Pure Appl. Geophys. 180 (2023), 3351–3370

https://doi.org/10.1007/s00024-023-03324-9

Pure and Applied Geophysics

Exceptionally Cold and Warm Spring Months in Kraków Against the Background of Atmospheric Circulation (1874–2022)

Zuzanna Bielec-Bąkowska[1] and Robert Twardosz[2]

Abstract—In the changing climate, exceptionally warm (EWMs) and dry spring months are increasingly observed. At the same time, exceptionally cold months (ECMs) are less frequent, although their impact on a warming climate becomes significant. Due to the role that such climatic anomalies play in the environment and their effects on human activity, it is very important to explain the causes of their occurrence. For this reason, in this study, the authors have attempted to determine the circulation conditions favourable to the occurrence of extremely cold (ECM) and warm (EWM) spring months in Kraków in the years 1874–2022. The study used the average temperature of individual spring months (March–May), as well as types of atmospheric circulation and air masses from the daily Calendar of Atmospheric Circulation Types for southern Poland. A distinct increase in spring air temperature (0.181 °C/10 years) and its individual months (0.162–0.191 °C/10 years) was confirmed. It was accompanied by a significant increase in the occurrence of EWM and a decrease in ECM. It was also found that the direction of air advection and the related temperature characteristics of air masses have the greatest impact on the occurrence of exceptionally cold or warm months. A slight positive effect of zonal circulation on the temperature increase at the beginning of the spring season and the advection of air from the south in April and east in May was found. In the case of the coldest months (ECMs), low temperatures most often developed in the presence of advection from the NW-N-NE directions.

Keywords: Poland, Kraków, air temperature, spring, atmospheric circulation.

1. Introduction

Recent decades have observed a significant increase in air temperatures which are particularly strongly marked on the European continent (IPCC, 2013; Krauskopf & Huth, 2020; Kundzewicz et al., 2020; Twardosz et al., 2021). One of the manifestations of climate warming in Europe is an increasing frequency and intensity of heat waves, as well as prolonged month periods and even entire seasons with extremely high air temperatures, deviating considerably from the long-term average (Twardosz & Kossowska-Cezak, 2021). Among these extreme climatic phenomena, the exceptionally hot summers of 2003 and 2010 have gone down in the history of Europe's climate. The anomalies triggered a range of serious consequences, such as a heavy death toll in western Europe, especially in France in 2003 (e.g. Campbella et al., 2018), and extensive forest fires in eastern Europe in 2010 (Zvyagintsev et al., 2011). With the memory of these extreme heatwaves in Europe still fresh, there came August 2015, which proved similarly hot, with record-breaking anomalies over large areas of the central part of the continent (Hoy et al., 2017; Krzyżewska & Dyer, 2018; Luterbacher et al., 2016; Muthers et al., 2017; Wypych et al., 2017). The summer of 2022 should also be considered exceptionally hot. In large areas of the northern hemisphere (including Western Europe and China), the air temperature exceeded 40 °C, many tropical nights and the occurrence of heat waves and droughts were recorded (Met Office, 2022, Jiang 2023, Lu et al., 2023). Since the beginning of the twenty-first century, the attention of researchers has been drawn to increasingly frequent exceptionally warm spring months, including two record warm and very dry months: April and May 2018 (Sinclair et al., 2019; Twardosz, 2019). In many areas of central Europe, they were the hottest months in the history of temperature monitoring (Błażejczyk et al., 2022). The observable general increase in the frequency of

---

[1] Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia in Katowice, ul. Będzińska 60, 41-200 Sosnowiec, Poland. E-mail: zuzanna.bielec-bakowska@us.edu.pl

[2] Faculty of Geography and Geology, Jagiellonian University, ul. Gronostajowa 7, 30-387 Kraków, Poland. E-mail: r.twardosz@uj.edu.pl

Birkhäuser

exceptionally warm months is also due to the prolongation of the period over which they occur during the year, mainly their earlier onset, i.e. as early as in April and/or May (Twardosz & Kossowska-Cezak, 2021). As a result, spring has become the fastest warming season in Europe with the increase reaching 0.061 °C/year in the years 1985–2020 (Twardosz et al., 2021).

Such early emergence of unusually warm and dry weather after a mild and snowless winter aggravates drought at the beginning of the growing season, leading to adverse consequences in agriculture and many other areas of the economy (Peters et al., 2020; Sinclair et al., 2019; Twardosz, 2019). Notably, the emergence of prolonged anomalous hot weather in spring is also extremely onerous for the human body, which has not yet adapted to heat after the winter (Muthers et al., 2017).

The awareness of the above facts has prompted the authors to pose a question about changes in the frequency and timing of such thermally anomalous spring months in the long term. Above all, it has become an inspiration to explain the underlying reasons by studying them against the backdrop of circulation conditions. The authors' previous research on changes in the occurrence of exceptionally cold and warm months over time focused on the European continent. The research covered different periods and various numbers of meteorological stations (Twardosz & Kossowska-Cezak, 2021; Skrzyńska and Twardosz, 2023), which means that they concerned a macro-scale. The authors sought to explain the overall circulation-related factors behind such extreme climatic events by analysing the distribution of the average pressure across Europe (Twardosz & Bielec-Bąkowska, 2022).

Obviously, in order to explain fully the impact of circulation on thermal conditions in a given area, it is necessary to use a classification of circulation types at a mesoscale that corresponds to the area under investigation. Kraków is perfectly suited for such synoptic and climatological studies since it has a homogeneous series of air temperatures measured since 1792 and a mesoscale typology of atmospheric circulation types for southern Poland since 1874, which has been prepared by Niedźwiedź (1981, 2022). This being the case, the aim of the present study is to gain insight into the variability of occurrence of exceptionally cold and exceptionally warm spring months in Kraków in the years 1874–2022 and to describe the underlying circulatory conditions. The inclusion of anomalously cold months in the research, which are less and less frequent, is motivated by the fact that they continue to pose a serious problem in agriculture, especially for novel crops, which are ever more willingly grown in Poland's warming climate (e.g. vine). The findings of the study will contribute to understanding the recent warming, which is a complex and spatially diverse process (Ji et al., 2014; Hegerl et al., 2018; Krauskopf & Huth, 2020; Skrzyńska and Twardosz, 2023) and which requires continuous monitoring in order to assess its potential social, economic and environmental implications.

2. *Data and Study Methods*

Two sets of data are used in the article. The first set consists of average monthly air temperature values from March to May from a meteorological station located in the centre of Kraków (50°04′N, 19°58′E, 206 m a.s.l.; Fig. 1) which is operated by the Department of Climatology of the Jagiellonian University. This station began operating in 1792, and since 1826, measurements have been made without any interruptions. Constant meteorological observations were made at the station, even during the world wars. This means that the temperature series from Krakow maintains the uniformity of time and place of observation. Measurements have been made in the same location since the beginning of the station's existence, i.e. in the former Astronomical Observatory of the Jagiellonian University located in the Botanical Garden of the Jagiellonian University ("historical station", weather instrument shelters by the north window of the second floor of the building, 12 m above ground level), thanks to which Krakow has one of the longest measurement series in Poland and Europe (Trepińska, 1997). During the period of operation of the station, the thermometers changed for obvious reasons, but this did not affect the uniformity of the temperature in any way (Ustrnul, 1997). The homogeneity of the series has also been

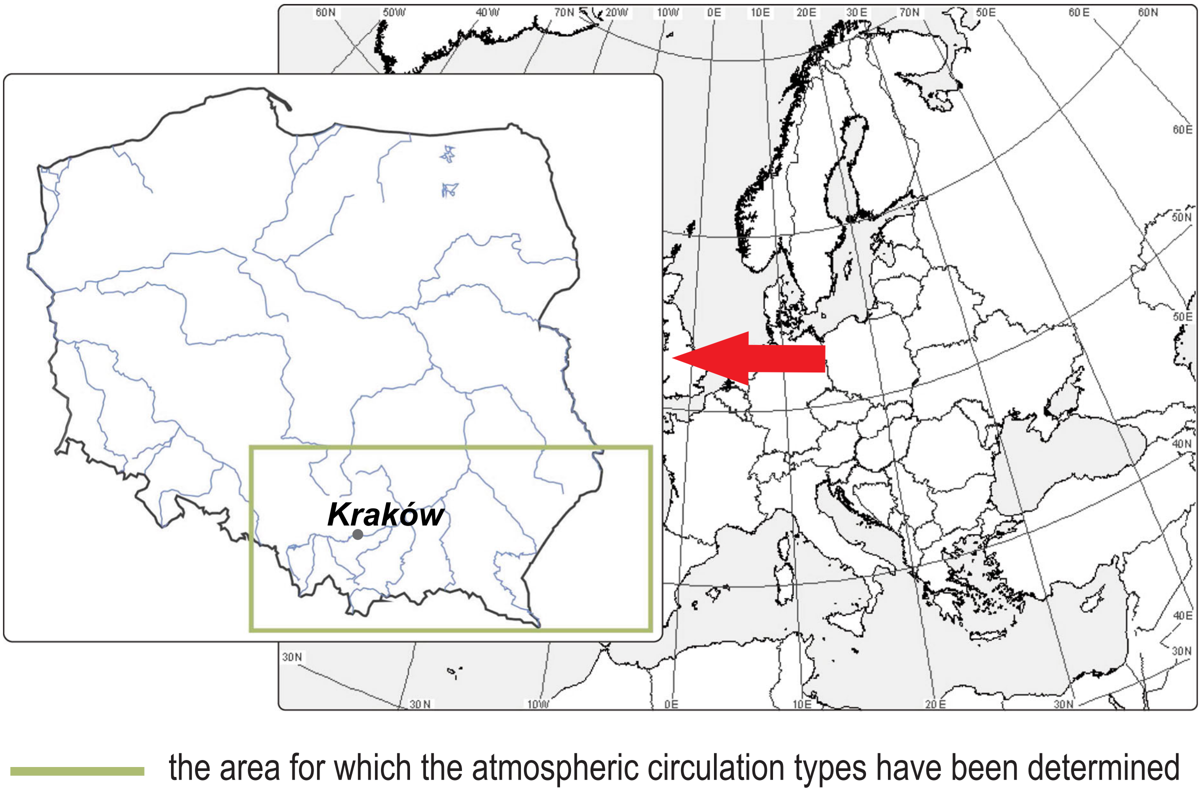

Figure 1
Location of study area

verified in many studies on temperature changes in Kraków.

Data for the 3 spring months from 1874–2022 is used. In order to identify the spring months and entire spring seasons in which the average temperature diverged significantly from the long-term average, use was made of criteria for identifying the occurrence of extreme events. According to them the frequency of extreme events should not be higher (lower) than the 10th, 5th or even 1st percentile (90th, 95th or 99th percentile, respectively) of all the cases analysed (Beniston et al. 2007, IPCC, 2007; Labajo et al., 2008). In this way, exceptionally cold and exceptionally warm months (ECMs – with a temperature $\leq$ 10th percentile of all values; EWMs—with a temperature $\geq$ 90th percentile), as well as exceptionally cold and exceptionally warm springs (ECSs/EWSs) from the entire 149-year period 1874–2022 were identified. In addition, those with values below the 5th (ECM/S_5) or 1st percentile (ECM/S_1) or above the 95th (EWM/S_{95}) or 99th percentile (EWM/S_{99}) were distinguished.

The second data set is the daily *Calendar of Atmospheric Circulation Types for southern Poland* compiled by Niedźwiedź (1981, 2022).

The calendar defines 20 types of circulation, 16 of which are types describing the advection of air over the area concerned. These are described with a code denoting the direction of air advection and the associated type of pressure system (‘a’ for anticyclonic systems: Na, NEa, Ea, SEa, Sa, SWa, Wa and NWa or ‘c’ for cyclonic systems: Nc, NEc, Ec, SEc, Sc, SWc, Wc and NWc). The remaining 4 types describe the following situations: Ca – central anticyclonic situation, Ka – anticyclonic wedge, Cc – central cyclonic situation, centre of low pressure, Bc – cyclonic trough, and X (number 21) unclassified situations (Niedźwiedz 1981; Twardosz, 2010).

In addition, the calendar is used as a basis for complex atmospheric circulation indices: Wi—western circulation zonal index, Si—southern circulation meridional index and Ci – cyclonicity index. The indices are similar to those developed by Murray and Lewis (1966) for the British Isles. In this paper, the index values were calculated for the spring months and the entire spring season by assigning appropriate weights to particular types of circulation (+ 2, + 1, 0, − 1, − 2). A detailed description of how these indices are calculated has been presented in several previous publications (e.g. Niedźwiedź, 2000; Niedźwiedź & Ustrnul, 2021). Given the different numbers of days in individual months, in their final version the indices are converted into percentage values so that they fall within the range from − 100 to + 100. For example, the value + 100 of the Wi index would mean the inflow of air from the west on all days of the month, while − 100 would denote advection from the east. The same applies to the Si index (+ 100—advection from the south; − 100 from the north) and the Ci index (+ 100—centre of low pressure or cyclonic trough over the area on each day, − 100—centre of high pressure or anticyclonic wedge).

In order to conduct a detailed analysis of the ECMs and EWMs identified, use is also made of the typology of air masses developed by Niedźwiedź (1981, 2022), which is employed to supplement the calendar referred to above. The author identified six air masses: A—Arctic, mPf—polar maritime (fresh), mPw—polar maritime warm, mPo—polar maritime old (transformed), cP—polar continental, T—tropical. There is also a separate type for various air masses during a day—vAm.

In the study, trends in air temperature changes were determined using an equation of linear regression, whereas trend significances were calculated using the Mann–Kendall test (Kendall, 1975; Mann, 1945). While examining the correlation of temperature changes in individual months and throughout the spring season and between temperature and circulation indices, the r-Pearson correlation analysis was used.

3. General Characteristics of the Variability of Spring Temperatures Against the Background of the Atmospheric Circulation Indices

The study investigates changes of temperature throughout the spring season and in individual spring months (March—May). The average spring temperature in the entire study period was 8.8 °C and ranged from 3.3 °C in March to 14.2 °C in May (Table 1). The lowest average monthly temperatures were typically above 0 °C, with negative values only recorded in March in 16 out of the 149 years. Four of these occurred in the nineteenth century, ten were recorded in 1917–1969, and the last two were in 1987 and

Table 1

Statistical characteristics of the average air temperature in spring and spring months [°C] in Kraków in the years 1874–2022

Value	Temperature (°C)			
	March	April	May	Spring
The lowest	− 2.6 (1886)	4.2 (1929)	9.3 (1874)	5.7 (1875)
1st percentile	− 2.5	5.2	9.5	6.0
5th percentile	− 1.1	5.8	11.3	6.5
10th percentile	− 0,1	6.1	12,.2	7.0
Average	3.3	8.9	14.2	8.8
90th percentile	6.2	11.2	16.3	10.6
95th percentile	7.2	11.8	17.1	11.2
99th percentile	7.5	13.2	17.9	11.8
The highest	7.9 (2014)	15.4 (2018)	18.6 (2018)	12.0 (2018)
Standard deviation	2.5	1.9	1.7	1.4
Coefficient of variability	75.0%	21.7%	12.2%	16.0%

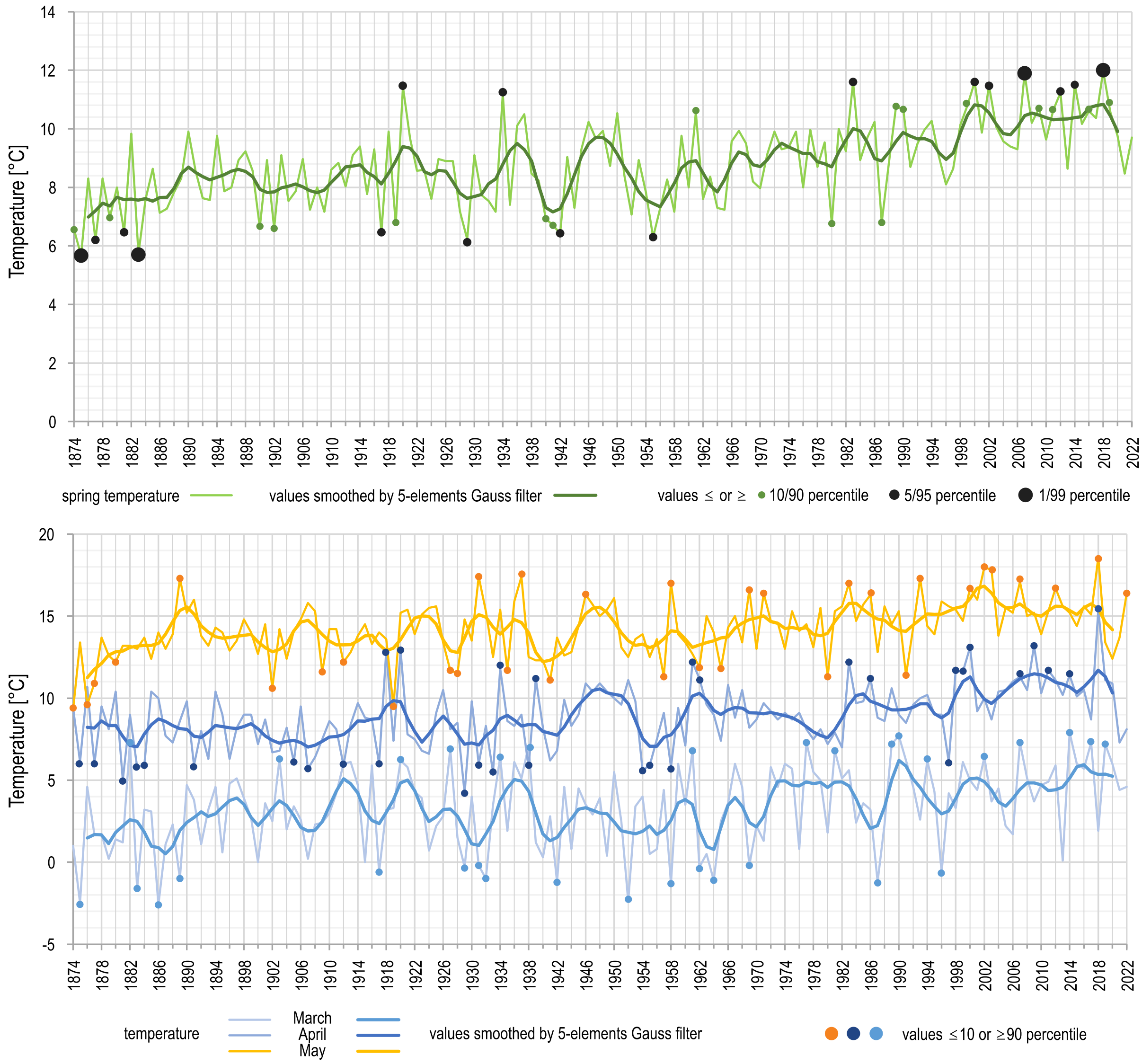

Figure 2
Average monthly air temperature (°C) in spring and spring months in Kraków in the years 1874–2022

1996 (Fig. 2). For both spring months and spring as a whole, they occurred in the early years of the study period (in the nineteenth century and, in April, in 1929), while the highest value was in the second decade of the twenty-first century (Table 1). This reveals a discernible upward trend in air temperature for spring as a whole and for individual spring months. The highest increase is observable for March, but it is the least stable (0.191 ± 0.045 °C/10 years; Table 2) as a result of the high temperature variability in this month (Table 1). The smallest rise in temperature is displayed by May (0.162 ± 0.030 °C/10 years), but it turns out to be the most stable due to lower temperature variations (Tables 1 and 2, Fig. 2). The existing trends in average temperature changes are statistically highly significant (Table 2).

Spring temperature changes are mainly attributable to changes in March. The correlation coefficient between these temperature values was 0.744, meaning that 55% of the spring temperature changes can be explained by changes in March. The

Table 2

Coefficient of linear regression (slope) average mean air temperature

Month/Season	Slope (°C/year)	R^2	p-value	95% confidence interval
March	0.0191 ± 0.0045	0.109	0.000038	0.010, 0.028
April	0.0189 ± 0.0034	0.177	0.000000	0.012, 0.026
May	0.0162 ± 0.0030	0.162	0.000000	0.010, 0.022
Spring	0.0181 ± 0.0023	0.304	0.000000	0.014, 0.023

The slope uncertainty is standard deviation (1σ)

Table 3

Statistical characteristics of Wi, Si and Ci circulation indices in the spring and in the spring months over southern Poland in the years 1874–2022

Value	Wi (%)				Si (%)				Ci (%)			
	March	April	May	Spring	March	April	May	Spring	March	April	May	Spring
The highest	72.6	61.7	40.3	32.5	41.9	46.7	29.0	28.5	50.0	53.3	48.4	31.3
Year	1961	1943	1902	1945	1916	1934	1984	1934	1988	1903	1983 2019	1970
Average	11.4	3.3	− 3.1	3.8	3.1	0.8	− 4.6	− 0.2	− 4.3	4.2	− 0.5	− 0.2
The lowest	− 46.8	− 55.0	− 56.5	− 25.7	− 35.5	− 35.0	− 41.9	− 25.0	− 74.2	− 43.3	− 51.6	− 39.7
Year	1904	1884	1889	1984	1893	2021	1919	1893	2022	2007 2020	2022	2022
Range	119.4	116.7	96.8	58.1	77.4	81.7	71.0	53.5	124.2	96.7	100.0	71.1
Standard deviation	23.0	20.3	19.8	12.0	17.6	14.6	13.1	9.8	23.6	19.4	20.4	13.1
Tendency (%/10 years)	− 0.29	0.04	0.21	− 0.01	− 0.23	− 0.21	0.34	− 0.03	− 0.35	0.27	**0.80**	0.24

Bold text—statistically significant at the level of 0.05

developments in the remaining months have much smaller effect on the thermal character of spring as a whole, with May having the lowest effect due to the weakest temperature variability ($r = 0.583$, $R^2 = 34\%$).

Statistically significant as they are, the correlation coefficients that were calculated between the average temperature values in spring months are small (about 0.250), which is manifest proof of the non-synchronic occurrence of extreme air temperatures over time (Fig. 2). This is reflected by an analysis of exceptionally cold and exceptionally warm spring months and springs (ECMs/Ss and EWMs/Ss; Fig. 2).

The strong increase in temperature is also reflected by the timing of ECMs and EWMs. The former (ECMs) would mainly occur in the first half of the multi-year period, while the latter (EWMs) occurred after 1950. Another notable fact is that, in the case of very cold or warm springs, temperature values of at least one month were also identified to represent the exceptionally low or high category, respectively. In the most manifest cases, such values were usually observed for two months (mostly March and April). Examples include the Marches and Aprils of the coolest springs (ECSs) that occurred in 1875 and 1883, as well as the April and May of the very warm spring of 2018 and all three months of the slightly cooler season of 2007.In the analyzed period, there were also 4 cases in which none of the months was classified as ECMs or EWMs, but the entire season was exceptionally cold (3 times) or warm (once). There were also years when two months were counted as ECMs or EWMs, but the whole spring was not classified as the warmest or coldest. An example may be the years 1931 and 1958, in which March and April were cold months (ECM_{10}), and May was warm (respectively: EWM_{95} and EWM_{90}) and the year

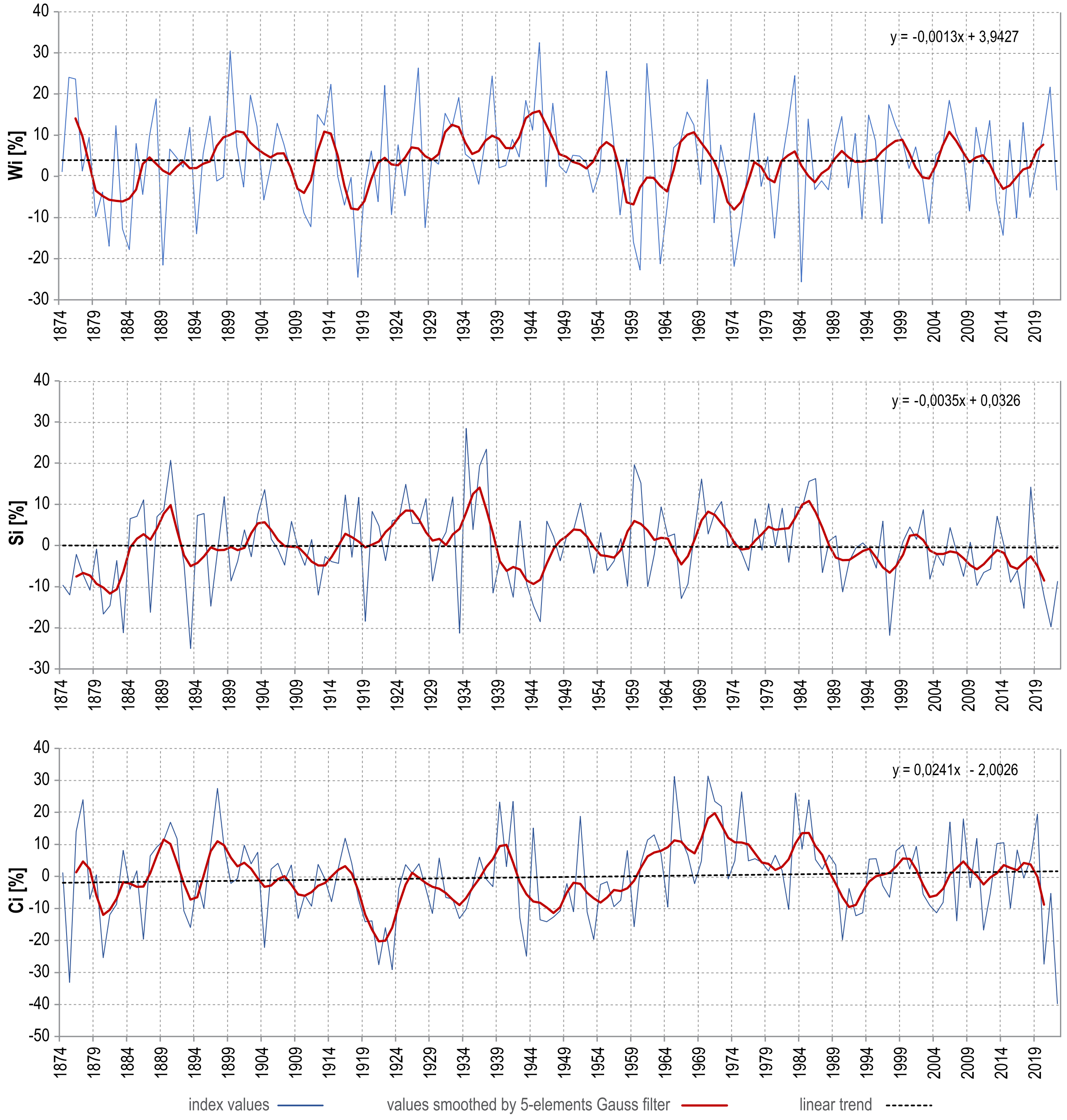

Figure 3
Average monthly values of circulation indices (%) in spring over southern Poland in the years 1874–2022

1968, in which April and May were very warm months—EWMs$_{90}$).

In order to identify the causes behind the trends in spring temperatures identified, an investigation was made of their relationship with atmospheric circulation. In the first step, the temperature rises were compared to the complex Wi, Si, and Ci circulation indices.

The analysis found that long-term changes in the indices over the period under consideration were not significant except for the Ci index in May (Table 3; Fig. 3). One consequence of this lack of clear trends is a weak correlation between the temperature

Table 4

Correlation coefficients of air temperature in Kraków with circulation indices over southern Poland (Wi, Si and Ci) in the spring and in the spring months in the years 1874–2022

Circulation indices	Correlation coefficients			
	March	April	May	Spring
Wi	**0.351**	– 0.012	– 0.146	0,040
Si	0.141	**0.521**	**0.603**	**0,282**
Ci	0.004	0.006	– 0.067	0,034

Bold text—statistically significant at the level of 0.05

changes in spring months and seasons and the above indices (Table 4). The above applies primarily to the relationships between temperature and the types of pressure systems (Ci index) that shaped the weather over the study area. This stems from the fact that in the transitional and thermally highly diverse season that is spring, the type and thermal characteristics of incoming air masses are determined by the direction of advection rather than by the pressure system. This is confirmed by the (statistically significant) relationship between the increased frequency of zonal circulation (Wi) and an increase in temperature in March (correlation coefficient r equal to 0.351). There is also an indication that advection of air masses from the western sector (Wi) causes a drop in temperature in May ($r = -0.146$; statistically insignificant). This results from the warming effect of air masses from the Atlantic in early spring and the similar, or sometimes lower than in Kraków, air temperature inflowing from the ocean in May. A stronger effect on temperature is found to have been produced by air advection from the south (Si), both for the entire spring ($r = 0.282$) and April and May ($r = 0.521$ and 0.603).

Given the rather weak relationship between long-term changes in the circulation indices and changes of temperature, further research focused on selected seasons (ECSs and EWSs) and months (ECMs and EWMs) rather than including the entire series of observations. All in all, 16–18 such cases were identified for the springs and individual months alike. The most thermally exceptional months (ECMs$_{5/1}$ and EWMs$_{95/99}$) and springs (ECSs$_{5/1}$ and EWCs$_{95/99}$) are presented in Table 5.

A detailed analysis of the circulation indices (Wi, Si and Ci) confirms the previously described effect of particular forms of circulation on monthly and seasonal temperatures (Table 5). However, in many cases, the exceptionally high or low average monthly or seasonal temperatures are attributable to the specific configuration of circulation types in a given period and the thermal characteristics of the prevailing air masses. One example is March 2014, which saw the highest average monthly air temperature in the study period. The values of the circulation indices reveal a low frequency of inflow of air masses from the west (Wi = – 12.9%) and a prevalence of air masses inflowing from the north (Si = – 9.7%) and of anticyclonic systems, which shaped the weather over the period (Ci = – 9.7%).

It was also found when analysing the exceptional values of the indices (Wi, Si and Ci; ≤ 10 or ≥ 90 percentile of all the values) that in more than half of the cases such values occurred in years that did not qualify as exceptional in temperature terms (ECMs or EWMs).

The difficulties in conclusive interpretation of the effect of particular forms of circulation (as described by the indices employed) are largely related to the change in the 'relative' thermal characteristics of the air masses (warmer/cooler) that arrived over the study area in spring. In this transitional season of the year, one time air masses that flow from a given direction may entail advection of warm air and another of cold air. This depends both on whether it is early, mid- or late season and on the weather conditions in the areas where the air masses originate in the individual years. It should also be remembered that the thermal conditions over the area under consideration in March

Table 5

Selected values of air temperature (°C) and circulation indices (%) (Wi, Si and Ci) over southern Poland in spring ($ECSs_{5/1}$ and $EWSs_{95/99}$) and in the spring months ($ECMs_{5/1}$ and $EWMs_{95/99}$) in Kraków in the years 1874–2022

March						April					May					Spring				
T (°C)		Year	Wi (%)	Si	Ci	T (°C)	Year	Wi (%)	Si	Ci	T (°C)	Year	Wi (%)	Si	Ci	T (°C)	Year	Wi (%)	Si	Ci
ECMs/ECSs	− 2.5	1875	8.1	− 21.0	− 30.6	4.2	1929	1.7	− 1.7	26.7	9.3	1874	− 21.0	− 17.7	17.7	5.7	1875	24.1	− 12.0	− 33.1
	− 2.6	1886	− 19.4	9.7	− 24.2	5	1881	− 28.3	− 8.3	− 11.7	9.5	1919	− 32.3	− **41.9**	− 19.4	5.7	1883	− 12.8	− 21.2	8.1
	− 2.4	1952	− 6.5	− 6.5	− 9.7	5.5	1933	30.0	− 30.0	− 23.3	9.6	1876	19.4	− 19.4	− 11.3	6.2	1877	1.3	− 7.1	24.0
	− 1.6	1883	0.0	− 12.9	9.7	5.6	1954	5.0	− 11.7	15.0	10.6	1902	**40.3**	− 4.8	25.8	6.2	1929	4.3	− 8.6	− 11.5
	− 1.3	1958	− 9.7	− 16.1	17.7	5.7	1907	− 18.3	8.3	20.0	10.9	1877	− 4.8	− 14.5	14.5	6.3	1955	25.6	− 6.1	− 1.6
	− 1.2	1942	− 8.1	17.7	− 33.9	5.8	1883	− 38.3	− 21.7	3.3	11.1	1941	22.6	− 9.7	25.8	6.4	1942	4.7	5.9	− 13.0
	− 1.2	1987	− 11.3	1.6	− 11.3	5.8	1938	16.7	− 20.0	5.0	11.3	1957	− 22.6	− 9.7	− 11.3	6.5	1881	− 17.0	− 14.6	− 12.0
	− 1.1	1964	− 37.1	11.3	− 12.9	5.8	1958	− 3.3	− 20.0	− 1.7	11.3	1980	− 37.1	− 11.3	1.6	6.5	1917	− 0.3	− 2.8	4.1
EWMs/EWSs	7.1	1938	56.5	− 21.0	− 16.1	11.7	2011	− 13.3	− 10.0	− 8.3	17	1983	22.6	12.9	**48.4**	11.2	1934	5.4	**28.5**	− 10.3
	7.2	1989	40.3	8.1	− 9.7	11.8	1934	0.0	**46.7**	− 8.3	17.1	2007	16.1	6.5	14.5	11.2	2012	13.6	− 5.8	− 5.1
	7.2	2019	46.8	− 8.1	3.2	12.2	1961	− 1.7	21.7	8.3	17.3	1889	− **56.5**	17.7	− 11.3	11.4	1920	6.2	8.3	− 13.9
	7.3	1882	46.8	4.8	− 6.5	12.2	1983	23.3	20.0	20.0	17.3	1993	− 29.0	6.5	4.8	11.5	2002	− 0.3	8.7	− 5.6
	7.3	1977	17.7	17.7	− 1.6	12.9	1918	− 28.3	38.3	41.7	17.4	1931	1.6	21.0	3.2	11.5	2014	− 14.3	0.1	10.5
	7.3	2007	1.6	8.1	− 12.9	12.9	1920	25.0	21.7	10.0	17.4	1937	− 17.7	17.7	− 43.5	11.6	1983	24.4	9.4	26.0
	7.3	2017	24.2	− 14.5	3.2	13.1	2000	− 23.3	20.0	15.0	17.8	2003	− 9.7	0.0	− 8.1	11.6	2000	1.9	4.5	2.3
	7.7	1990	37.1	− 17.7	− 40.3	13.2	2009	− 35.0	25.0	− 25.0	18	2002	− 8.1	24.2	16.1	11.9	2007	10.4	− 1.8	− 13.9
	7.9	2014	− 12.9	− 9.7	− 9.7	15.4	2018	23.3	20.0	8.3	18.6	2018	− 43.5	1.6	− 6.5	12.0	2018	− 5.1	14.2	5.5

Bold text—the lowest or the highest value of circulation indices in the years 1874–2022

Table 6

Frequency (%) of the occurrence of advection directions of air masses and weak-advection situations in ECMs and EWMs and in the entire 1874–2020 period over southern Poland (explanations in the text)

Period	The direction of advection								Weak-advection situations					Sum	a	c
	N	NE	E	SE	S	SW	W	NW	Ca	Ka	Cc	Bc	X			
March																
ECMs	9.1	7.7	14.9	13.1	6.3	8.7	11.9	7.3	2.0	10.7	5.4	1.0	2.0	100.0	57.3	40.7
1874–2020	6.0	5.1	9.8	10.5	7.0	9.9	18.4	11.1	1.8	9.2	0.8	8.2	2.1	100.0	52.0	45.9
EWMs	3.0	3.4	7.2	7.3	5.0	11.3	26.3	13.4	1.4	10.8	8.6	0.5	1.6	100.0	54.3	44.1
April																
ECMs	8.9	10.9	12.0	10.6	3.3	4.1	14.6	14.8	1.1	9.1	2.0	8.1	0.4	100.0	44.8	54.8
1874–2020	7.1	7.6	10.1	9.4	7.2	8.5	13.2	8.9	1.2	11.3	1.7	11.7	2.1	100.0	45.1	52.8
EWMs	5.8	4.7	9.8	14.0	11.1	11.1	11.6	6.9	0.7	9.8	1.8	11.1	1.8	100.0	38.7	59.6
May																
ECMs	10.6	14.0	11.2	5.1	3.4	5.9	12.0	12.1	0.8	10.4	1.9	10.8	1.7	100.0	47.4	50.9
1874–2020	7.1	7.7	10.6	9.2	6.7	8.3	14.0	9.6	1.5	10.8	1.4	11.1	2.0	100.0	50.3	47.9
EWMs	3.9	8.2	13.5	11.4	10.1	7.3	7.1	5.8	1.1	12.7	1.3	16.8	0.9	100.0	49.2	49.9

Table 7

The difference in the frequency (%) of advection directions of air masses and weak-advection situations in the ECMs and in the entire 1874–2020 period over southern Poland (explanations in the text)

Period	The direction of advection								Weak− advection situations					Sum	a	c
	N	NE	E	SE	S	SW	W	NW	Ca	Ka	Cc	Bc	X			
March																
ECMs$_1$	3.7	9.4	3.1	2.4	− 7.0	4.6	− 7.2	− 6.3	1.4	0.5	4.0	− 8.2	− 0.5	0.0	20.6	− 20.1
ECMs$_5$	3.7	3.5	9.0	− 0.3	0.0	− 2.4	− 8.8	− 5.8	1.4	3.7	3.5	− 7.1	− 0.5	0.0	− 1.4	1.9
ECMs$_{10}$	2.5	0.1	2.7	4.8	0.2	− 1.9	− 4.7	− 1.9	− 1.0	0.1	5.6	− 7.0	0.3	0.0	6.5	− 6.8
April																
ECMs$_1$	− 0.4	2.4	6.5	7.3	− 5.5	− 5.1	− 3.2	1.1	− 1.2	− 3.0	0.0	3.3	− 2.1	0.0	1.6	0.5
ECMs$_5$	4.6	4.0	3.2	1.2	− 3.3	− 6.2	0.1	8.3	− 0.1	− 4.1	1.1	− 7.3	− 1.5	0.0	1.0	0.5
ECMs$_{10}$	− 1.7	4.5	2.4	2.3	− 3.5	− 3.9	3.5	4.4	− 0.8	− 2.6	0.0	− 2.6	− 2.1	0.0	− 2.2	4.2
May																
ECMs$_1$	12.3	10.1	13.6	− 4.4	− 6.7	− 8.3	− 9.1	− 1.6	− 1.5	− 4.4	1.9	0.2	− 2.0	0.0	4.5	− 2.7
ECMs$_5$	1.5	7.9	2.8	− 7.1	− 2.4	2.4	0.0	2.2	− 1.0	− 3.8	− 0.3	− 1.4	− 0.9	0.0	− 6.8	7.5
ECMs$_{10}$	3.0	3.2	− 3.0	− 2.0	− 2.7	− 3.9	− 1.1	1.3	− 0.3	4.5	0.7	− 0.6	0.8	0.0	− 1.5	0.5

largely resemble those that are characteristic of winter, while those in May tend to be close to summer temperatures. In rare cases, masses of hot air may flow in from non-typical directions. Examples include the advection of tropical air (T; based on *Calendar…*) in the presence of an Nc situation in March 1960, or of continental air (cP) with a Wa situation in March 1955 and with a Wc situation in May 2001.

4. Exceptionally Cold and Warm Months Against the Background of Circulation Types

4.1. ECMs and EWMs Against the Background of Cyclonic and Anticyclonic Situations

The results they had obtained earlier prompted the authors to conduct an in-depth analysis, taking into account the types of circulation that prevailed over the study area in the timespan being investigated. The analysis found a weak correlation between the occurrence of higher or lower temperature values in

Table 8

The difference in the frequency of advection directions of air masses and weak-advection situations in the EWMs and in entire 1874–2020 period over southern Poland (explanations in the text)

Period	The direction of advection								Weak-advection situations					Sum	A	c
	N	NE	E	SE	S	SW	W	NW	Ca	Ka	Cc	Bc	X			
March																
EWMs$_{90}$	− 3.1	− 1.9	− 2.0	− 1.1	− 1.9	3.0	10.6	− 0.2	− 1.2	− 0.8	6.9	− 7.9	− 0.5	0.0	0.3	0.2
EWMs$_{95}$	− 3.8	− 1.9	− 6.6	− 6.2	− 1.1	1.4	5.2	3.4	0.4	4.8	11.5	− 7.1	0.1	0.0	1.3	− 1.3
EWMs$_{99}$	0.5	− 0.3	6.3	− 4.0	− 5.4	− 6.7	2.5	11.5	1.4	3.7	0.8	− 8.2	− 2.1	0.0	15.8	− 13.7
April																
EWMs$_{90}$	0.0	− 1.0	− 0.1	2.3	0.3	0.3	1.0	1.9	− 1.2	− 2.2	0.8	− 2.1	0.0	0.0	− 6.7	6.7
EWMs$_{95}$	− 2.4	− 6.3	0.5	6.6	7.5	6.9	− 3.2	− 7.6	− 1.2	− 2.0	− 1.0	2.3	− 0.1	0.0	− 12.4	12.5
EWM$_{99}$	− 3.7	− 2.6	− 3.5	9.0	9.5	1.5	− 8.2	− 3.9	3.8	2.0	0.0	− 1.7	− 2.1	0.0	9.9	− 7.8
May																
EWMs$_{90}$	− 3.4	0.4	− 1.8	− 0.7	2.2	− 0.3	− 3.1	− 0.8	− 0.3	2.5	0.7	5.8	− 1.2	0.0	− 8.8	9.8
EWMs$_{95}$	− 4.5	0.1	12.6	0.5	4.3	0.7	− 10.1	− 7.1	− 0.2	1.4	− 1.4	4.4	− 0.7	0.0	11.0	− 10.5
EWMs$_{99}$	1.0	2.0	− 2.6	18.2	6.2	− 8.3	− 14.0	− 8.0	− 1.5	0.5	0.3	8.2	− 2.0	0.0	− 0.3	2.1

a given month and the type of baric system that controlled the inflow of air masses to south-eastern Poland. However, it can be seen that exceptionally cold and warm Marches (ECMs and EWMs respectively) were accompanied by an increased frequency of anticyclonic systems. This association was strongest in the months that were most exceptional in temperature terms (ECMs$_1$ and EWM$_{99}$), when it was even about 20% higher than in the long-term study period (Tables 6, 7, 8). This was largely caused by a large decrease in the frequency of cyclonic troughs (Bc—by as much as 8.2%). A slight predominance of cyclonic situations was visible in April, although it mainly concerned EWMs, with one exception, namely EWMs$_{99}$, which saw about 10% more high-pressure systems than in the entire period under review. By contrast, it is very difficult to identify any clear regularities regarding the relationship between ECM and EWM temperatures and pressure systems in May.

4.2. *Occurrence of ECMs and Their Relationship with Air Advection Directions*

When analysing the directions of advection of air masses in spring ECMs, it is clear that, against the background of the entire study period, air masses arriving from the northern and eastern directions were more frequent while those incoming from the south and west showed a lower frequency (Table 6). The trends described differed slightly depending on the month concerned. In March, advection from the N–NE–**E–SE** directions was more frequent than the long-term average (in total, they accounted for 44.8% of all cases), and advection was less frequent from the S–SW–**W–NW** directions (34.1%; the directions marked in bold saw particularly high differences). In April, inflow of air masses exclusively from the S and SW directions was recorded less frequently (less than half as frequently, representing only 7.4% of the cases studied). Among the remaining advection situations (which accounted for a total of 71.9%), a significant increase in frequency (by almost 6%) was observed in the case of advection from the NW. In May, air masses from the NW–**N–NE**–E directions were recorded more often than the average over the timespan under study (a total of 48.0%), as opposed to air from the **SE–S**–SW–W directions, which was much less frequent (26.4%). An analysis that took into account the monthly temperature value (ECMs$_{1-10}$) found the same trends (Table 7). However, in each of the additionally distinguished groups, as well as in each month (March–May), the differences in the frequency of individual directions of advection relative to the long-term average varied slightly, with no easily identifiable pattern behind them. However,

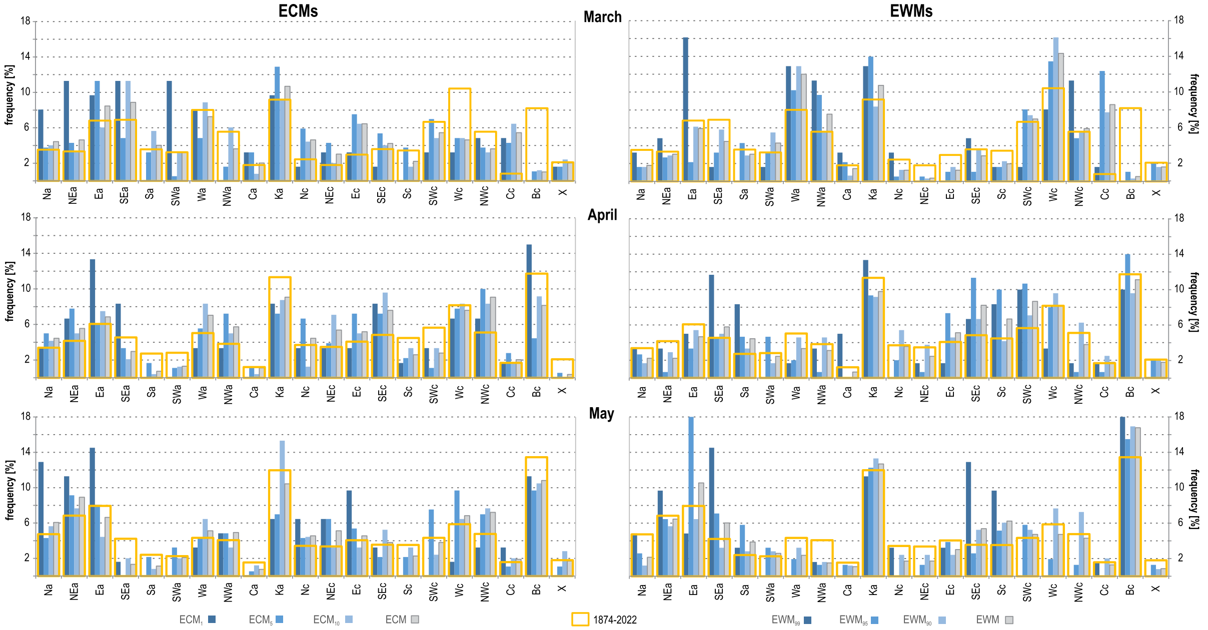

Figure 4

Frequency (%) of circulation types in exceptionally a) cold (ECMs) and b) warm (EWMs) spring months compared to their frequency in the multiannual period in Kraków in the years 1874–2022

there was very clearly a higher frequency of advection from the N–NE–E directions and a significantly lower frequency from the S–SW–W directions in the coldest Mays (ECMs$_1$).

4.3. *Occurrence of EWMs and Their Relationship with Directions of Air Advection*

As the study shows, EWMs were likewise under the influence of two groups of directions that were more and less favourable to higher values of air temperature. In March, advection of air masses from the west (SW–**W**–NW) was much more frequent than the long-term average, accounting for 51.2% of all cases in total (Table 6). This was 12% more than the long-term average and about 46% more than the average for exceptionally cold months. The influx of masses from other directions accounted for only 26%. In April, temperatures would be higher in the presence of advection from the south sector (SE-S-SW; 36.2% of all cases), exceeding the average for the long-term and for the cold months by approx. 11% and 18%, respectively. In May, the directions of advection of the warmest air masses shifted towards the easterly sector (NE–E–SE–S), and their aggregate frequency reached 43.2% and was 10% above the long-term average and the average for the cold months. The trends described differ slightly depending on the value of monthly temperature, effects mainly noted in the warmest months (EWMs$_{99}$; Table 8), which is not only due to the thermal conditions of the air masses themselves, but also to the small number of months assigned to the individual groups. The change in the thermal characteristics of air masses arriving from a given direction in the individual months (March–May) was also much more distinct, notably in the case of westerly advection (W). Its markedly increased frequency in March adds to the increase in temperatures, while in April and May, days observing such advection in the EWMs are much less frequent than the long-term average.

4.4. *Occurrence of ECMs and EWMs and Their Relationship with Types of Atmospheric Circulation*

The study has also analysed the prevalence of all types of circulation in ECMs and EWMs. In addition to confirming the above-described trends, it has found several features that are typical of the individual

Table 9

The number of circulation types and the maximum number of days with the same type of circulation (Max) in ECMs and EWMs in Krakow in the years 1874–2020

Months	March			April			May		
	Year	Number of types	Max	Year	Number of types	Max	Year	Number of types	Max
ECM									
ECMs$_1$	1875	14	5	1881	13	6	1874	13	5
	1886	12	6	1929	14	6	1919	10	7
ECMs$_5$	1883	15	4	1883	10	8	1876	12	4
	1942	13	7	1907	12	**10**	1877	14	4
	1952	16	5	1933	12	6	1902	12	6
	1958	14	5	1938	14	6	1941	13	5
	1964	13	7	1954	14	7	1957	15	8
	1987	10	7	1958	12	5	1980	10	7
ECMs$_{10}$	1889	13	5	1875	11	8	1880	12	6
	1917	14	3	1877	12	6	1909	8	9
	1929	11	8	1884	9	**11**	1912	14	5
	1931	11	6	1891	12	5	1927	14	6
	1932	15	6	1905	13	5	1928	14	5
	1962	19	3	1912	11	8	1935	12	8
	1969	12	6	1917	15	5	1962	12	6
	1996	11	**15**	1931	11	9	1965	15	4
	–	–	–	1955	11	4	1991	12	6
	–	–	–	1997	14	6	–	–	
EWM									
EWMs$_{90}$	1903	11	7	1939	14	**10**	1946	10	7
	1920	13	7	1962	15	6	1958	12	9
	1927	9	7	1986	15	5	1969	11	9
	1934	10	7	1998	14	7	1970	14	6
	1938	10	7	1999	12	4	1983	8	9
	1961	6	**13**	2007	11	9	1986	14	5
	1981	14	7	2011	13	4	2000	14	8
	1991	13	5	2014	14	6	2012	15	5
	1994	9	**11**	–	–		2021	14	6
	2002	13	6	–	–		2022	12	6
EWMs$_{95}$	1882	12	9	1918	10	7	1889	11	**11**
	1977	13	5	1920	12	4	1931	10	8
	1989	12	5	1961	13	5	1937	12	8
	2007	12	8	1983	12	6	1993	10	8
	2017	12	8	2000	11	5	2003	12	7
	2019	10	7	–	–		2007	11	5
EWMs$_{99}$	1990	8	7	2009	10	7	2002	9	8
	2014	14	7	2018	13	6	2018	10	7

Bold text—the lowest or the highest value

groups of cold (ECMs$_{1–10}$) and warm months (EWMs$_{90-99}$), and changes in these features by month (March–May).

In ECMs in March, an increased frequency of advection from the N–NE–E–SE directions, especially of anticyclonic types, and a discernible decrease in the frequency of NWa, Wc and Bc are clearly visible (Fig. 4a). It is also worth noting the increase in the occurrence of a central cyclone (Cc), which is most likely associated with a higher frequency of northerly advection. In April, these differences tend to be smaller. However, the share of advection from S and SW, both in the presence of anticyclonic and cyclonic systems, declines significantly, while the inflow of cool air from SEc, NWc and NWa increases in frequency. May saw no such increase, but instead a clear decrease in the frequency of SEa types was observed.

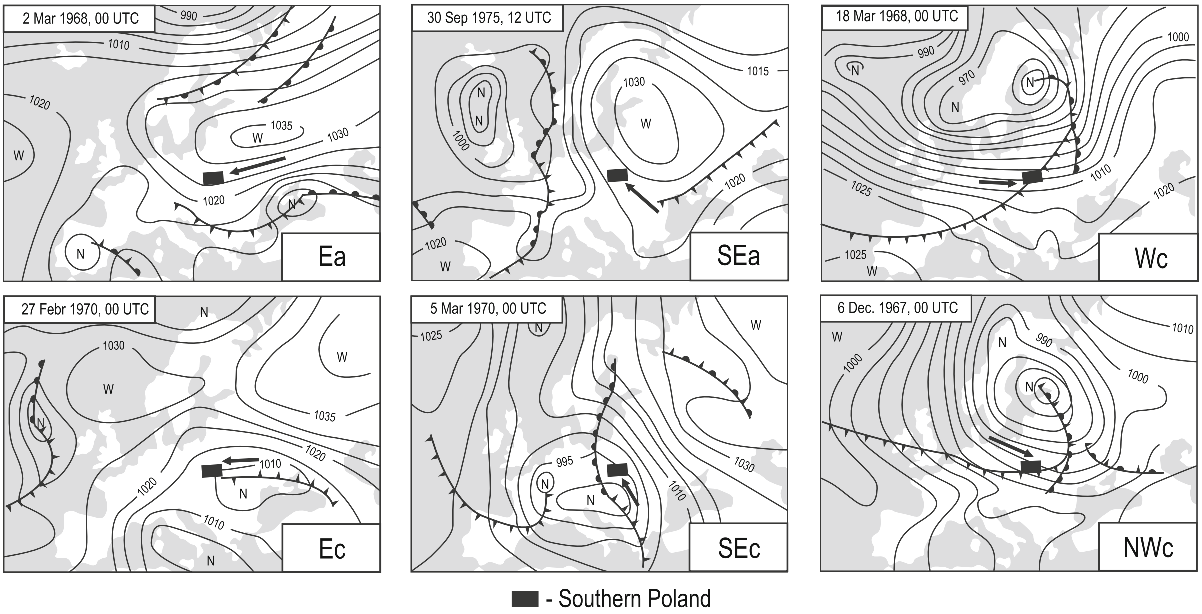

Figure 5
Selected examples of distinguished atmospheric circulation types on synoptic maps of Europe (Niedźwiedź, 1981)

Among the EWMs, March stands out for a substantial increase in the frequency of inflow from the Wa and Wc and NWa and NWc directions, as well as for the frequent occurrence of an anticyclonic wedge (Ka) and occasionally of a cyclonic trough (Bc; Fig. 4b). In April, there was a greater number of days with influx of air from the SE–S–SW directions in connection with low-pressure systems that brought in warmer air from southern and western Europe. This characteristic was slightly less pronounced in May, which also saw more frequent advection of air masses from NEa, SEa and Sa, and a very low frequency of advection from the western sector.

Such large variations in the occurrence of the circulation types in spring ECMs and EWMs prompted the authors to check whether the number of the types recorded in each of them changed significantly depending on monthly temperature. In a pattern that emerged a vast majority of months fell within a range of 10 to 15 circulation types per month (Table 9), while the exceptions with either fewer than 10 types (ECMs: 9 in April and 8 in May, and EWMs: 6 and 9 in March and 8 in May) or a more than 15 types (ECMs: 16 and 19 types in March) were few and far between. An attempt at identifying months with a marked dominance of one or several types of circulation yielded inconclusive results, as the study period included only seven months, in which one type reoccurred 10 or more times (Table 9).

For ECMs, the greatest frequency of one type of circulation—as many as 15 occurrences—was recorded in March 1996. The situation was of the SEa type (Fig. 5), which, as the *Calendar of Atmospheric Circulation Types for Southern Poland* indicates, was associated with the influx of very frosty continental polar air masses (cP). A similar situation took place in April 1884 and 1907, when the SEc type (Fig. 5) prevailed 11 and 10 times, respectively. In EWMs, an exceptionally high frequency of one type of circulation was recorded four times. Two of these cases occurred in March 1961 and 1994. Both years recorded equally often, 13 and 11 times respectively, the Wc type (Fig. 5), during which warmer polar marine air (PPm) flowed over the study area. Notably, 1961 also recorded 7 days with advection of air from the north-west (NWc) and 6 from the west (Wa; Fig. 5). In April, it was the Wc type that marked its presence most frequently (10 times in 1939), while in May the inflow of cool air from the east (Ec; Fig. 5) occurred 11 times in 1889.

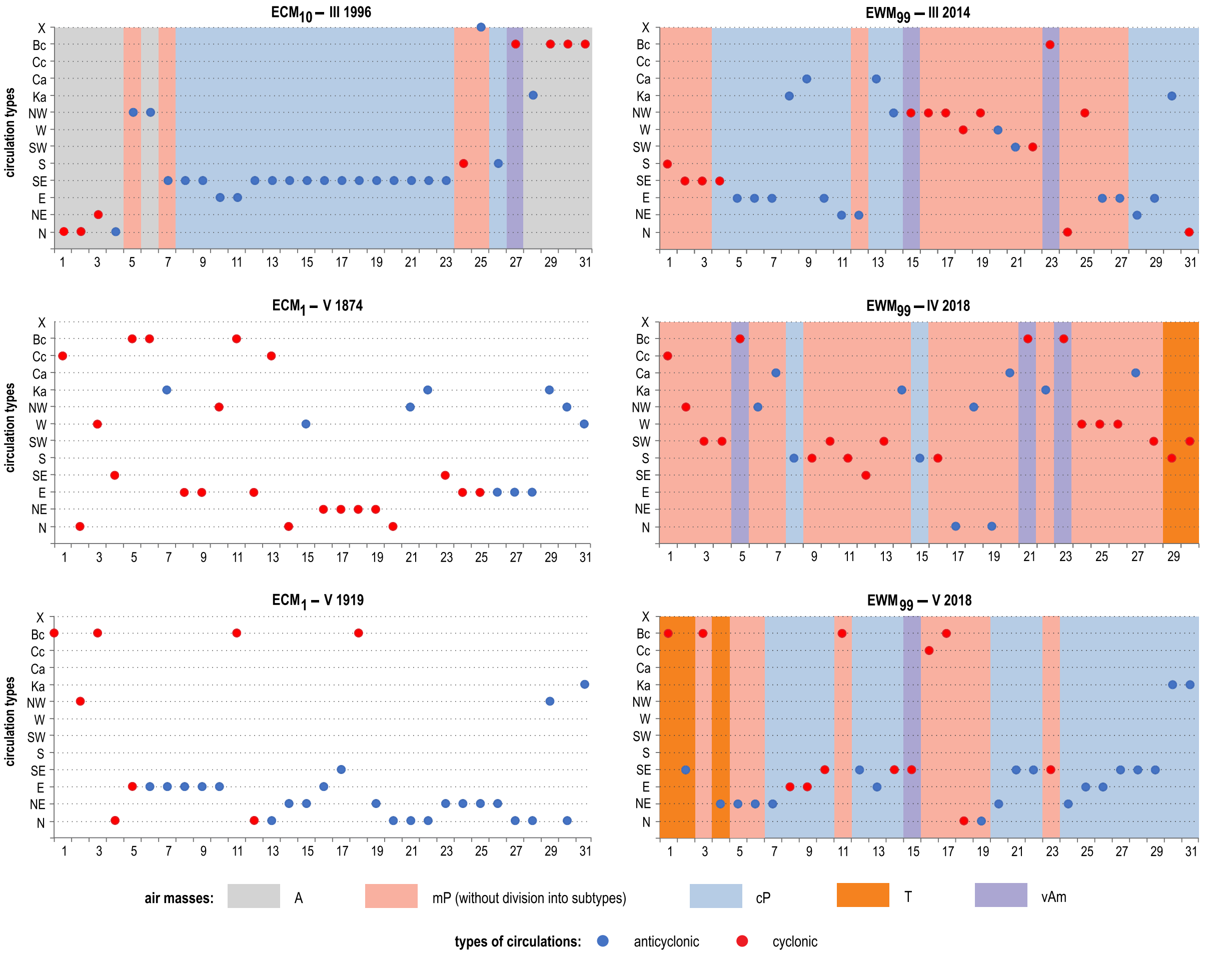

Figure 6

Types of circulation occurring in selected ECMs and EWMs in spring in Krakow in the years 1874–2022. In addition, the accompanying types of air masses determined according to the Calendar of Atmospheric Circulation Types for southern Poland were added (for the years 1951–2022)

Such a great variety of circulation types provides evidence of the fact that the thermal characteristics of an air mass arriving over a given area are determined by the direction of advection rather than by the associated pressure system. It should also be remembered that the direction of incoming air masses rarely changes in a radical way from one day to another. Usually the directions are similarly translated into similar thermal and humidity characteristics of the incoming air mass. Therefore, when seeking to identify the relationships between temperature changes over longer spring periods (e.g. months), it seems advisable to also investigate the sequence of circulation types. This is exemplified by the selected ECMs and EWMs presented in Fig. 6. As can be seen, in some cases, exceptionally low/high monthly temperatures followed from a sequence or series of days with inflow of air from 1–4 similar directions (e.g. ECM_{10}—March 1996 and ECM_{1}—May 1919). In other months, very low/high monthly temperatures were associated with a much greater diversity of synoptic situations (ECM_{1}—May 1874 or EWM_{99}—March 2014). It is also worth highlighting that even the occurrence of a very long sequence of similar types of circulation, accompanied by air masses clearly indicative of an influx of very cool/warm air, did not go hand in hand with the occurrence of extreme monthly temperature values. One example is

March 1996, which recorded 17 days with advection from the SEa and Ea directions which were associated with the influx of polar-continental air masses for 16 days (Fig. 6). In addition, for the first 5 days and the last 4 days of the month, arctic air (PA) was transported into the area examined. Nevertheless, although this month qualified as exceptionally cold, its temperature was the highest of all the ECMs considered.

5. *Discussion and Conclusions*

Climate change is inherently associated with changes in the temperature and length of seasons which have been described in the literature (Twardosz et al., 2021; Wang et al., 2021). Some of the most significant of these are observable in the spring season. In particular, they have caused the growing season to extend and have changed the start dates of the season itself and of the individual vegetation phases (Buermann et al., 2018; Maignan et al., 2008; Wang et al., 2011, 2021; Yu et al., 2010). This prompted the present study, which investigates the trends of these changes in Poland (using the example of Kraków) and seeks to understand their underlying factors relating to circulation. Rather than taking into account entire seasons or extreme heat events, which have been widely researched, the study investigates the temperature in the individual months in spring. In addition, it uses the mesoscale *Calendar of Atmospheric Circulation Types for southern Poland* compiled by Niedźwiedź (1981, 2022) in order to analyse the relationship between atmospheric circulation and temperature.

Based on this, it was found that the area under study also saw a distinct increase in air temperature in spring and the individual spring months over the 1874–2022 period investigated. The increase ranged from 0.162 °C/10 years in May to 0.191 °C/10 years in March, and amounted to as much 0.181 °C/10 years for spring as a whole. It was the temperature in March, in which there are winter-like conditions, that had the greatest effect on the spring temperature. A strong increase in temperature is also confirmed by the variability in occurrence of ECMs and EWMs over time, with the former more frequent in the first half of the study period and the latter in the post-1950 period. The above trend also entails a noticeable increase/decrease in the number of warm/cold spells observable from the mid-twentieth century (Brunner et al., 2017; Sulikowska et al., 2022). Another notable finding is that the changes in monthly air temperature values were largely asynchronous, as a result of which it was very rare for more than one month to qualify as an ECM or EWM during an exceptionally warm or cold spring.

The spring temperature changes in the northern hemisphere are considered to have been caused, inter alia, by changes in the surface area of sea ice in the Arctic, which causes distinct changes in the macroscale circulation in the atmosphere over Eurasia. These developments translate into an increased frequency of advection of warmer air masses, thereby influencing both spring air temperatures themselves and the frequency of spring extreme heat events (Ding & Wu, 2020; Sun et al., 2022). The above implies that these changes should be reflected by changes in circulation over various areas, primarily in the frequency of prevalence of directions of air advection and in the presence and positioning of blocking systems (Brunner et al., 2017).

In order to find relationships between the changes in air temperature referred to above and changes in atmospheric circulation, the former were compared both with complex circulation indices (Wi, Si, and Ci) and with the direction of inflowing air masses and individual types of circulation. The findings imply a weak correlation between changes in temperature and changes in the values of the said indices, in particular with regard to the type of pressure system. Slightly stronger relationships are noticeable as regards the positive effect on temperature of zonal flow in early spring and the advection of air from the south in April, May and throughout the spring season. The above relationships are partially confirmed for the thermally exceptional seasons (ECSs and EWSs) and months (ECMs and EWMs). However, in some cases, the exceptional thermal conditions of those months/seasons rather developed under the influence of a specific configuration of circulation types that prevailed at that time.

A more detailed analysis shows that the occurrence of exceptional monthly temperatures in March, and in the case of EWMs also in May, is associated with the occurrence of anticyclonic systems, which is partly confirmed by Brunner et al. (2017). However the temperature was much more often determined by the direction of air advection and the related temperature characteristics of air masses. However, here it is also difficult to identify unambiguous regularities concerning all months and distinguished groups of months with extreme temperatures (ECMs$_{1-10}$ and EWMs$_{90-99}$). Generally, in the case of the coldest months (ECMs), low temperatures most frequently developed in the presence of advection from the NW-N-NE-E directions. Meanwhile, for exceptionally warm months (EWMs), the prevalent direction of advection of warm air masses would change from westerly in March, through southerly, to south-easterly in April and to easterly in May. In parallel, the frequency of warm air masses associated with cyclonic systems declined in favour of anticyclonic systems. These regularities are confirmed by the findings of Sulikowska et al. (2022), who have identified similar developments for thermal extremes in spring. It is also worth noting that both Poland and Europe see noticeable changes in the occurrence of air advection from western directions, which may have a major effect on air temperature. In spring, advection from the west declines only slightly (Bielec-Bąkowska, 2022), but in summer a significant increase in advection from the E is recorded and forecast, which implies that increase in temperature is already possible in late spring. Meanwhile, advection from the west becomes more frequent in winter, which in turn may increase the temperature at the beginning of March (Herrera-Lormendez et al., 2022; Niedźwiedź & Ustrnul, 2021).

The regularities described above have been confirmed through an analysis of the frequency of all the types of atmospheric circulation occurring over the area concerned. However, again there were significant differences in their occurrence depending on the month (March—May) and monthly air temperature (ECM$_{1-10}$ and EWM$_{90-99}$). In addition, discernible changes in the number of situations that involved weak advection have been identified (Ca, Ka, Cc and Bc). There were also only a few situations when an exceptional temperature in a month was caused by one or several types of circulation and the accompanying air masses. The study highlights a need for in-depth analysis of the effects of sequences of individual types of circulation. A focus should be on the types that precede the influx of cool air masses, including the presence of blocking systems that are conducive to the occurrence of very low temperatures (mainly in early spring) or high temperatures (in May; Brunner et al., 2017).

The great variety of circulatory conditions that underlie ECMs and EWMs means there is great unpredictability and a lack of sufficient repeatability to identify clear circulation patterns that add to the occurrence of such long (monthly) periods with exceptionally high or low temperatures. The occurrence of ECMs or EWMs is rather linked to the presence of one or two longer periods with air temperature significantly different from the long-term average. The great variety of the considered circulation conditions is related to Poland's location in the centre of Europe, which sees a confrontation of the key features of European climate (maritime v continental or subtropical v subarctic), which also applies to the presence of the dominant directions of advection and the role of pressure systems over the period of a year (Brunner et al., 2017; Cahynová & Huth, 2009; Mellado-Cano et al., 2020). This is confirmed by the identification of a separate type of climate for Poland in many climate classifications and by the frequently stressed transitional nature of the climate (Martyn, 1992). In addition, spring itself is a transitional season, when the climate characteristics of winter (most conspicuous in March) and of summer (in May) clash. It must also be remembered that researchers tend to define seasons by dividing them into months-long periods, which do not usually correspond to thermal and circulatory seasons (Nowosad, 2000; Piotrowicz, 2010). Other previous studies have also found that changes in climate conditions are not necessarily correlated with changes in the frequency of particular types of circulation, but rather with changes in the thermal and humidity characteristics of the associated air masses (Bartoszek & Kaszewski, 2022; Bartoszek & Matuszko, 2021; Brunner et al., 2017; Cahynová & Huth, 2009; Herrera-Lormendez et al., 2022).

Author contributions Zuzanna Bielec-Bąkowska: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Visualization, Writing - original draft preparation, Editing.Robert Twardosz: Conceptualization, Data curation, Methodology, Investigation, Writing- Reviewing and Editing, Supervision.Authors have read and agreed to the published version of the manuscript.

Data availability

Meteorological data (the average monthly air temperature) from the Research Station of the Climatology Department of the Jagiellonian University in Kraków is not available to the public. Calendar of Atmospheric Circulation Types for southern Poland is available from: http://www.kk.wnoz.us.edu.pl/nauka/kalendarz-typow-cyrkulacji (access 31.12.2018) or in Author by request.

Declarations

Competing interests The authors declare no competing interests.

REFERENCES

Bartoszek, K., & Kaszewski, B. M. (2022). Changes in the frequency and temperature of air masses over east-central Europe. *International Journal of Climatology, 42*(16), 8214–8231. https://doi.org/10.1002/joc.7704

Bartoszek, K., & Matuszko, D. (2021). The influence of atmospheric circulation over Central Europe on the long-term variability of sunshine duration and air temperature in Poland. *Atmospheric Research, 251*, 105427. https://doi.org/10.1016/j.atmosres.2020.105427

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, Ch., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., & Woth, K. (2007). Future extreme events in European climate: An exploration of regional climate model projections. *Climatic Change, 81*, 71–95. https://doi.org/10.1007/s10584-006-9226-z

Bielec-Bąkowska, Z. (2022). Long-term changes in circulation conditions over southern Poland for the period 1874–2020. *Miscellanea Geographica, 26*(4), 237–248. https://doi.org/10.2478/mgrsd-2022-0010

Błażejczyk, K., Twardosz, R., Wałach, P., & Czarnecka, K. (2022). Heat strain and mortality effects of prolonged Central European heatwave—An example of June 2019 in Poland. *International Journal of Biometeorology, 66*(1), 149–161. https://doi.org/10.1007/s00484-021-02202-0

Brunner, L., Hegerl, G., & Steiner, A. K. (2017). Connecting atmospheric blocking to European temperature extremes in spring. *Journal of Climate, 30*(2), 585–594. https://doi.org/10.1175/JCLI-D-16-0518.1

Buermann, W., Forkel, M., O'Sullivan, M., Sitch, S., Friedlingstein, P., Haverd, V., Jain, A. K., Kato, E., Kautz, M., Lienert, S., Lombardozzi, D., Nabel, J. E. M. S., Tian, H., Wiltshire, A. J., Zhu, D., Smith, W. K., & Richardson, A. D. (2018). Widespread seasonal compensation effects of spring warming on northern plant productivity. *Nature, 562*, 110–114. https://doi.org/10.1038/s41586-018-0555-7

Cahynová, M., & Huth, R. (2009). Changes of atmospheric circulation in central Europe and their influence on climatic trends in the Czech Republic. *Theoretical and Applied Climatology, 96*(1–2), 57–68. https://doi.org/10.1007/s00704-008-0097-2

Campbella, S., Remenyib, T. A., Whiteb, Ch. J., & Johnstona, F. H. (2018). Heatwave and health impact research: A global review. *Health & Place, 53*, 210–218. https://doi.org/10.1016/j.healthplace.2018.08.017

Ding, Z., & Wu, R. (2020). Quantifying the internal variability in multi-decadal trends of spring surface air temperature over mid-to-high latitudes of Eurasia. *Climate Dynamics, 55*, 2013–2030. https://doi.org/10.1007/s00382-020-05365-5

Hegerl, G., Brönnimann, S., Schurer, A., & Cowan, T. (2018). The early 20th century warming: Anomalies, causes, and consequences. *WIREs Climatic Change, 9*, e522. https://doi.org/10.1002/wcc.522

Herrera-Lormendez, P., Mastrantonas, N., Douville, H., Hoy, A., & Matschullat, J. (2022). Synoptic circulation changes over Central Europe from 1900 to 2100: Reanalyses and Coupled Model Intercomparison Project phase 6. *International Journal of Climatology, 42*(7), 4062–4077. https://doi.org/10.1002/joc.7481

Hoy, A., Hänsel, S., Skalak, P., Ustrnul, Z., & Bochníček, O. (2017). The extreme European summer of 2015 in a long-term perspective. *International Journal of Climatology, 37*(2), 943–962. https://doi.org/10.1002/joc.4751

IPCC (2007). *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.)]. Cambridge

University Press, Cambridge, United Kingdom and New York, NY, USA, 996.

IPCC (2013). *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535. https://doi.org/10.1017/CBO9781107415324

Ji, F., Wu, Z., Huang, J., & Chassignet, E. P. (2014). Evolution of land surface air temperature trend. *Nature Climate Change, 4*, 462–466. https://doi.org/10.1038/nclimate2223

Jiang, S. (2023). Compound Heat Vulnerability in the Record-Breaking Hot Summer of 2022 over the Yangtze River Delta Region. *International Journal of Environmental Research and Public Health, 20*, 5539. https://doi.org/10.3390/ijerph20085539

Kendall, M. G. (1975). *Rank correlation methods* (4th ed.). Charles Griffin.

Krauskopf, T., & Huth, R. (2020). Temperature trends in Europe: Comparison of different data sources. *Theoretical and Applied Climatology, 139*, 1305–1316. https://doi.org/10.1007/s00704-019-03038-w

Krzyżewska, A., & Dyer, J. (2018). The August 2015 mega heatwave in Poland in the context of past events. *Weather, 73*(7), 207–214. https://doi.org/10.1002/wea.3244

Kundzewicz, Z. W., Pińskwar, I., & Koutsoyiannis, D. (2020). Variability of global mean annual temperature is significantly influenced by the rhythm of ocean-atmosphere oscillations. *Science of the Total Environment, 747*, 141256. https://doi.org/10.1016/j.scitotenv.2020.141256

Labajo, J. L., Martín, Q., Labajo, A. L., Piorno, A., Ortega, M., & Morales, C. (2008). Recent trends in the frequencies of extreme values of daily maximum atmospheric pressure at ground level in the central zone of the Iberian Peninsula. *International Journal of Climatology, 28*, 1227–1238. https://doi.org/10.1002/joc.1631

Lu, R., Xu, K., Chen, R., Chen, W., Li, F., & Lv, C. H. (2023). Heat waves in summer 2022 and increasing concern regarding heat waves in general. *Atmospheric and Oceanic Science Letters, 16*(1), 100290. https://doi.org/10.1016/j.aosl.2022.100290

Luterbacher, J., Werner, J. P., Smerdon, J. E., Fernández-Donado, L., González-Rouco, F. J., Barriopedro, D., Ljungqvist, F. C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J. H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., et al. (2016). European summer temperatures since Roman times. *Environmental Research Letters, 11*(2), 024001. https://doi.org/10.1088/1748-9326/11/2/024001

Maignan, F., Bréon, F. M., Vermote, E., Ciais, P., & Viovy, N. (2008). Mild winter and spring 2007 over western Europe led to a widespread early vegetation onset. *Geophysical Research Letters*. https://doi.org/10.1029/2007GL032472

Mann, H. B. (1945). Non–parametric tests against trend. *Econometrica, 13*(3), 245–259. https://doi.org/10.2307/1907187

Martyn, D. (1992). *Climates of the world.* Published by Elsevier.

Mellado-Cano, J., Barriopedro, D., García-Herrera, R., & Trigo, R. M. (2020). New observational insights into the atmospheric circulation over the Euro-Atlantic sector since 1685. *Climate Dynamics, 54*, 823–841. https://doi.org/10.1007/s00382-019-05029-z

Murray, R., & Lewis, R. P. W. (1966). Some aspects of the synoptic climatology of the British Isles as measured by simple indices. *Meteorological Magazine, 95*, 193–203.

Muthers, S., Laschewski, G., & Matzarakis, A. (2017). The Summers 2003 and 2015 in South-West Germany: HeatWaves and Heat-Related Mortality in the Context of Climate Change. *Atmosphere, 8*(11), 224. https://doi.org/10.3390/atmos8110224

Niedźwiedź, T. (1981). *Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły* [‘Synoptic situations and its influence on spatial differentiation of selected climatic elements in upper Vistula basin’], Rozprawy habilitacyjne UJ, 58, Kraków

Niedźwiedź, T. (2022). *Kalendarz typów cyrkulacji atmosfery dla Polski południowej* [Calendar of Atmospheric Circulation Types for southern Poland]. Retrieved 31 Dec, 2018 from: http://www.kk.wnoz.us.edu.pl/nauka/kalendarz-typow-cyrkulacji

Niedźwiedź, T. (2000). Variability of the atmospheric circulation above the Central Europe in the light of selected indices. *Przegląd Geograficzny, 107*, 379–389.

Niedźwiedź, T., & Ustrnul, Z. (2021). Change of Atmospheric Circulation. In M. Falarz (Ed.), *Climate change in Poland: past, present, future* (pp. 123–150). Switzerland: Springer.

Nowosad, M. (2000). Sezony cyrkulacyjne w dorzeczu górnej Wisły w okresie 1874–1998 [Circulation seasons in the upper Vistula river basin in the period of 1874–1998]. *Acta Universitatis Nicolai Copernici. Geografia, 31*(106), 201–214.

Met Office. (2022). Unprecedented extreme heatwave, July 2022—met Office. Retrieved 12 June, 2023 from https://www.metoffice.gov.uk.pdf.interesting

Peters, W., Bastos, A., Ciais, P., & Vermeulen, A. (2020). A historical. geographical and ecological perspective on the 2018 European summer drought. *Philosophical Transactions of the Royal Society B, 375*, 20190505. https://doi.org/10.1098/rstb.2019.0505

Piotrowicz, K. (2010). *Sezonowa i wieloletnia zmienność typów pogody w Krakowie* [Seasonal and long-term weather type variability in Krakow]. IGiGP UJ. Kraków

Sinclair, V. A., Mikkola, J., Rantanen, M., & Räisänen, J. (2019). The summer 2018 heatwave in Finland. *Weather, 74*, 403–409. https://doi.org/10.1002/wea.3525

Skrzyńska, M., & Twardosz, R. (2023). Long-term changes in the frequency of exceptionally cold and warm months in Europe (1831–2020). *International Journal of Climatology, 43*, 2339–2351. https://doi.org/10.1002/joc.7978

Sulikowska, A., Wypych, A., & Ustrnul, Z. (2022). Cyrkulacyjne uwarunkowania ekstremów termicznych wiosną w Europie Środkowej [Atmospheric conditions of thermal extremes in spring in Central Europe]. *Conference proceedings „Pogoda i klimat—przeszłość. teraźniejszość. przyszłość”* [“Weather and climate - the past. present. future”]. Kraków

Sun, J., Liu, S., Cohen, J., & Yu, S. (2022). Influence and prediction value of Arctic sea ice for spring Eurasian extreme heat events. *Communications Earth & Environment, 3*, 172. https://doi.org/10.1038/s43247-022-00503-9

Trepińska, J. (1997). *Wahania klimatu w Krakowie (1792–1995) [Fluctuations of climate in Cracow (1792–1995)].* Instytut Geografii Uniwersytetu Jagiellońskiego, Kraków

Twardosz, R. (2010). An analysis of diurnal variations of heavy hourly precipitation in Kraków using a classification of circulation types over southern Poland. *Physics and Chemistry of the Earth, 35*, 456–461. https://doi.org/10.1016/j.pce.2009.11.003

Twardosz, R. (2019). Anomalously warm months in 2018 in Poland in relation to airflow circulation patterns. *Weather, 74*(11), 374–382. https://doi.org/10.1002/wea.3588

Twardosz, R., & Bielec-Bąkowska, Z. (2022). Continental-scale monthly thermal anomalies in Europe during the years 1951–2018 and their occurrence in relation to atmospheric circulation. *Geographia Polonica, 95*(1), 97–116. https://doi.org/10.7163/GPol.0228

Twardosz, R., & Kossowska-Cezak, U. (2021). Large-area thermal anomalies in Europe (1951–2018). *Temporal and spatial patterns. Atmospheric Research, 251*, 105434. https://doi.org/10.1016/j.atmosres.2020.105434

Twardosz, R., Walanus, A., & Guzik, I. (2021). Warming in Europe: recent trends in annual and seasonal temperatures. *Pure and Applied Geophysics, 178*, 4021–4032. https://doi.org/10.1007/s00024-021-02860-6

Ustrnul, Z. (1997). *Uzupełnianie weryfikacja danych krakowskiej serii pomiarowej temperatury i ciśnienia powietrza z lat 1792–1825 [Completing and verification of Cracow measurement data series for the 1972–1825].* In Trepińska, J. (ed.), Wahania klimatu w Krakowie (1792–1995) [Fluctuations of climate in Cracow (1792–1995)]. Instytut Geografii Uniwersytetu Jagiellońskiego, Kraków

Wang, J., Guan, Y., Wu, L., Guan, X., Cai, W., Huang, J., Dong, W., & Zhang, B. (2021). Changing Lengths of the Four Seasons by Global Warming. *Geophysical Research Letters, 48*(6), e2020GL091753. https://doi.org/10.1029/2020GL091753

Wang, X., Piao, S., Ciais, P., Li, J., Friedlingstein, P., Koven, C. D., & Chen, A. (2011). Spring temperature change and its implication in the change of vegetation growth in North America from 1982 to 2006. *Proceedings of the National Academy of Sciences, 108*(4), 1240–1245. https://doi.org/10.1073/pnas.1014425108

Wypych, A., Sulikowska, A., Ustrnul, Z., & Czekierda, D. (2017). Temporal variability of summer temperature extremes in Poland. *Atmosphere, 8*(3), 51. https://doi.org/10.3390/atmos8030051

Yu, H., Luedeling, E., & Xu, J. (2010). Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. *Proceedings of the National Academy of Sciences, 107*, 22151–22156. https://doi.org/10.1073/pnas.1012490107

Zvyagintsev, A. M., Blum, O. B., Glazkova, A. A., Kotelnikov, S. N., Kuznetsova, I. N., Lapchenko, V. A., Lezina, E. A., Miller, E. A., Milyaev, V. A., & Popikov, A. P. (2011). Air pollution over European Russia and Ukraine under the hot summer conditions of 2010. *Izvestiya, Atmospheric and Oceanic Physics, 47*(6), 699–707. https://doi.org/10.1134/S0001433811060168

(Received March 17, 2023, revised June 18, 2023, accepted June 23, 2023, Published online July 7, 2023)