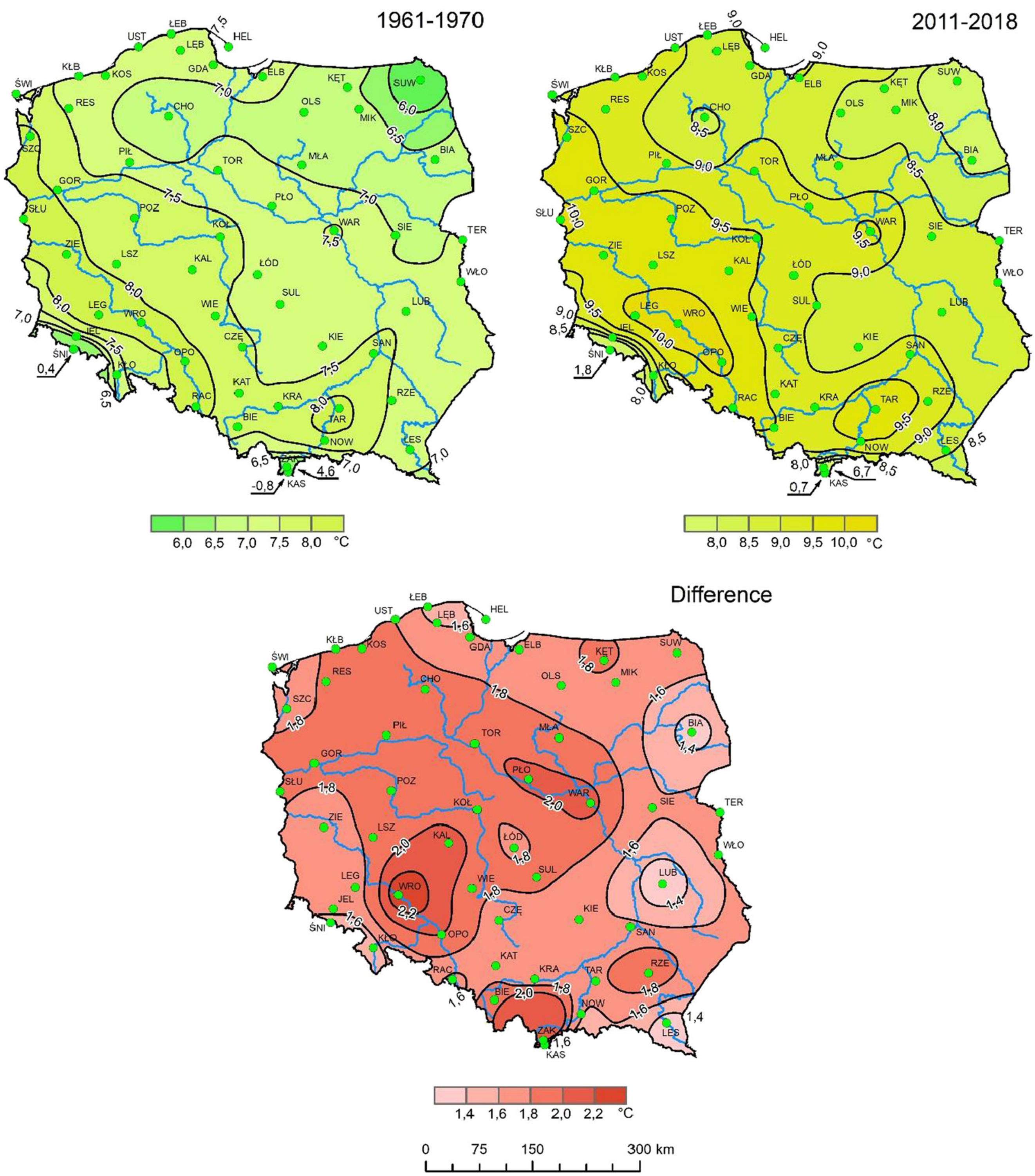

Fig. 6 Spatial distribution of mean annual values of air temperature in Poland in 1961–1970 and 2011–2018, and of the differences

In all the months, the influence of elevation is apparent, both in the Polish Plain (Kashubian Lake District and the highlands in the south of Poland) and in the mountains; e.g. on Mt. Kasprowy Wierch, the mean air temperature in January was − 7.9 °C, and in July it was 7.7 °C.

The annual amplitude of air temperature, determined as the difference between the warmest and the coldest month in a given year, demonstrates substantial variability in Poland. It was smallest on the Baltic coast (19.2 °C in Ustka), where seawater has a warming effect in winter and a cooling effect

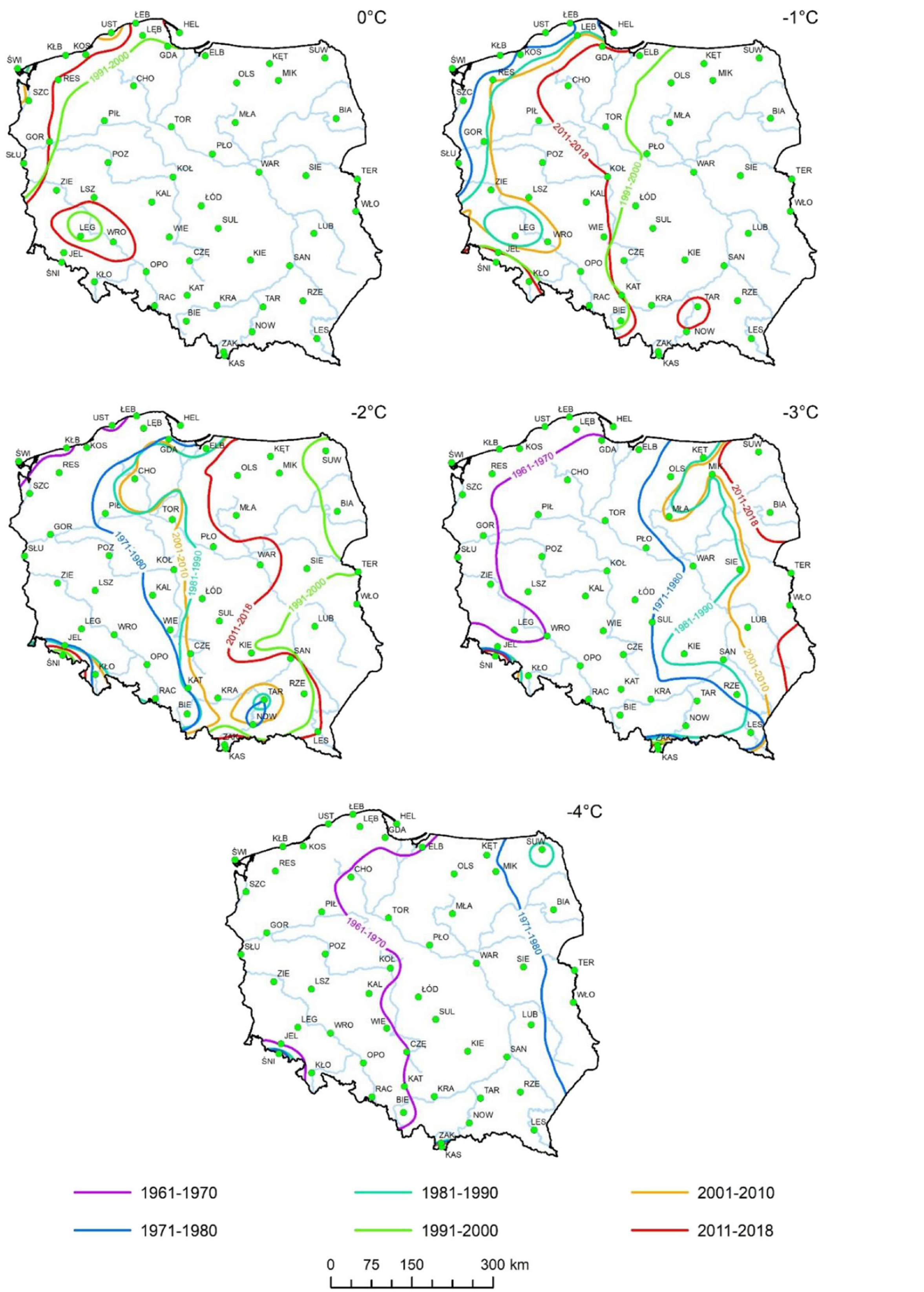

Fig. 7 Location of 0, − 1, − 2, − 3 and − 4 °C isotherms in Poland in January by decade in the period 1961–2018

in summer. The amplitude grows from the west (21.1 °C in Słubice) to the east (24.2 °C in Włodawa), mainly because of temperature changes occurring in winter months. This proves the intermediate nature of the climate in Poland—the declining oceanic influence and increasing continentality (Marsz 1995). The amplitude in the mountains is even smaller (17.8 °C on Śnieżka and 18.2 °C on Kasprowy Wierch). On mountaintops, the temperature in winter is not so low as their absolute height would imply. There are often inversional patterns, where the air temperature is higher on the tops than at the feet of the mountains (Migała 2005; Błażejczyk 2019).

3.2 Changes in air temperature in Poland

The course of air temperature in Poland shows a substantial year-by-year variability and a clear upward trend (Fig. 4).

As in other parts of the globe, so too in Poland—what is mainly observed is warming. In the analysed period, the air temperature was found to range from 0.25 °C/10 years in Lesko to 0.43 °C/10 years in Wrocław. Over the years 1961–2018, air temperature in Wrocław increased by a total of 2.5 °C. The total increase was smaller in the east of Poland (1.6 °C in Białystok and 1.5 °C in Lublin), in Kashubian Lake District (1.6 °C in Lębork) and in the mountains (1.5 °C in Lesko and 1.6 °C in Kłodzko) (Fig. 5).

The rate of temperature increase varied between individual months; in January, air temperature was found to rise the most in the south of Poland, e.g. in Włodawa by 0.61 °C/10 years and in Rzeszów by 0.62 °C/10 years. In February, it increased the most in Suwałki—by 0.51 °C/10 years; a smaller increase was observed at the Baltic Sea, e.g. by 0.32 °C/10 years in Łeba, and in the mountains (0.12 °C/10 years on Śnieżka). In April, the greatest increase in air temperature occurred in northern Poland (0.52 °C/10 years in Koszalin) and locally in Carpathian basins (0.53 °C/10 years in Zakopane); a smaller warming was observed in south-eastern Poland (0.27 °C/10 years in Lesko, and 0.28 °C/10 years in Lublin). In July, the increase was evident and reached 0.56 °C/10 years in Bielsko-Biała in the south of the country, and 0.32 °C/10 years (Białystok) and 0.38 °C/10 years (Hel) in the north. In autumn (October), the changes in air temperature were the smallest, and they were not statistically significant.

The beginning of the twenty-first century is characterised by a much higher air temperature as compared with previous decades (Fig. 6). The mean annual air temperature for the years 1961–1970 in Poland ranged from 5.9 °C in Suwałki to 8.3 °C in the Silesian Lowland (Legnica, Słubice): however, in 2011–2018, it increased to 7.5 °C in Suwałki and 10.1 °C in Legnica and Słubice. So, between the two periods, the temperature increased by as much as 1.3 °C in the east and 2.3 °C in the Silesian Lowland and Central Poland. However, the

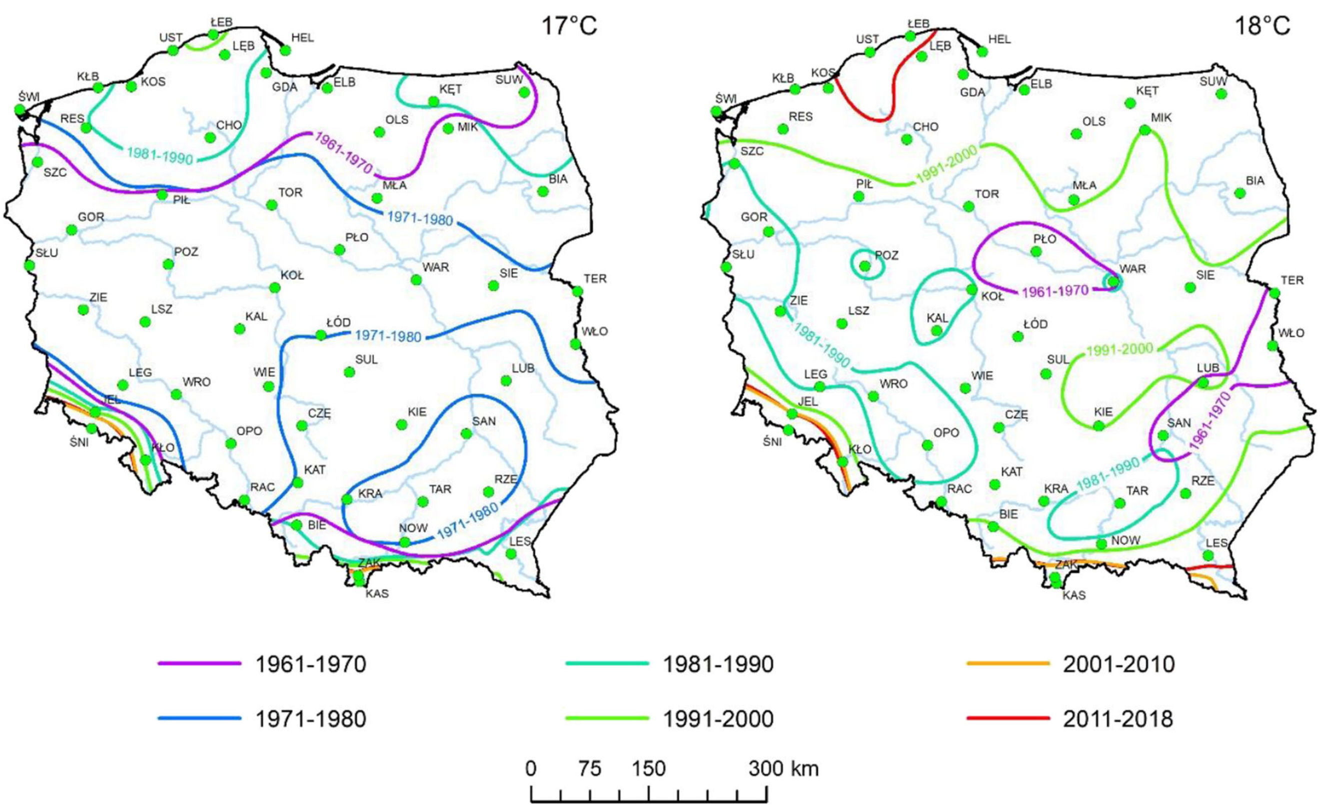

Fig. 8 Location of 17 and 18 °C isotherms in Poland in July by decade in the period 1961–2018

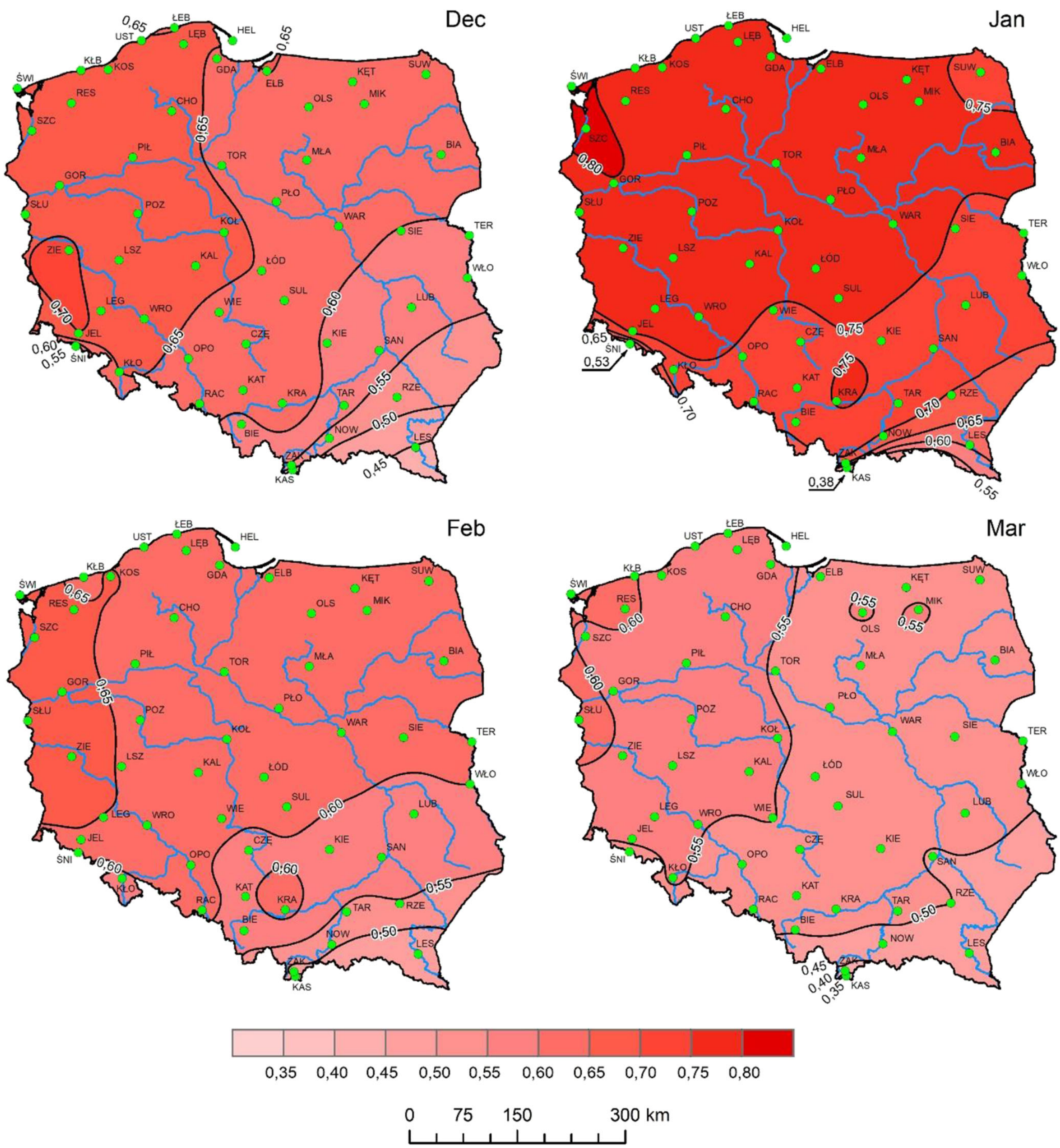

Fig. 9 Correlation between NAO and air temperature in selected months in Poland in 1961–2018

arrangement of isotherms and the position of the warmest and coldest areas remained unchanged.

There was an evident shift of isotherms in Poland in the analysed period. It was studied in detail for January and July to reveal that in January, in the years 1961–1990, there were no areas with a mean air temperature above 0 °C, whereas in 1991–2000 the 0 °C isotherm covered the entire north-west of Poland and occurred in the Silesian Lowland. In the subsequent decade, with the occurrence of frosty winters (2006, 2010), a positive temperature was only recorded at the Baltic Sea. In 2011–2018, the 0 °C isotherm again covered a larger portion of the country: the coastline, the Szczecin Lowland and the Silesian Lowland (Fig. 7). The − 1 °C isotherm was absent in 1961–1970, but in subsequent decades it moved eastwards and ran in a meridional pattern across Central Poland. The isotherm reached its easternmost position in the years 1991–2000. Similar changes can be observed in the case of the − 2 °C isotherm which, in 1961–1970, occurred only on the Baltic coast, but in subsequent decades it moved as far as the east part of the country, reaching its furthest position in 1991–2000 and 2011–2018. Thus, it shifted 600 km to the east. The − 3 °C isotherm covered the coastline and the west of Poland in 1961–1970, but in 2011–2018, in the Suwałki Lakeland and Podlasie only, the mean air temperature was lower. The − 4 °C isotherm was not present in 1991–2000 or 2001–2018, except for mountainous areas, but in 1961–1970 its arrangement was meridional in Central Poland. In the mountains, the January isotherms covered higher and higher elevated areas in the analysed decades.

In July, too, the positions of isotherms changed between decades. The 17 °C isotherm in 1961–1970 covered the north of Poland (Pomeranian and Masurian Lake Districts) and the mountains: the Carpathians and the Sudetes (Fig. 8). In the next decade, July was cooler and the reach of the isotherm was greater. Higher mean temperatures were only noted in the lowlands (Silesian, Szczecin, Wielkopolska and Mazovian) and in Sub-Carpathian basins. In subsequent decades, the isotherm retreated to the north and covered only the Pomeranian Lake District and the Lithuanian Lakeland. In 1981–1990, the coldest regions were the Baltic coast (Łeba area) and the mountains. From 1991, the isotherm did not occur anywhere except in the mountains. The July 18 °C isotherm marked the warmest parts of Poland. In 1961–1970, it was observed only in the Mazovian Lowland, Sandomierz Basin and Lublin Highland. In 1971–1980, there were no areas with such a high mean air temperature. In subsequent decades, the area where the temperature exceeded 18 °C extended from the Silesian Lowland and the Sub-Carpathian region (in 1981–1990) to cover nearly all of Poland in 2011–2018. Only in the mountains and on the coast (Łeba and Ustka) was the temperature lower.

3.3 The influence of NAO on changes in air temperature in Poland

The correlation between the North Atlantic Oscillation (NAO) and the mean annual air temperature in Europe is spatially variable (Heape et al. 2013). In North Europe, the correlation is positive, because an increase in NAO denotes that westerly advection increases, which leads to warming. On the other hand, in the Mediterranean basin NAO+ brings cooler weather (negative correlation). This is particularly evident in winter.

In the analysed years in Poland, the Pearson linear correlation coefficient (r) with regard to the NAO and the mean annual air temperature decreases in an eastern direction. However, its extreme values were reached in the south (Zakopane, r = 0.29) and north of the country (Gdańsk, r = 0.47). The strongest correlation of air temperature occurred in winter indicating a latitudinal position of isocorrelates, with the highest values in the north of Poland (0.75–0.80). In other seasons, the correlation was insignificant; in summer, the values were negative (up to − 0.30) and the isocorrelate system was meridional. By analysing the individual months, it was observed that the strongest correlation occurred from December to March (Fig. 9). In January, the Pearson linear correlation coefficient (r) reached 0.81 in Świnoujście (Fig. 10). A weaker correlation was found for the stations located in the mountains (Mt. Śnieżka, 0.53; Mt. Kasprowy Wierch, 0.38), where local influences are observed, connected with foehnic circulation and the occurrence of air temperature inversions (Migała 2005).

3.4 Case study: the influence of atmospheric circulation and solar radiation on air temperature in Toruń

The influence of atmospheric circulation on air temperature in Toruń (a city in the central Poland) was analysed based

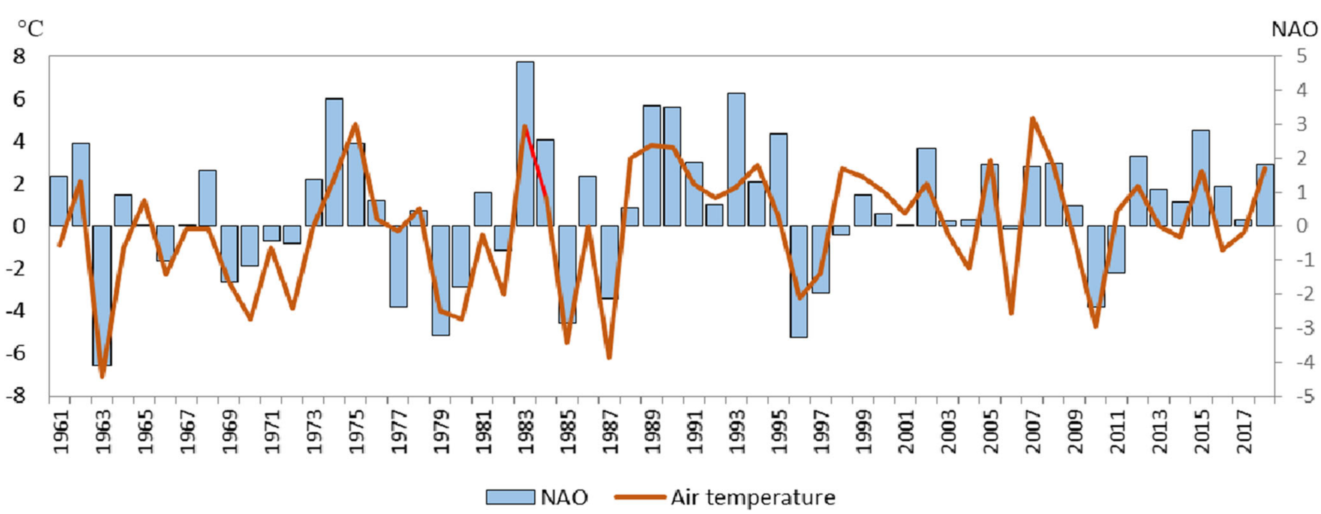

Fig. 10 Course of mean air temperature in Świnoujście and NAO in the years 1961–2018

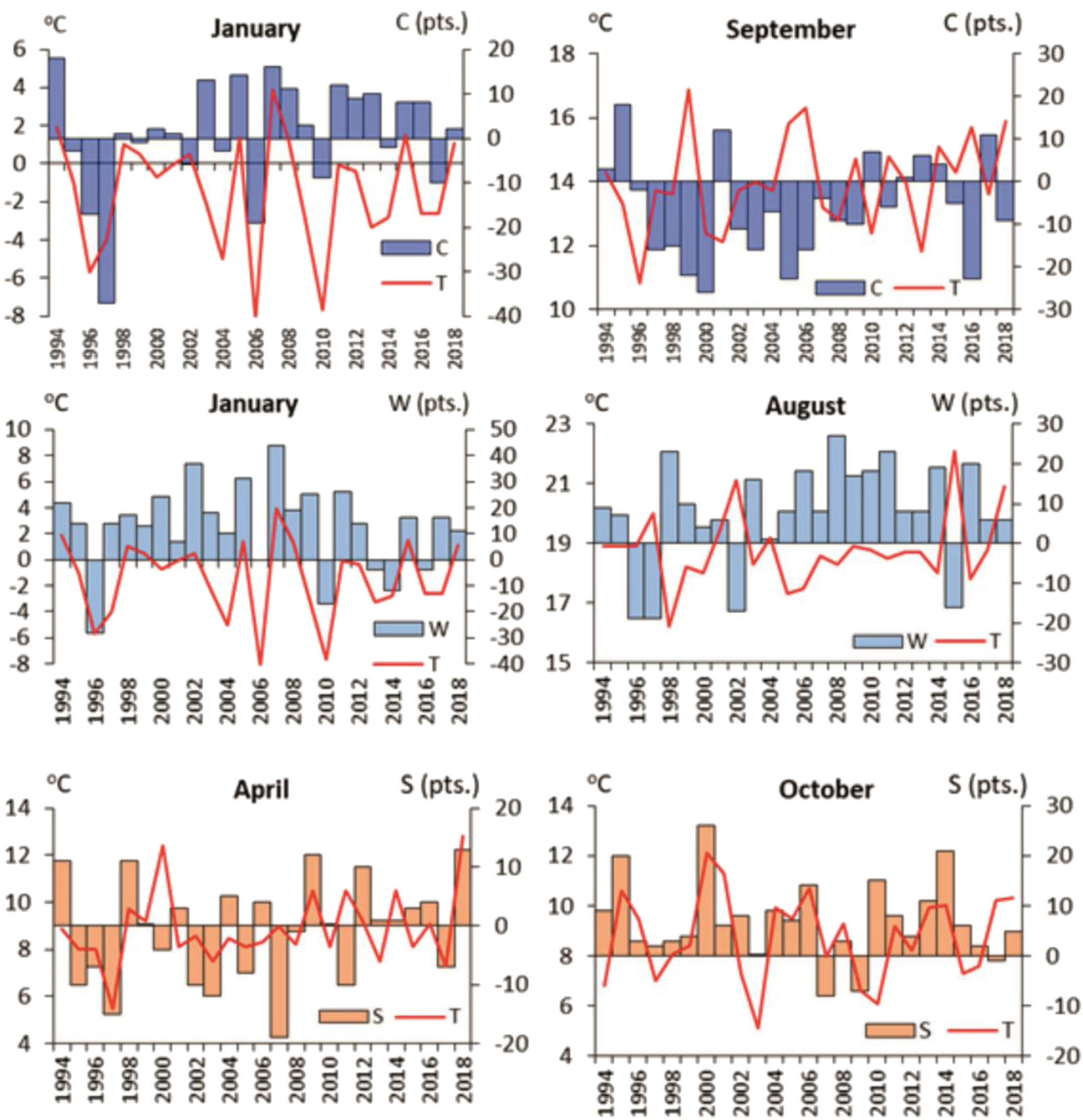

Fig. 11 Course of mean values of air temperature (T) in Toruń and of the cyclonicity index (C), zonality index (W) and meridionality index (S) of atmospheric circulation in 1994–2018

on the following indices: cyclonicity (C), zonality (W) and meridionality (S), calculated by reference to the records of daily synoptic (weather) patterns in 1994–2018. In the area of Toruń at the time, anticyclonic patterns slightly prevailed (51.8%) over cyclonic weather (46.1%). Unspecified patterns (X) accounted for 2.1% of cases. The Toruń region was often influenced by an anticyclonic wedge (Ka = 11.4%) and cyclonic patterns with westerly advection (SWc - 9.5%, Wc - 8.5%, NWc 7.8%). Among anticyclonic weather situations, the most frequent was SEa advection (6.9%) and NWa (5.6%). This regularity is confirmed by data obtained from long-term studies (Przybylak and Maszewski 2009). In the analysed period, anticyclonic patterns prevailed in 15 of the years (e.g. in 1997, they accounted for 62.7% of cases, whereas cyclonic patterns occurred in 35.3%), and in 10 of the years cyclonic patterns prevailed (e.g. in 2010, they accounted for

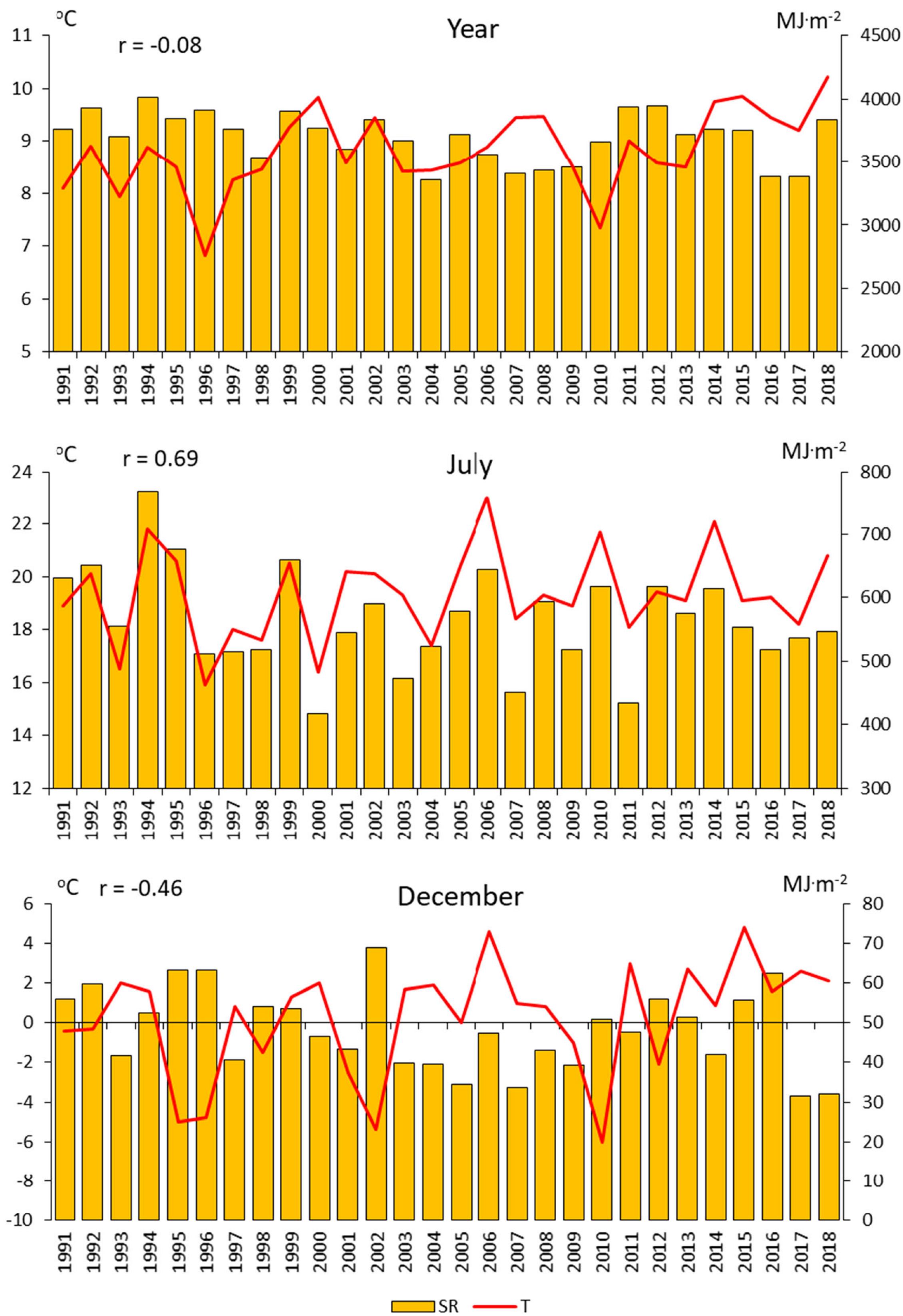

Fig. 12 Course of solar radiation (SR) and air temperature (T) in Toruń in 1991–2018

59.7% of cases, whereas anticyclonic patterns occurred in 37.8%).

After the monthly values of circulation indices were calculated, it was found that the type of barometric centre—cyclonic or anticyclonic—had a major influence on air temperature. However, their effects are opposite in the cold and warm half of the year (Fig. 11). In January, increased cyclonicity caused higher air temperatures in Toruń (r = 0.65). Barometric lows usually come from the Atlantic Ocean in winter, bringing warmer air masses. In the warm half of the year, on the other hand, when a cyclone arrives it brings a definite cooling. Anticyclones, typically associated with sunny weather and ample quantities of solar radiation, cause air temperature to increase. The strongest correlation with the cyclonicity index was found for September (r = − 0.47).

The direction from which air masses flow is also important. The zonality index is positive when a westerly advection prevails. Intensified inflow of air masses from that direction results in evident warming in winter (r = 0.72 in January) and cooling in summer (r = − 0.69 in August) (Fig. 11). As a result of such opposite effects, no significant correlations with mean annual values were found. In the transitional seasons, the correlations were weak.

The meridionality index (S) is positive when a southerly advection prevails. Its correlation with air temperature was statistically significant in only 3 months in Toruń: April (r = 0.43), October (r = 0.49) and November (r = 0.45) (Fig. 11). Especially in autumn, positive air temperature anomalies are caused by southerly advection of tropical air. The phenomenon, being quite frequent and very likely to occur, is traditionally referred to as an 'Indian summer' due to it relatively high air temperatures and sunshine duration, or—in Poland—a 'golden Polish autumn' due to the golden colour of treeleaves.

Air temperature also depends on the heat balance and its major component—solar radiation. On the basis of available data, the relationship between air temperature in Toruń (city in the central part of Poland) and the amount of incoming solar radiation was analysed for the years 1991–2018. The total annual solar radiation in Toruń was 3,699.7 MJ m^{-2} in that period (with a mean monthly irradiance of 117.2 W m^{-2}). During the year, the largest amount of solar energy reached the ground in June: 574.1 MJ m^{-2} (221.5 W m^{-2}), and the smallest in December: 48.2 MJ m^{-2} (18.0 W m^{-2}). No statistically significant trend was observed for the solar radiation, but it started clearly to change—from 3,355.7 MJ m^{-2} in 2017 to 4,014.2 MJ m^{-2} in 1994 (Fig. 12). Yet, the changes did not affect the values of air temperature. The correlation was found to be statistically insignificant, and the Pearson coefficient only reached − 0.08.

Nevertheless, the correlations were statistically significant in individual months (Fig. 12). In summer, an increase in the amount of incoming solar radiation resulted in higher mean monthly air temperatures. The strongest correlation (r = 0.69) was found in July. The increase in solar radiation is associated with a greater frequency of anticyclonal situations. In July, a negative correlation was observed between the cyclonic index and air temperature (− 0.36). Anticyclonal situations cause an increase in air temperature, which results from a lower degree of cloudiness and an increased inflow of solar radiation.

In winter, there is not much incoming solar radiation and the correlation was found to be the opposite (e.g. in December r = − 0.46). The apparent contradiction is connected with the effects of circulation factors. Frosty winters occur in Poland with easterly advection of continental air masses. At the time, Poland is often exposed to a barometric high associated with good weather. On the other hand, an increase in air temperature in winter is frequently caused by cyclones (in January, the correlation of temperature with the cyclone index amounted to 0.65) and with the advection of warmer maritime air masses bring greater cloudiness and are characterised by lower insolation.

4 Summary and discussion

The analysis confirmed that the air temperature in Poland increased in the years 1961–2018 by an average of 0.33 °C/10 years in the case of lowland stations. The value is higher than established in previous research, which indicates that the warming is accelerating. In 2001, Kożuchowski and Żmudzka found a significant increase in air temperature in Poland over the last two decades of the 20th century based on observational data from the years 1951–2000. The trend was maintained at the beginning of the 21st century (Michalska 2011). Biernacik et al. (2010) and Marosz et al. (2011) stated that in 1951–2008 it amounted to 0.24 °C/10 years. Similar values were obtained by Wójcik and Miętus (2014) for the years 1951–2010 (0.22 °C/10 years).

In the analysed years, the greatest increase in air temperature occurred in the Silesian, Wielkopolska and Mazovian lowlands, and on the central part of the Baltic coast, exceeding 0.4 °C/10 years. The area of the country with a considerable increase in air temperature became much larger. Previously, Marosz et al. (2011) demonstrated that air temperature increased at the highest rate on the coast and in the Carpathians (0.24 °C/10 years), but more slowly in the highlands and the Sudetes (0.18 °C/10 years). At some stations, a dramatic increase in air temperature was connected with local conditions (such as the UHI), which is confirmed by the concentricity of the isometric lines.

The changes in air temperature were not uniform throughout the year, which suggests that the reasons, too, were varied. In the analysed period, the greatest warming occurred in summer months (0.48 °C/10 years in July). A substantial warming was also characteristic in winter (0.46 °C/10 years in January) and spring (0.41 °C/10 years in April). Whereas Marosz et al. (2011) found that the greatest trend in 1951–2010 was observed in winter (0.52 °C/10 years in February), but not in July and August (only 0.28 °C/10 years and 0.27 °C/10 years, respectively), Marsz and Styszyńska et al. (2019) proved that the increase in air temperature in summer months in Poland after 1988 was connected with a greater sunshine duration. The cause of the increase in sunshine duration was a change in macro-circulation conditions. Between 1987 and 1989, circulation epochs changed, according to the classification of Wangenheim-Girs; the E circulation epoch ended and W began, the latter favouring an increase in sunshine duration and air temperature. In Poland, heatwaves are more and more frequent, also because of atmospheric circulation (Wibig 2018).

The reason for the winter increase in temperature could be an increased activity of atmospheric circulation from the west. In the analysed period, it was found that the correlation between the NAO (Hurrell 1995) and air temperature in Poland was positive, which had already been indicated in the research conducted by Przybylak et al. (2003); Koźmiński and Michalska (2012); Bednorz et al. (2018); Kossowska-Cezak and Twardosz (2018); Marsz and Styszyńska (2018); and Styszyńska et al. (2019). Results of analyses carried out for Europe (Heape et al. 2013) also confirm this. The influence of NAO on air temperature is particularly evident from December to March (NAO_{DJFM}) (Marsz 2013). A positive phase of NAO+, during which the pressure gradient between the Azores High and the Icelandic Low increases, triggers an intensified westerly circulation and an inflow of maritime air masses, thus causing warming in Northern Europe, but also cooling in the Mediterranean basin (Heape et al. 2013). In northern Poland, the correlation between NAO and air temperature in January was as high as 0.81. The greater increase in air temperature in winter compared with summer leads to a decrease in the annual amplitude of air temperature, which indicates a progressing oceanity of Poland's climate (Michalska 2011).

There was also a considerable shift of isotherms in Poland. In winter, the isotherms moved by a few hundred kilometres to the east. In January, in 1991–2000, the 0 °C isotherm was observed, covering the Baltic coast and the Szczecin Lowland in subsequent years. In summer, the reach of isotherms with higher temperatures covered increasingly greater areas. The isotherms moved to the north and south into highland and mountainous regions. Extreme weather conditions, including heatwaves, became increasingly frequent (Ustrnul et al. 2010).

The case study for Toruń (Central Poland) demonstrated that changes in the quantity of incoming solar energy were the reason for the increase in air temperature. Greater incoming solar radiation causes air temperature to increase; in July in 1991–2018 in Toruń, for example, the correlation reached 0.69. It was validated by research conducted by Marsz and Styszyńska et al. (2019) who confirmed a relationship between air temperature changes and sunshine duration. Both solar radiation and sunshine duration depend on cloudiness. A study by Żmudzka (2008) demonstrated that increased cloudiness leads to a reduction in air temperature (in July, the correlation was − 0.75 and in winter the relationship was exactly the opposite).

Changes in atmospheric circulation are another essential factor influencing thermal conditions (Degirmendžič et al. 2004). In the years 1994–2018 in Toruń, it was observed that in winter air temperature increases in cyclonic weather situations (in July the correlation was 0.65) but decreases in the warm half of the year (− 0.47 in September). The advection direction is also important, as intensified inflow of air masses from the west causes air temperature to rise in winter ($r = 0.72$ in January) and fall in summer ($r = -0.69$ in July). The role of meridionality is especially evident in autumn ($r = 0.49$ in October).

On a global scale, the increase in air temperature in different regions of the world is subject to modifications depending on regional factors. In Poland, the most vital are changes in atmospheric circulation that also affect cloudiness and incoming solar radiation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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