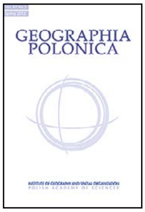

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LONG-TERM AND SEASONAL VARIABILITY OF AIR MASSES TEMPERATURE IN KRAKÓW (1961-2023)

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Abstract

This study attempted to determine temperature changes in southern Poland due to changes in the thermal characteristics of individual air masses. For this purpose, the daily air temperature values at the Kraków-Balice synoptic station were used, as well as the types of atmospheric circulation and air masses for southern Poland from the daily *Calendar of Atmospheric Circulation Types for southern Poland*. The study showed that the temperature increase of individual air masses was most significant in tropical air masses and was noticeable in both average and extreme daily temperature values. It was also found that the increase in temperature in particular air masses is associated with an increased number of warmer days, although not necessarily hot ones.

Keywords

atmospheric circulation • air masses temperature • southern Poland • Europe

Introduction

The climate change observed in recent decades is most extensively manifested through an increase in air temperature and changes to both the sums and annual course of precipitation, as well as through a higher frequency of extreme climatic events (IPCC, 2021). Major changes, particularly to air temperature, are recorded in the Arctic (Serreze & Barry, 2011) and the northern hemisphere, including Europe (Krauskopf & Huth, 2020; Twardosz et al., 2021). At the same time, these changes to climatic conditions are clearly linked between the two mentioned areas (Francis & Vavrus, 2012; Screen, 2014). They are strongly influenced by changes in the atmospheric circulation, a significant contributor to the energy balance of these particular regions (Alekseev et al., 1991), which is very visible, especially at high latitudes, throughout the year (Serreze & Francis, 2006). The increase in air temperature leads to changes in other meteorological elements, including snow cover and atmospheric humidity, which are also related to changes in, among others, cloud cover and precipitation (Cattiaux et al., 2011; Serreze & Barry, 2011).

In recent decades, climate change in Europe is clearly visible not only through changes to mean values of meteorological factors, but also through the increased frequency and intensity of extreme climatic events. An example of this is the occurrence of increasingly strong and long heat waves, extremely hot and dry summers (Sinclair et al., 2019; Met Office, 2022), or entire periods of extremely high or low temperatures (Twardosz & Bielec-Bąkowska, 2022; Skrzyńska & Twardosz, 2023). The occurrence of such weather anomalies is inherently connected with severe consequences to the natural environment (droughts and an increasing number of fires; Zvyagintsev et al., 2011), economy (including problems with transport and agriculture; Peters et al., 2020; Gössling et al., 2023), or human life and health (Campbella et al., 2018).

For these reasons, climate change is not only carefully observed, but also its causes are investigated. Particularly important are changes in atmospheric circulation, which in certain regions of the world, are usually the main factor that directly determines the current changes in climatic conditions. Many indices and characteristics of air flow over the particular area are used when analysing circulation-related climate conditions at a particular site. The most important include, among others, those describing changes in large scale circulation described by circulation indices such as AO, NAO or El Niño–Southern Oscillation (Trigo et al., 2002; Zuo et al., 2015; Cai et al., 2020). The other group includes classifications of circulation patterns that refer to the direction of air advection and the type of pressure system occurring over a given region, as well as to weather types. The latter provide a complex description of the most important weather characteristics present on a given day (examples of such classifications have been provided, inter alia, by Piotrowicz & Ciaranek, 2020; Petrou et al., 2022). Often, relationships are sought between changes in climatic conditions and changes in the frequency of occurrence, intensity, or tracks of pressure system movements (Pezza et al., 2007; Zarrin et al., 2010; Bielec-Bąkowska, 2014; Pfahl, 2014). Much less frequently, the analyses involve the type of air mass (Lee, 2020; Bartoszek & Kaszewski, 2022; Petrou et al., 2022) or atmospheric fronts (Schemm et al., 2017; Sykulski & Bielec-Bąkowska, 2017).

The two latter elements characteristic of atmospheric circulation are an important factor affecting Europe's climatic conditions. This is related to the small sizes and significant fragmentation of the continent, as well as to the fact that it remains under the influence of frequent changes in air advection from over the Arctic and Atlantic Ocean, as well as tropical air masses from over Africa and the continental from vast continent of Asia. An important aspect of such variability also involves changes in the thermal characteristics of the air masses over the year as well as weather conditions in the source areas, including the temperature of ocean surface (Dole et al., 2011). For this reason, the prevalence of characteristic circulation types, particularly vast and long-lasting high-pressure systems, as well as the sequences of certain types providing advection of air with specific thermal properties, is responsible for extreme thermal conditions, including those covering large areas of the continent (Bielec-Bąkowska & Twardosz, 2023).

Central Europe, including Poland, with its very frequent cases of collision between these air masses, forms an exceptional area, the climate of which is often called transitional on this account (Martyn, 1992). At the same time, in this region, as well as in other regions of the world, a significant increase in air temperature is recorded (Ustrnul et al., 2021). Therefore, it was decided to verify whether the temperature increase in southern Poland also included changes to the thermal characteristics of particular air masses. This became the basis for formulating the purpose of the research presented in the study, devoted to long-term and seasonal changes in the temperature of air masses in the considered region. The study analysed whether there are seasonal and long-term changes to the frequency of advection of distinct air masses, their temperature, as well as flow direction. Furthermore, it was assessed whether the changes in the thermal characteristics of air masses are associated with an increased number of days with increasingly higher temperatures (not necessarily extreme) or with the occurrence of days with extremely high temperatures for a given air mass over the year, seasons or month.

Materials and research methods

The research is based on the daily values of minimum, average, and maximum air temperature at the Kraków-Balice synoptic station (for the period 1961-2023), as well as the types of atmospheric circulation and air masses from the daily *Calendar of Atmospheric Circulation Types for southern Poland* (1951-2023) compiled by Niedźwiedź (1981, 2024).

The study analysed changes in the temperature of air masses occurring in the atmospheric surface layer based on measurements at a height of 2 m above sea level. Publicly available temperature data comes from a synoptic station that is part of the network of meteorological stations of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) representing non-urban areas (https://danepubliczne.imgw.pl). The data selected have been considered homogenous and are used in many scientific studies. At the same time, previous research has proven that the research area selected reflects the climatic conditions prevalent in much of Central Europe below 500 m a.s.l. (Trepińska, 1997). This allows the results to be considered representative of a larger European region.

The second dataset is the daily *Calendar of Atmospheric Circulation Types for southern Poland*. The distinct types of synoptic situation characterise the atmospheric conditions prevalent in southern Poland. They describe the direction of air advection and type of pressure system prevailing in southern Poland, as well as the types of air mass and atmospheric fronts moving over the study area on a given day. The study mainly uses the information noted on the types of air mass. They were marked with the symbols proposed by the author, and their description is provided in Table 1. Furthermore, the direction of inflow during particular types of air mass has been specified using the information on the circulation types they accompany. Among 21 circulation types, 16 are advection types the letter symbol of which indicates the direction of advection and the type of pressure system it was related to ("a" – anticyclonic or "c" – cyclonic situation), 4 other types include situations with no clear advection, and finally X – unclassified situations or a pressure col (Tab. 1; Niedźwiedź, 1981).

In the first stage of the study, changes in annual, seasonal and monthly air temperature values in Kraków in the years 1961-2023 were determined. For this purpose, daily minimum (Tmin), average and maximum (Tmax) temperature values were used. When examining the long-term changes in minimum and maximum daily temperature, the 1st or 99th percentile values were taken into account, respectively. Additionally, seasonal and long-term changes in the occurrence of selected thermally characteristic days were presented: warm (Tmax > 25°C), hot (Tmax > 30°C), frosty (Tmax < 0°C) and severe frosty (Tmin < -10°C) days. Based on the annual values of the average daily temperature, 10% (6) of the warmest and 10% of the coldest years of the period considered were also distinguished. Then, it was checked whether their occurrence confirms a significant increase in temperature since the 1990s, and using average seasonal temperature values, whether their average annual temperature was the result of high or low temperature values occurring throughout the year or mainly, for example, in a specific season.

The next stage of the work was the analysis of seasonal and long-term changes in the frequency of occurrence of individual air masses distinguished based on the *Calendar of Atmospheric Circulation Types for southern*

Table 1. Types of atmospheric circulation and air masses (according to catalogue of Niedźwiedź, 2024)

Types of atmospheric circulations			
Anticyclonic circulations		Cyclonic circulations	
Symbol	Direction of advection	Symbol	Direction of advection
Na	North	Nc	North
NEa	North-East	NEc	North-East
Ea	East	Ec	East
SEa	South-East	SEc	South-East
Sa	South	Sc	South
SWa	South-West	SWc	South-West
Wa	West	Wc	West
NWa	North-West	NWc	North-West
Ca	central anticyclonic situation (high centre)	Cc	central cyclonic situation (low centre)
Ka	anticyclonic wedge or ridge of high pressure	Bc	through of low pressure
X	unclassified situations or pressure col		
Types of air masses			
A	arctic		
mP	polar maritime (fresh)		
wmp	polar maritime warm		
omP	polar maritime old (transformed)		
cP	polar continental		
T	tropical		
vAm	various air masses in day		

Poland and the determination of the frequency and long-term changes in the directions of their inflow over Poland. For this purpose, the number of days with individual types of air masses and the circulation types associated with them was used.

In the next part of the study, seasonal and long-term changes in the temperature of air masses were determined. The average temperature values for the year and individual months were calculated as the average value of all days with a specific type of air mass occurring in a given year or month, respectively. Due to multi-year changes in the frequency of occurrence of individual types of air masses in subsequent years and during the year, the results obtained should be treated with due caution and interpreted as a signal of changes in the direction and magnitude of the increase in temperature of a given air mass. For this reason, it was decided to check whether the observed temperature increase was associated with a small number of days with extremely high temperatures or rather a greater number of warmer days, although not necessarily extremely hot. For this purpose, the 50th, 70th and 90th percentile of daily temperature values in Kraków-Balice were calculated for each month. Calculations were carried out for daily minimum, average and maximum values. Then, it was calculated how many days with a given air mass had a temperature higher or equal to a given percentile. Finally, it was summarized how many such days occurred in individual months and the year (annual values were calculated as the sum of monthly values). Also in this case, the obtained results should be interpreted with caution, especially in the case of Arctic and tropical air masses, which occur very rarely and most often appear in the cold or warm half of the year, respectively.

When analysing long-term trends in temperature change and the frequency of particular air masses, Pearson correlation coefficients were applied (in the case of statistically significant changes, they rarely exceeded the value of 0.4 and this concerned mainly changes defined for the year and summer months), while the significance of the changes (calculated at the level of 0.05) was verified using the Mann-Kendall test (Mann, 1945; Kendall, 1975).

Long-term temperature changes in Kraków-Balice

Over the period from 1961 to 2023, mean annual air temperature at the Kraków-Balice station was 8.5°C, and ranged from 6.6°C in 1980 to 11.8°C in 2023 (Tab. 2; Fig. 1). Whereas the temperature range was from -29.9°C (daily minimum recorded on January 13, 1987) to 37.3°C (daily maximum recorded on August 8, 2013). As in many other regions of the world, in the period under consideration there was a strong and significant increase in average annual temperature, particularly pronounced since the 1990s, which in the case of annual values amounted to 0.40°C/decade (Fig. 1). Except for October and November, the increase was also seen in the temperatures for the remaining months, with the values ranging from 0.23°C/decade (in September) to 0.59°C/decade (in January), and for the seasons – from 0.21 to 0.28°C/decade in autumn and spring respectively and from 0.50 to 0.52°C/decade in summer and winter respectively. Similar changes are seen in the 99 percentile of daily maximum temperature (0.49°C/decade) and the 1 percentile of daily minimum temperature (0.92°C/decade) temperature values recorded in a given year. As far as specific months are concerned, however, such strong changes are mainly visible in the warmest and coldest months and in the summer (0.53 and 0.38°C/decade respectively) and winter (0.53 and 1.04°C/decade respectively). In the case of the daily minimum temperature, the statistically significant change also concerned autumn and amounted to 0.27°C/decade.

Despite the increase in the mean annual temperature value recorded in Kraków-Balice, 10% (6 years) of the lowest annual values (6.6-7.0°C) were recorded different decades of the 20th century. Even 2010, scoring 13th on the thermal criterion, was also rather cool

Table 2. Values [°C] and trends [°C /10 years] of temperature changes in Kraków-Balice in the years 1961-2023

Temperature	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Values [°C]													
The highest daily maximum	1994 16.6	2021 19.8	1968 24.1	2012 30.0	2002 32.6	2019 34.2	2019 35.6	2013 37.3	2015 34.8	2001 27.1	1968 22.5	1998 19.3	2013 37.3
Average daily	-2.4	-0.8	3.1	8.5	13.5	17.0	18.5	18.0	13.6	8.7	3.6	-0.7	8.5
The lowest daily minimum	-29.9 1987	-29.3 1963	-26.8 1968	-6.9 2013	-3.2 2007	-0.1 1966	5.4 1962	2.7 1984	-3.1 1970	-7.4 1988	-17.2 1985	-29.5 1961	-29.9 1987
Tendency [°C /10 years]													
99 percentile of daily maximum	**0.68**	**0.82**	0.44	0.30	0.31	**0.44**	**0.57**	**0.52**	0.13	**0.42**	0.35	**0.48**	**0.49**
Average daily	**0.59**	**0.47**	**0.36**	**0.24**	**0.25**	**0.46**	**0.52**	**0.53**	**0.23**	0.2	0.21	**0.45**	**0.40**
1 percentile of daily minimum	**1.01**	0.72	0.48	-0.03	0.14	**0.45**	**0.41**	**0.41**	**0.41**	0.11	0.10	**1.00**	**0.92**

statistically significant values at the 0.05 level are bolded

(Tab. 3, Fig. 1). The six warmest years (9.9-11.8°C), however, are exclusively found in the years starting from 2000, including five years since 2015. When comparing the average seasonal temperature values in these years, it was stated that in the coolest years spring and summer, and sometimes autumn and winter, were also very cold and cold (constituting 25% lowest values in the long-term period; Tab. 3). In the case of the warmest years, temperatures in all the seasons almost always scored among the 40% top values in the long-term period. At the same time, among the 6 warmest years mentioned in each season, at least 2 years were among the 10% warmest.

The described temperature changes are reflected in the number of days characteristic

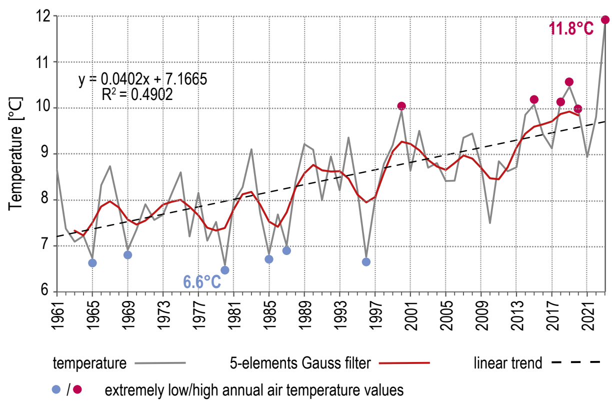


Figure 1. Average annual temperature [°C] in Kraków-Balice in the years 1961-2023

Table 3. Average annual and seasonal air temperature [°C] in Katowice-Balice in the 10% of the coldest and warmest years in the period 1961-2023 (No. – number of the year from the coldest to the warmest in the analyzed period)

Year	Temperature [°C] and year number									
	year	no.	spring	no.	summer	no.	autumn	no.	winter	no.
The coldest years										
1980	6.6	1	5.4	1	16.0	5	7.6	12	-1.9	19
1965	6.7	2	6.0	3	15.9	3	6.9	1	-0.9	37
1996	6.8	3	6.9	8	17.2	23	8.6	30	-3.5	12
1985	6.8	4	8.4	29	16.4	8	7.0	4	-2.7	16
1969	6.9	5	7.0	9	16.7	11	9.0	40	-5.3	4
1987	7.0	6	5.7	2	17.0	20	9.3	47	0.9	52
The warmest years										
2000	9.9	58	10.5	63	17.8	32	10.6	62	0.3	45
2020	10.0	59	8.6	37	19.2	53	10.0	56	-0.5	40
2015	10.1	60	8.9	42	19.9	61	9.4	50	1.9	60
2018	10.1	61	10.5	62	19.8	59	10.2	57	0.8	48
2019	10.5	62	9.6	53	20.6	63	10.3	59	2.6	62
2023	11.8	63	8.7	39	19.4	55	11.3	63	–	–

in terms of thermal conditions, including warm (Tmax > 25°C), hot (Tmax > 30°C), frosty (Tmax < 0°C) and severe frosty (Tmin < -10 °C) days. As in other regions of Europe, the number of days characterized by high-temperature values increases significantly, and the number of cold days decreases. In Kraków, in 1961-2023, the highest average and maximum number of warm and hot days occurred in the summer months (Tab. 4). In the case of warm days, it was, on average, 13.8 days in July and 12.6 in August, while in the case of hot days, 2.8 in July and 2.7 in August. Since the 1990s, there have been years in which even over 20 warm and over 10 hot days were recorded in the summer months (including 27 warm days in August 1992 and June 2019 and 17 hot days in July 2006 and 15 days in August 2015). The annual number of days described increased by 5.19 days/decade in the case of warm days and 1.74 in the case of hot days. This increase in the summer months ranged by 1.14-1.78 and 0.38-0.69 days/decade, respectively (Tab. 4). The decrease in the annual number of frosty and severe frosty days amounted to -3.55 and -2.60 days/decade and was noticeable since the end of the 1990s, and extremely few such days occurred after 2010. The largest changes occurred in December and January, ranging in the case of frosty days from -0.95 to -1.11 and severe frosty days from -0.68 to -1.21 days/decade respectively.

Seasonal and long-term changes in air mass occurrence in southern Poland

In the period 1951-2023, the region analysed, as the whole of Poland (Więcław, 2010; Bartoszek & Kaszewski, 2022), was dominated by polar air masses which constituted 78.6% of all cases on average, including 57.9% maritime-type masses (Tab. 5). The inflow of Arctic masses from the northern sector (7.7% on average during the year) and tropical air from the southern directions (3.2%) was recorded much less frequently. There was also a sig-

Table 4. Average and maximum number of warm (Tmax > 25°C), hot (Tmax > 30°C), frosty (Tmax < 0°C) and severe frosty (Tmin < -10°C) days and the tendency [days/ 10 years] of their changes in Kraków-Balice in the years 1961-2023

Days	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Average number of days													
Warm	–	–	–	0.8	3.8	9.2	13.8	12.6	3.4	0.3	–	–	43.8
Hot	–	–	–	–	0.2	1.3	2.8	2.7	0.1	–	–	–	7.2
Frosty	12.1	7.8	2.5	0.0	–	–	–	–	–	0.0	2.3	9.0	33.7
Severe frosty	7.1	4.0	1.1	–	–	–	–	–	–	–	0.5	4.1	16.8
Maximum numer of days													
Warm	–	–	–	6	11	27	26	27	13	2	–	–	86
Hot	–	–	–	–	4	8	17	15	2	–	–	–	30
Frosty	28	27	13	1	–	–	–	–	–	1	16	29	74
Severe frosty	25	17	12	–	–	–	–	–	–	–	5	15	52
Tendency [day/10 years]													
Warm	–	–	–	0.00	0.32	**1.14**	**1.78**	**1.69**	0.29	-0.02	–	–	**5.19**
Hot	–	–	–	–	0.03	**0.38**	**0.69**	**0.62**	0.02	–	–	–	**1.74**
Frosty	**-1.11**	-0.77	**-0.51**	0.01	–	–	–	–	–	-0.01	-0.21	**-0.95**	**-3.55**
Severe frosty	**-1.21**	-0.48	-0.14	–	–	–	–	–	–	–	-0.09	**-0.68**	**-2.60**

statistically significant values at the 0.05 level are bolded; "–" – days did not occur

Table 5. Average seasonal frequency [%] and tendency [%/10 years] of changes in the frequency of types of air masses occurrence in southern Poland in the years 1951-2023

Type of air mass	Frequency [%] of air masses					Tendency [%/10 years]				
	spring	summer	autumn	winter	year	spring	summer	autumn	winter	year
A	11.5	2.6	8.0	8.8	7.7	0.11	-0.31	0.09	0.52	0.11
mP	13.9	25.3	16.3	13.7	17.3	0.08	-0.42	**-0.93**	**-0.73**	**-0.50**
wmP	8.0	4.9	11.9	10.4	8.8	**1.13**	**0.89**	**1.40**	**0.89**	**1.05**
omP	30.3	34.3	30.5	32.0	31.9	1.13	**0.89**	**1.40**	0.89	**-1.15**
cP	22.7	17.6	20.0	22.4	20.7	-0.92	-0.63	0.07	**-1.90**	**-0.81**
T	3.3	5.7	3.0	0.9	3.2	**-0.74**	**1.00**	**-0.48**	**-0.37**	-0.15
vAm	10.4	9.6	10.4	11.6	10.5	**1.33**	**1.07**	**1.30**	**1.96**	**1.43**
Sum	100.0	100.0	100.0	100.0	100.0	-	-	-	-	-

statistically significant values at the 0.05 level are bolded

nificant percentage of days on which several types of air masses occurred over the study area (10.5% per year on average), which is related to the high frequency of low-pressure systems, with accompanying weather fronts, moving over Central Europe. The abovementioned shares of specific types of air masses during the seasons usually changed slightly. The exception was summer and, additionally, in the case of Arctic air (A) spring, and in the case of tropical air masses (T) winter (Fig. 2).

When analysing changes in the occurrence of particular air masses during a year, it was found that the smallest changes in their monthly frequency occur in the case of old polar maritime air (omP), polar-continental (cP), and various air masses (vAm). The range of the monthly values of a given air mass frequency was 6.7-9.0%, 6.2-10.9%, and 7.3-9.8% of all cases respectively (Fig. 2). A much greater variation is observed within the remaining air masses frequencies. Polar maritime warm air (wmP) and Arctic air (A) most frequently flows in during the cool season, with a peak in October for wmP and in April for A. Over the year, their frequency changed within the range of 4.4-13.8% and 1.9-15.1% respectively. In turn, with regards to polar maritime (mP) and tropical (T) air masses, there was a clear maximum in their frequency in the summer, with peak in July and August respectively, and with their inflow fluctuating within the range 5.7-14.0% (mP) and 2.0-16.5% (T).

The long-term trends in annual and seasonal frequency of occurrences of particular air masses indicates quite clear changes (Tab. 5, Fig. 3), which concern primarily the occurrence of polar air masses flowing from the Atlantic (mP, omP, wmP) and polar continental air masses (cP) from Asia. In the first case, in the years 1961-2023 a decrease in the occurrence of mP by -0.50% per decade and of omP by -1.15% per decade was recorded, along with an increased frequency of wmP by 1.05% per 10 years (this corresponds to changes of -1.82, -4.19, and 3.85 days/decade respectively). In recent decades, cP air was also rarer, with changes of -0.81% (-2.97 days) per 10 years. There is also a distinct increase in the frequency of various air masses (vAm) moving over the study region (by 1.43% or 4.51 days per 10 years), as well as changes in the frequency of tropical air (T) involving increases in the summer and decreases in the remaining seasons (Tab. 5). It is also worth noting that the changes are statistically significant, and often concern not only annual values, but also several (in the case of mP and omP masses) or all of the seasons in a year (in the case of wmP, T and vAm masses; Tab. 5).

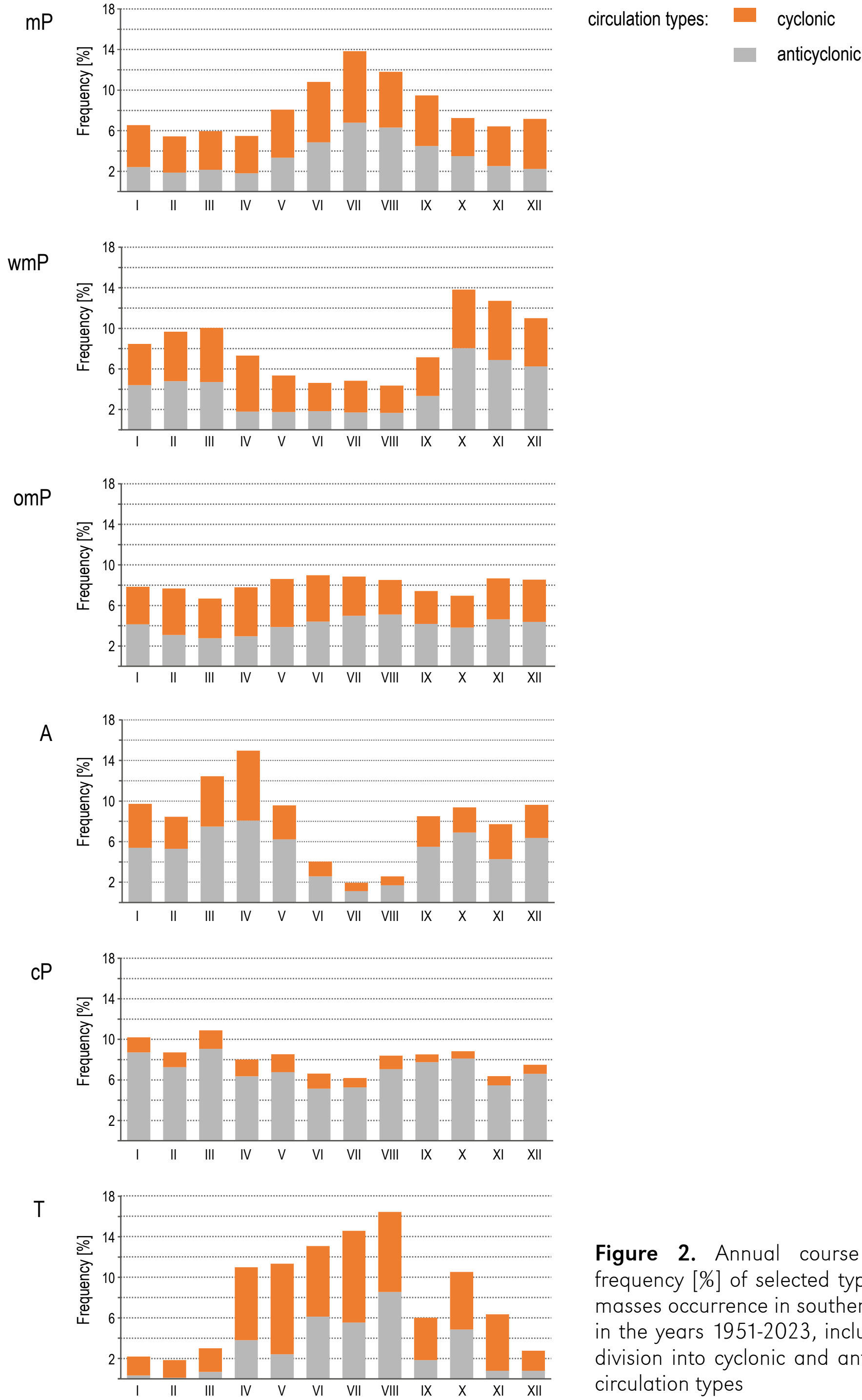


Figure 2. Annual course of the frequency [%] of selected types of air masses occurrence in southern Poland in the years 1951-2023, including the division into cyclonic and anticyclonic circulation types

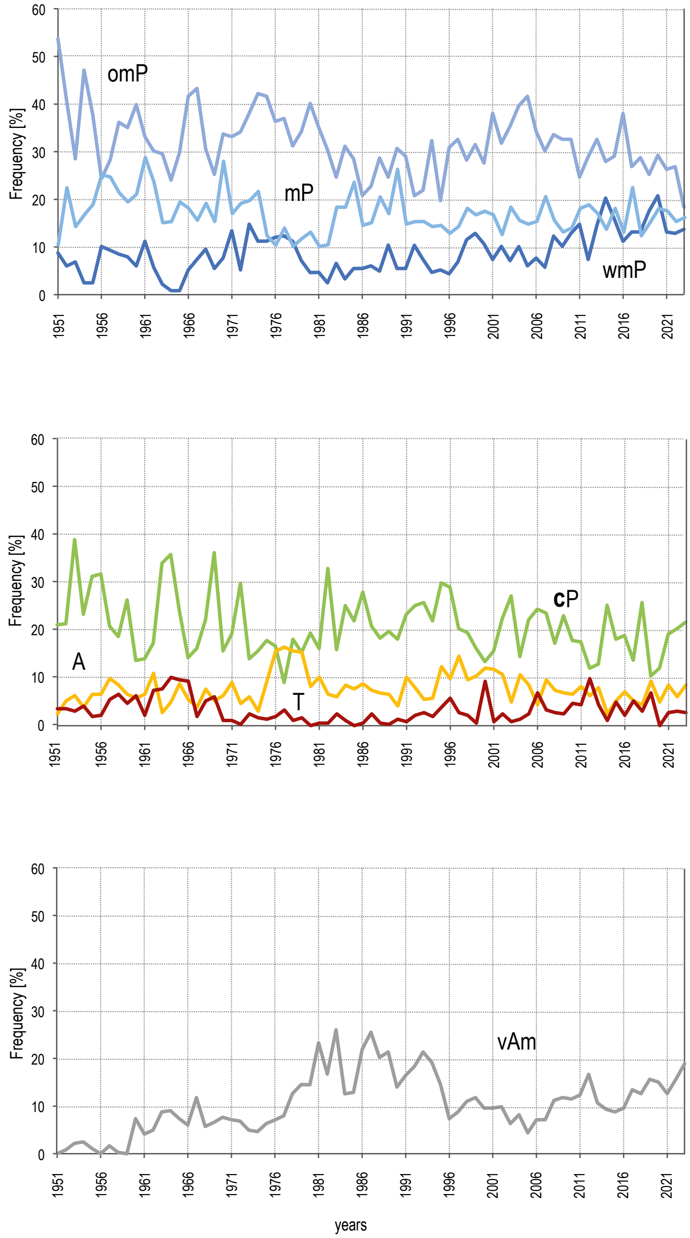


Figure 3. Frequency [%] of particular types of air masses occurrence in southern Poland in the years 1951-2023

Seasonal and long-term changes of directions of air masses advection in southern Poland

The air mass types analysed are related to specific pressure systems and directions of advection. The maritime variation of polar air (mP, omP, wmP) prevailing in Poland is associated with low-pressure and high-pressure systems with similar frequency (Fig. 2, Tab. 6). The latter much more frequently involve Arctic air masses (A – approximately 61% of all cases) and polar-continental air (cP – approximately 84%), whereas the advection of tropical air usually accompanies the movement of low-pressure systems across Poland with a related weather front system (T – approximately 63%). What is also important is the direction of advection of a given air mass. This is clearly visible in Central Europe where all the major types of air mass where collide. and it is precisely Poland's location at the heart of the continent that determines the "transitional" nature of its climate. In the period under consideration, the air masses are characterised by a rather clear inflow direction, usually covering a sector of approximately 90° range. In the case of polar maritime air, advection was predominantly from the western sector. However, in the case of the following air masses:

- mP – in as much as 68.1% cases, these were air masses inflowing from the West (W) and North-West (NW),
- omP – most frequently these arrived from the West (W) and South-West (SW) (26.0% in total), and when Poland was covered by a high-pressure wedge (Ka – 13.5%) and a cyclonic trough (Bc – 11.4%),
- wmP – air advection prevailed from the South (S), South-West (SW), and West (W), constituting 75.6% of all cases in total (Fig. 4, Tab. 6).

Arctic (A) and tropical (T) air arrived from a very clearly marked sector: northern (NW-NE; 65.2% of cases) and southern (SW-SE; 68.0%) respectively, whereas 54.3% of polar-continental (cP) air arrived from the S-E sector and as much as 17.6% during the occurrence of a high-pressure wedge (Ka).

The abovementioned regularities of flow direction change during the year. The largest directional changes are mainly concerned with the magnitude of the air masses' advection frequency from particular directions. In most cases, it is impossible to identify significant long-term changes in the frequency of advections of the air masses from particular directions. Major changes (statistically significant at the $p < 0.05$ level or lower) include:

- A decrease in the frequency of cP air inflowing from the East (E; by 1.3 days/decade with mean annual number of days of approximately 73) and from the South (S;

Table 6. Frequency [%] of the directions of particular air masses types advection in southern Poland in the years 1951-2023, taking into account non-advection cases and division into cyclonic (C) and anticyclonic (A) types

Type of air mass	Frequency [%] of air masses															
	N	NE	E	SE	S	SW	W	NW	Ca	Ka	Cc	Bc	X	sum	A	C
A	26.3	12.9	6.8	2.0	0.8	0.6	6.6	26.0	3.9	9.8	0.7	2.6	1.0	100.0	60.9	38.1
mP	9.4	2.6	0.6	0.2	0.6	2.1	38.3	29.8	2.1	5.1	0.9	6.6	1.7	100.0	42.3	56.0
wmP	0.5	0.2	1.1	4.0	14.0	31.7	29.9	5.5	1.8	4.6	0.3	5.8	0.6	100.0	47.2	52.2
omP	6.3	7.5	7.6	5.4	6.7	10.1	15.9	6.2	4.0	13.5	2.0	11.4	3.4	100.0	48.4	48.2
cP	1.9	7.7	19.9	21.5	12.9	6.8	2.4	1.0	5.3	17.6	0.3	1.5	1.2	100.0	83.6	15.2
T	0.1	0.1	1.7	8.7	32.0	28.3	7.3	0.2	0.8	7.1	1.7	11.0	0.9	100.0	36.0	63.1
vAm	3.3	2.6	1.0	1.3	3.3	9.0	25.7	10.4	0.4	2.2	2.4	35.3	3.0	100.0	16.2	80.8

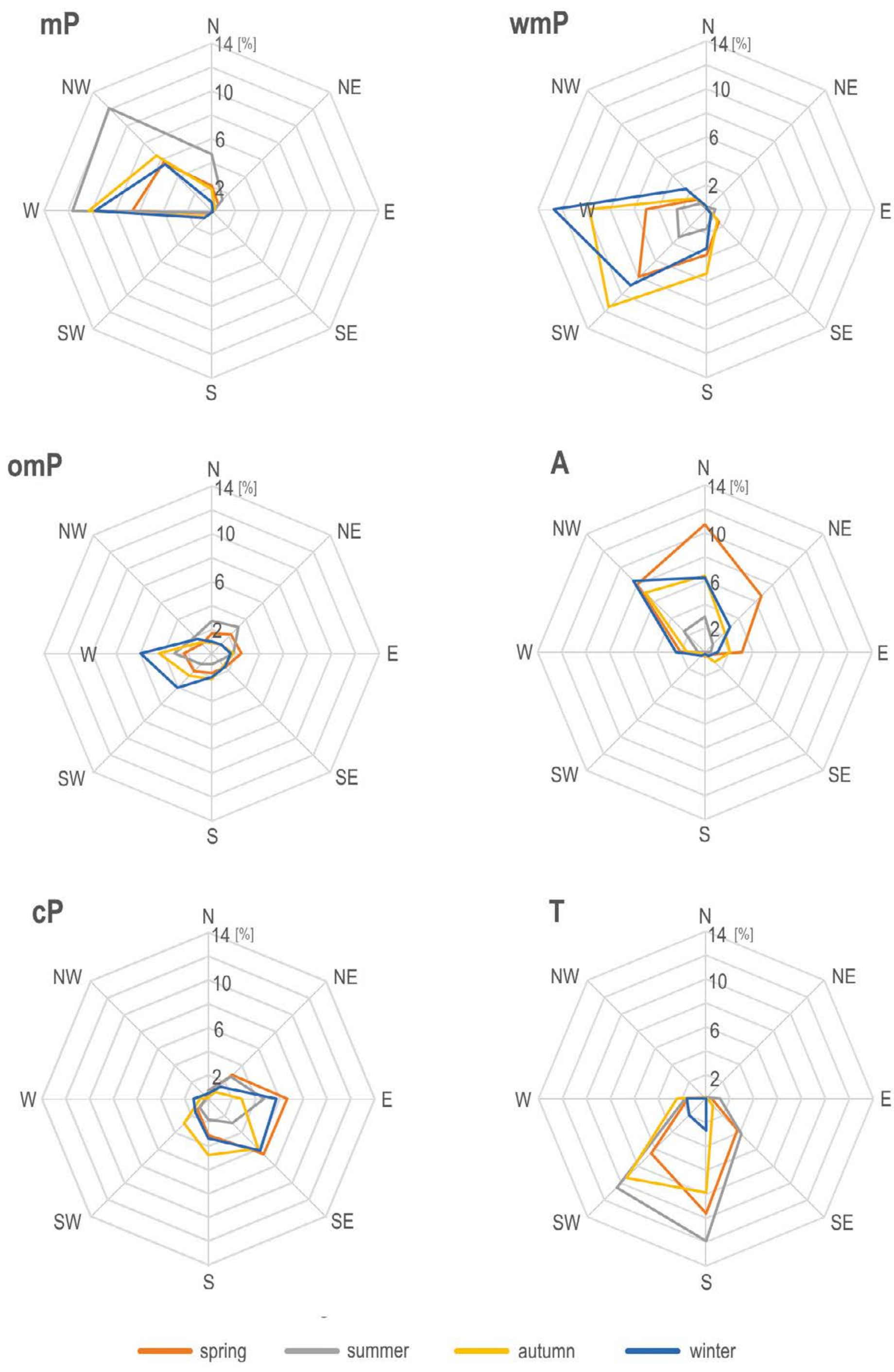


Figure 4. Frequency [%] of the directions of selected types of air masses inflow in southern Poland in the years 1951-2023

by 2.0 days/decade), as well as an increase during Ka situations (by 1.3 days/decade),
- A decrease in the frequency, by 1.2 days/decade, of mP air inflowing from the West (with an average annual frequency of about 62 days) and by 1.6 and 1.0 days/decade of omP air from the South and West respectively (with an average of ca. 113 days),
- An increase in the frequency, by 2.6 days per 10 years, of wmP air inflowing from the South-West (with an average of approximately 33 days per year).

It is also noted that the frequency of air masses associated with the low-pressure systems decreased by 0.9 days/decade for T air, by 2.4 days/decade for cP air masses, by 2.7 days/ decade for mP air, and by 3.4 days/decade for omP air masses, whereas for wmP air masses, it increased by 1.6 days/decade. Anticyclonic situations are slightly more frequently accompanied by advection of wmP (by 2.1 days/decade) and A air (by 0.8 days/decade).

Seasonal changes in the temperature of air masses in southern Poland

It is common knowledge that advection of the air mass types significantly affects the air temperature. Of greatest impact are the Arctic (A), tropical (T), and polar-maritime warm (wmP) air masses (Fig. 5). In the first case, the mean monthly temperature of days with this air mass in Krakow was lower than the mean monthly temperature for the entire period which was calculated without distinguishing between specific air masses from -2.7°C in December to -4.7°C in July. During advection of tropical (T) and polar-maritime warm (wmP) air, the mean monthly temperature values were higher. In both cases (T and wmP), the largest differences were recorded in winter and early spring (reaching up to 6.9°C in February and 4.7°C in January, respectively). Polar-maritime fresh and old (mP and omP) air masses increased the temperature in the cold and decreased it in the warm seasons of the year, but their impact was much weaker (particularly of omP) and did not exceed the average temperature increase by 3.8°C and 1.0°C in January, and its decrease by 2.0°C and 0.5°C in August for mP and omP respectively. Polar-continental (cP) air most affected air temperature in the cold half of the year (in January, it was lower by 5.1°C when compared to the mean from all days in the analysed period). In the warmest months, its impact was slightly lower than that of wmP and was less than half that of T (in July reaching values that are higher by 2.1°C than average) (Fig. 5).

Long-term changes in the temperature of air masses in southern Poland

The analysis also included an assessment of long-term temperature changes in specific air masses. On this basis, it was concluded that the average annual temperature values did not show significant changes in the case of Arctic (A) and polar-continental (cP) air (Fig. 6). In the case of other types of air mass, the temperature values increased from 0.18°C/decade for polar-maritime old (omP) to 1.44°C/decade for tropical air masses (T). Temperature changes of individual air masses also occurred in particular months. This most frequently occurred in the summer and winter months and least frequently in the spring and autumn (Tab. 7). Most frequently, these changes ranged from 0.25°C/10 years to 0.49°C/10 years, although in the case of Arctic and tropical air masses, in some months, they were much higher and even exceeded 1°C/10 years (1.16°C/10 years in April in the case of tropical air masses). However, it should be remembered that the annual number of days with individual air masses and the frequency of their occurrence during the year were subject to changes. For this reason, the described changes should be treated with some caution and interpreted as a signal of changes in the direction and value of the temperature increase of a given air mass.

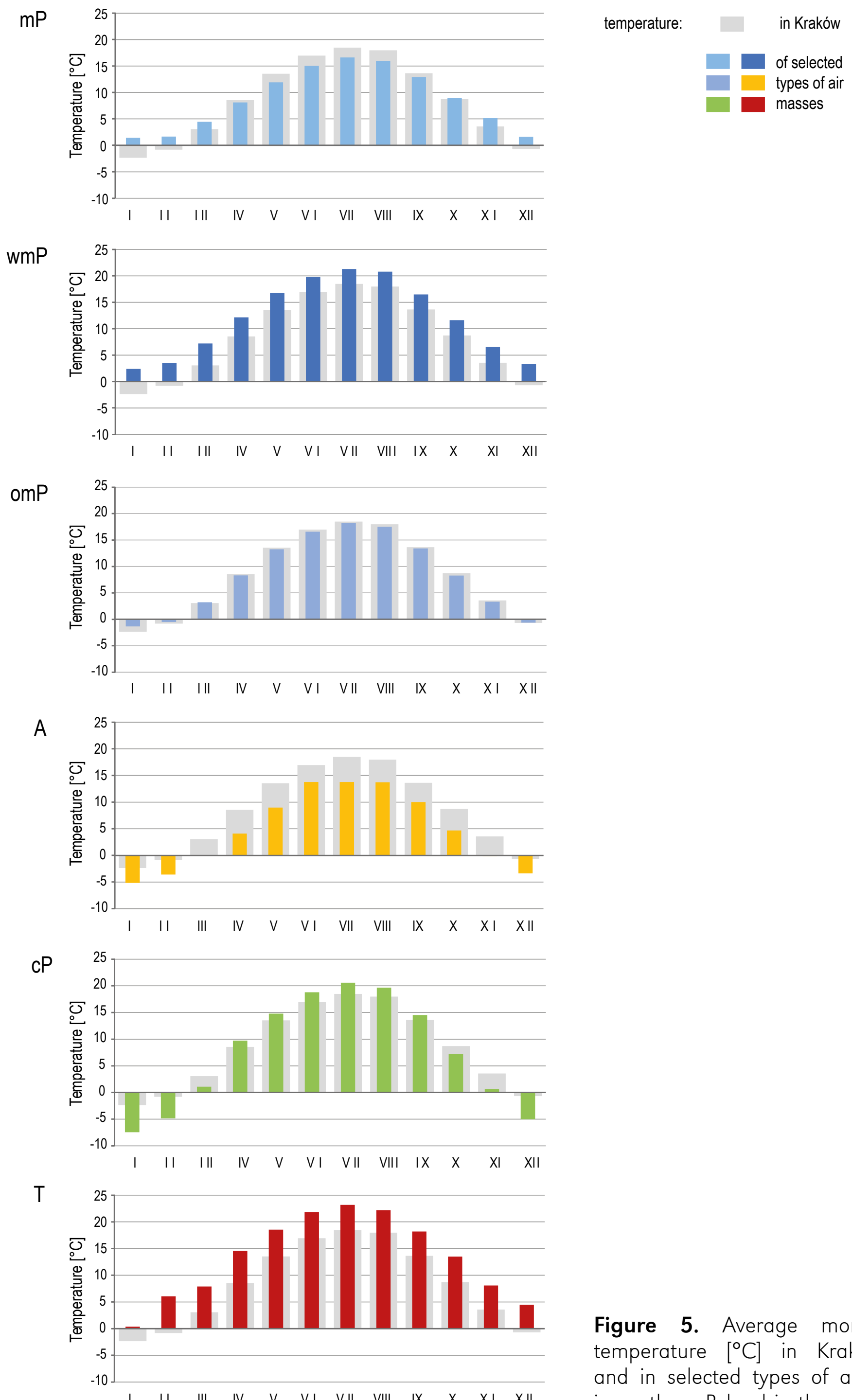
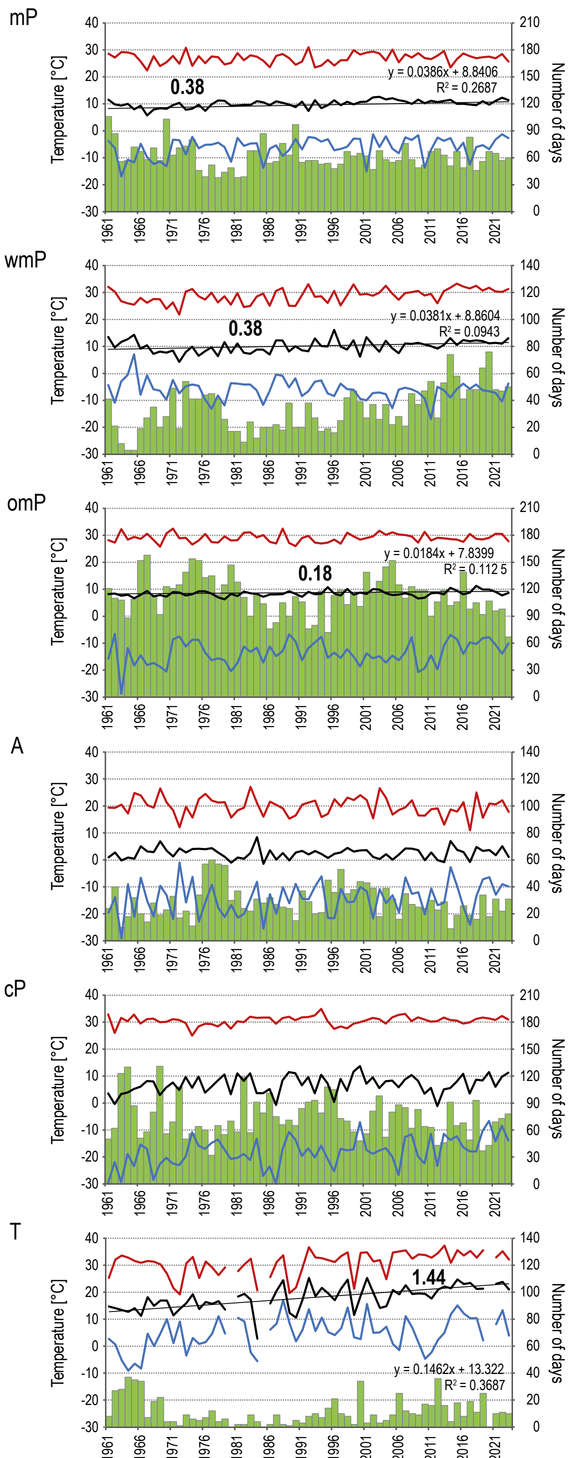


Figure 5. Average monthly air temperature [°C] in Kraków-Balice and in selected types of air masses in southern Poland in the years 1961-2023



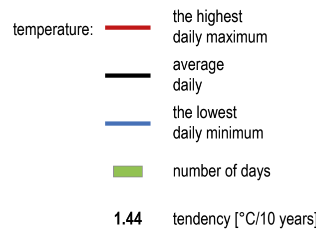


Figure 6. The lowest daily minimum, average daily and the highest daily maximum temperature [°C] and number of days with the selected types of air masses in Kraków-Balice in the years 1961-2023

Table 7. Trends [°C/10 years] in average daily temperature in Kraków-Balice and in particular types of air masses in the years 1961-2023

Months												Year
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
A												
0.92	**0.99**	0.15	-0.03	**0.47**	0.29	0.16	**0.48**	0.28	0.05	**0.40**	**0.56**	0.00
mP												
0.38	**0.26**	0.14	0.09	0.22	**0.40**	**0.40**	**0.34**	**0.29**	0.17	0.31	**0.29**	**0.38**
wmP												
0.39	**0.44**	0.26	**0.52**	**0.29**	**0.39**	**0.37**	**0.43**	0.29	0.20	**0.35**	**0.44**	**0.38**
omP												
0.21	**0.42**	0.20	0.18	0.19	**0.30**	**0.49**	**0.45**	0.21	0.17	0.18	0.21	**0.18**
cP												
0.28	0.10	0.46	0.21	0.27	0.21	**0.37**	**0.33**	-0.02	-0.33	0.05	0.22	0.43
T												
0.60	**0.50**	**0.60**	**1.16**	**0.83**	**0.76**	**0.77**	**0.48**	**0.86**	**0.25**	0.04	**-1.02**	**1.44**
Kraków-Balice												
0.59	**0.47**	**0.36**	**0.24**	**0.25**	**0.46**	**0.52**	**0.53**	**0.23**	0.20	0.21	**0.45**	**0.40**

statistically significant values at the 0.05 level are bolded

This applies in particular to annual values and changes concerning rarely occurring air masses, such as tropical or Arctic air masses.

The next step involved verification whether the observed temperature increase in particular air masses was associated with a small number of days with extremely high temperatures or rather a greater number of warmer days, although not necessarily extremely hot. For this purpose, the values of the 50th, 70th and 90th percentile of daily mean and extreme temperature values in Kraków-Balice were calculated for each month and for entire multi-year period. From this it was noted that the greatest changes are found in polar-maritime warm (wmP) air masses, which were present on approximately 33 days on average per year. In the case of this air mass, an increase in the number of days was recorded for all three thermal thresholds, and for the minimum, mean and maximum daily temperature values (Tab. 8, Fig. 7). For mean daily values, the changes were 4.93 days/decade (≥ 50th percentile), 4.28 days/decade (≥ 75th percentile), and 2.71 days/decade (≥ 90th percentile) respectively, while for the maximum daily temperature values they reached 5.14, 5.32, and 3.07 days/decade respectively. A similar increase was also recorded in the case of many monthly values, although it very rarely exceeded 0.50 days/decade. Such changes were much smaller in polar-maritime fresh and transformed (mP and omP) air masses, and they almost exclusively concerned mean daily temperature values. These were 1.24, 1.09, and 0.32 days/decade respectively for mP air masses and 2.20, 2.56, and 1.49 days/decade respectively for omP air masses. It is also worth mentioning the temperature of the increasingly frequent Arctic air masses (A), which exceeds the 50th percentile. This concerned the maximum, mean

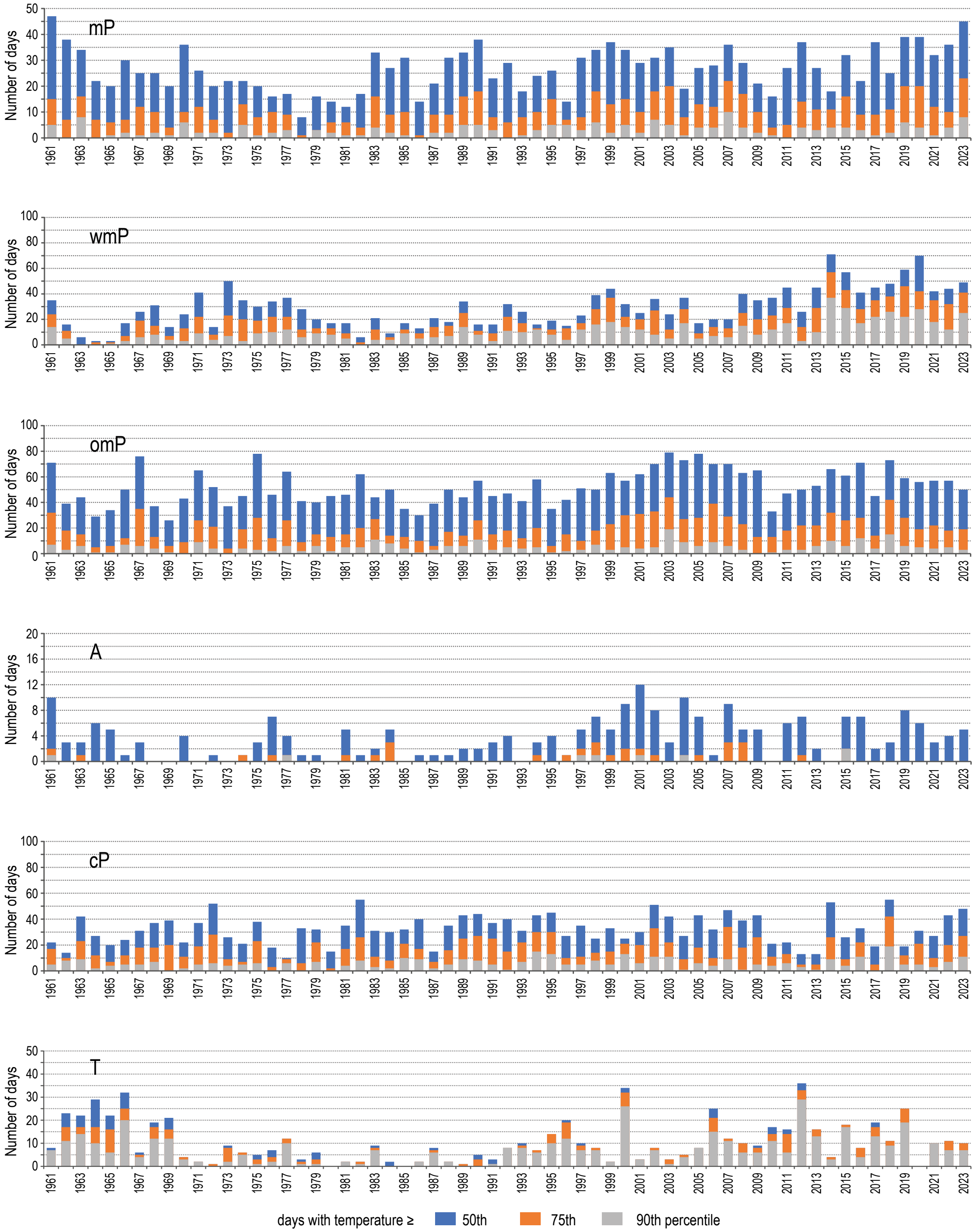


Figure 7. Annual number of days with average daily temperature ≥ 50th, 75th and 90th percentile of temperature in Kraków-Balice in particular type of air masses in the years 1961-2023

Table 8A. Trends [days/10 years] of changes in number of days with temperature ≥ 50th percentile of temperature in Kraków-Balice in particular type of air masses in the years 1961-2023

Temperature	≥ 50th percentile												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
A													
Daily minimum	0.28	0.18	0.02	-0.01	0.17	0.11	0.00	0.03	0.04	-0.03	0.16	0.14	0.73
Average daily	0.18	0.16	-0.01	0.01	0.02	-0.02	-0.03	0.04	0.06	0.03	0.02	0.16	0.48
Daily maximum	0.12	0.14	0.00	-0.03	0.03	0.01	-0.03	-0.04	0.02	0.04	0.06	0.19	0.41
mP													
Daily minimum	0.20	-0.05	-0.07	0.13	0.18	0.22	0.54	0.44	0.18	0.10	-0.11	-0.15	1.83
Average daily	0.23	-0.07	0.10	0.08	0.13	0.16	0.37	0.22	0.09	0.06	-0.14	-0.16	1.24
Daily maximum	0.24	0.00	0.21	0.11	0.10	0.18	0.28	0.14	0.11	0.19	-0.12	-0.17	1.36
wmP													
Daily minimum	0.15	0.15	0.00	0.32	0.18	0.28	0.63	0.04	0.25	0.32	0.34	0.06	3.68
Average daily	0.17	0.27	0.26	0.41	0.27	0.22	0.58	0.08	0.24	0.50	0.60	0.08	4.93
Daily maximum	0.23	0.30	0.30	0.44	0.34	0.18	0.59	0.03	0.27	0.60	0.61	0.11	5.14
omP													
Daily minimum	0.14	0.05	-0.11	0.08	0.22	0.50	0.65	0.15	0.29	0.20	-0.07	0.10	2.20
Average daily	0.05	0.18	0.19	0.21	0.06	0.47	0.64	0.41	0.17	0.02	0.00	0.29	2.68
Daily maximum	0.12	0.19	0.08	0.11	-0.15	0.13	0.55	0.26	-0.03	-0.33	-0.02	0.44	1.35
cP													
Daily minimum	0.08	-0.32	-0.12	0.17	0.08	-0.31	0.04	0.37	-0.07	-0.19	0.17	0.16	-0.19
Average daily	0.04	-0.17	0.38	0.70	0.27	-0.25	-0.03	0.48	0.05	-0.11	0.19	-0.02	0.93
Daily maximum	-0.05	-0.15	0.39	0.70	0.39	-0.23	-0.08	0.23	0.07	-0.12	0.09	-0.04	0.65
T													
Daily minimum	0.19	-1.11	-0.20	0.13	-0.06	0.63	0.41	0.59	-0.16	-0.30	-0.61	-0.18	0.29
Average daily	0.14	-1.11	-0.10	0.08	-0.08	0.64	0.33	0.51	-0.18	-0.26	-0.48	-0.04	0.23
Daily maximum	0.14	-1.11	-0.10	0.09	-0.05	0.61	0.31	0.48	-0.23	-0.20	-0.43	0.02	0.23

0.66 / -0.55 – statistically significant values at the 0.05 level

and minimum daily temperature values, and the changes in the number of days with such temperature were 0.41, 0.48, and 0.73 days/decade respectively. In the case of tropical air masses (T), the changes mainly concerned the summer months when the air occurs most frequently, and ranged from 0.41 to 0.68 days/decade. An exception was provided by the increase in the annual number of days with a temperature greater or equal to the 90th percentile, visible in the case of the lowest and the highest daily temperature values and which was 0.83 and 0.6 days/decade.

It was also verify whether, in the previously mentioned 6 extremely warm and cold years, any clear changes in the circulation can be observed. For this purpose, the frequency of occurrence of particular air mass types in

Table 8B. Trends [days/10 years] of changes in number of days with temperature ≥ 75th percentile of temperature in Kraków-Balice in particular type of air masses in the years 1961-2023

Temperature	≥ 75th percentile												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
A													
Daily minimum	0.06	0.08	-0.01	0.00	0.01	0.02	0.00	0.00	0.04	-0.03	0.03	0.08	0.20
Average daily	0.03	0.03	-0.05	0.01	0.00	-0.01	0.00	0.00	0.00	-0.02	0.03	0.04	0.04
Daily maximum	0.05	0.03	-0.07	0.01	0.00	-0.02	0.00	0.00	0.00	0.00	0.04	0.02	0.05
mP													
Daily minimum	0.37	-0.02	0.01	0.05	0.10	0.05	0.36	0.27	0.17	0.16	0.01	-0.07	1.53
Average daily	0.28	0.12	0.11	0.01	0.06	0.08	0.10	0.11	0.10	0.04	-0.01	0.07	1.09
Daily maximum	0.20	0.19	0.02	-0.03	0.04	0.03	0.04	0.00	0.03	0.06	-0.02	0.05	0.61
wmP													
Daily minimum	0.22	0.05	0.11	0.16	0.00	0.22	0.49	0.20	0.17	0.11	0.27	0.12	2.49
Average daily	0.26	0.36	0.21	0.46	0.29	0.17	0.76	0.15	0.19	0.42	0.40	0.29	4.28
Daily maximum	0.42	0.49	0.40	0.52	0.35	0.19	0.66	0.14	0.28	0.59	0.56	0.48	5.32
omP													
Daily minimum	0.08	0.08	0.16	0.19	0.21	0.42	0.52	0.34	0.23	0.11	0.05	0.16	2.56
Average daily	0.13	0.20	0.08	0.13	-0.04	0.23	0.42	0.24	0.20	0.07	-0.08	0.27	1.84
Daily maximum	0.02	0.15	0.00	0.11	0.00	0.15	0.29	0.14	-0.01	-0.16	-0.06	0.17	0.78
cP													
Daily minimum	0.06	-0.16	0.03	-0.02	0.14	-0.08	0.14	0.36	0.08	-0.06	0.08	-0.01	0.35
Average daily	-0.01	-0.04	0.15	0.32	0.17	-0.01	0.25	0.49	-0.03	-0.09	-0.02	-0.01	0.78
Daily maximum	-0.03	0.01	0.24	0.37	0.21	0.04	0.17	0.37	0.08	-0.07	0.01	0.02	0.99
T													
Daily minimum	0.05	-0.74	0.05	0.37	0.13	0.68	0.40	0.63	-0.07	-0.25	-0.56	-0.20	0.75
Average daily	0.21	-0.93	-0.04	0.19	0.16	0.68	0.43	0.60	-0.08	-0.16	-0.37	-0.16	0.77
Daily maximum	0.25	-0.93	-0.04	0.17	0.09	0.64	0.40	0.52	-0.06	-0.01	-0.19	-0.08	0.81

0.66 / -0.55 – statistically significant values at the 0.05 level

extremely warm or cold years was compared with mean frequency over the long term. On this basis, it was stated that a clear pattern determining the share of particular air masses in the abovementioned years is difficult to identify (Tab. 9). Usually, however, fewer days with polar-maritime warm and old air (wmP and omP) and sometimes with polar-continental air (cP) were recorded in the coldest years. In the warmest years, days with polar-maritime warm (wmP) air usually were more frequent. In contrast, the advection of masses with polar-maritime old and continental air (omP and cP) was sometimes recorded less frequently.

Table 8C. Trends [days/10 years] of changes in number of days with temperature ≥ 90th percentile of temperature in Kraków-Balice in particular type of air masses in the years 1961-2023

Temperature	≥ 90th percentile												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	year
A													
Daily minimum	0.01	0.01	-0.04	0.01	-0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.00
Average daily	0.01	0.01	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.02
Daily maximum	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
mP													
Daily minimum	0.17	0.08	0.08	0.04	0.06	0.04	0.15	0.15	0.17	0.02	-0.05	-0.04	0.88
Average daily	0.23	0.10	0.01	-0.02	0.00	0.03	0.01	0.00	0.03	0.04	-0.05	-0.06	0.32
Daily maximum	0.13	0.07	-0.02	0.00	0.01	-0.01	-0.01	0.00	0.02	-0.01	-0.03	0.02	0.19
wmP													
Daily minimum	0.13	0.09	0.09	0.07	0.06	0.24	0.31	0.06	0.06	0.06	0.13	0.20	1.51
Average daily	0.19	0.24	0.25	0.29	0.15	0.10	0.40	0.01	0.25	0.25	0.25	0.32	2.71
Daily maximum	0.33	0.35	0.30	0.25	0.18	0.08	0.30	0.05	0.21	0.35	0.30	0.39	3.09
omP													
Daily minimum	0.13	0.14	0.04	0.06	0.11	0.24	0.30	0.21	0.12	0.12	-0.08	0.10	1.49
Average daily	0.04	0.07	0.03	0.12	0.02	0.04	0.11	0.00	0.04	-0.03	-0.02	0.02	0.44
Daily maximum	0.01	0.01	-0.02	0.08	-0.02	-0.04	0.04	0.01	-0.06	-0.04	-0.01	0.02	0.00
cP													
Daily minimum	0.02	0.00	0.01	-0.03	0.18	0.05	-0.01	0.20	0.07	0.03	0.01	-0.01	0.39
Average daily	0.00	-0.02	-0.05	-0.02	0.19	0.02	0.18	0.20	0.13	-0.02	-0.02	0.00	0.41
Daily maximum	0.00	0.01	0.04	0.07	0.14	-0.05	-0.02	0.13	0.08	-0.02	-0.04	0.00	0.21
T													
Daily minimum	0.06	-0.56	0.00	0.34	0.16	0.49	0.30	0.50	0.06	-0.12	-0.35	-0.09	0.83
Average daily	0.00	-0.74	-0.01	0.29	0.33	0.56	0.48	0.50	-0.01	-0.20	-0.48	-0.08	0.80
Daily maximum	0.00	-0.74	-0.12	0.28	0.29	0.54	0.47	0.42	0.01	0.10	-0.04	-0.14	0.96

0.66 / -0.55 – statistically significant values at the 0.05 level

Discussion and conclusion

In the study, using the example of air temperature measured at the Kraków-Balice station in the period 1961-2023 and the information regarding types of atmospheric circulation and air masses, thermal changes in air masses occurring in southern Poland were assessed.

On this basis, it was stated that in the analysed period at the Kraków-Balice station, mean annual air temperature was 8.5°C and the increase in its annual value was 0.40°C/decade. The temperature increase concerned all seasons and most months, but it was approximately twice smaller in the transitional seasons than in winter and summer. It is worth pointing out that the strong tempera-

Table 9. The frequency [%] of particular types of air masses occurrence in southern Poland in the coldest and warmest years in the period 1961-2023

Year	The frequency [%]						
	A	mP	wmP	omP	cP	cP	vAm
The coldest years							
1980	8.2	13.4	4.6	40.2	19.1	0.0	14.5
1965	8.8	19.7	0.8	29.9	23.8	9.6	7.4
1996	9.8	13.1	4.4	30.9	28.7	5.7	7.4
1985	7.7	23.8	5.5	28.5	21.6	0.0	12.9
1969	5.2	15.6	5.5	25.2	35.9	6.0	6.6
1987	7.4	15.3	6.0	22.7	20.5	2.5	25.5
The entire period							
The highest	16.4	35.9	29.0	20.8	43.3	10.1	26.0
Average	8.0	20.1	16.9	9.1	31.0	3.1	11.9
The lowest	2.5	8.8	10.4	0.8	18.4	0.0	4.1
The warmest years							
2000	12.0	17.8	10.7	27.6	13.1	9.3	9.6
2020	4.9	18.3	20.8	29.2	11.7	0.0	15.0
2015	5.2	18.4	15.9	29.0	17.8	4.9	8.8
2018	4.4	12.6	13.2	28.8	25.5	3.0	12.6
2019	9.3	15.3	17.5	25.2	10.1	6.8	15.6
2023	8.5	16.4	13.7	18.4	21.4	2.7	18.9

ture increase also concerned daily extreme values, particularly values of 1 percentile of daily minimum temperature (0.92°C/decade). The changes confirm the general patterns observed worldwide (IPCC, 2021) and in Poland (Ustrnul et al., 2021; Marosz et al., 2023), as well as the fact that, similar to the situation across Europe, they are significantly higher than on other continents (WMO, 2022).

The location of the area investigated means that, as in other Central European regions (Więcław, 2010), polar air masses are predominant, particularly those flowing from over the Atlantic Ocean. However, Arctic and tropical air masses are particularly rare, and their occurrence changes most during the year. The research has confirmed the results of prior studies on the long-term variability of air masses over the study area (Bielec-Bąkowska, 2022) and also in other regions of Poland (Bartoszek & Kaszewski, 2022). It indicates a clear decrease in the frequency of polar-continental (cP), polar-maritime fresh and transformed air (mP and omP), as well as an increase in polar-maritime warm air (wmP) and the number of days with various air masses (vAm). In the latter case, this is confirmed by a higher frequency of cold weather fronts and various fronts (in one day) from the mid-1970s until the end of the period analysed (Bielec-Bąkowska, 2022) which, in the period 1951-2023, constituted approximately 42% and 28% of all days with vAm respectively. Arctic air (A) was slightly more frequent over the study area from the 1970s until the end of the 20th century, but the frequency has decreased again in recent decades. The increase can partly be related to the increased occurrence of strong anticyclonic systems at the time (Bielec-Bąkowska & Piotrowicz, 2021). Changes in the frequency of occurrence of tropical air masses are interesting as they point to a clear increase in their frequency in the summer, with a decrease in the other seasons. This, in turn, may result from an increased frequency of cyclonic situations and air flowing from a southerly direction, which is very often associated with this circulation type and involves incoming tropical air (Niedźwiedź & Ustrnul, 2021; Bielec-Bąkowska, 2022).

An important aspect here is the direction of advection of particular air masses, which determines not only their thermal properties, but also the ones related to moisture. In the study area, the prevailing directions of air mass inflow are clearly limited to a rather narrow sector, although general patterns slightly change throughout the year. It is thus worth noting a decrease in advections from the East, South-East, and West occurring in this part of Europe, as well as an increased frequency of advection from southerly directions (Niedźwiedź & Ustrnul, 2021; Bielec-Bąkowska, 2022; Herrera-Lormendez et al., 2022) which has been reflected in the changes in the frequency of directions of inflowing air masses. The largest of them concern cP masses (decrease in the frequency of advections from the East and South), mP, and omP (decrease in the frequency of advections from the West and South), as well as an increase in the frequency of inflowing wmP air masses from the South-West and during cyclonic situations.

The impact of the air masses investigated on air temperature changed both in the long-term and annually. The greatest impact on temperature change in a given period was observed for the advection of Arctic (A) and tropical air masses (T), but also for the increasingly more frequent polar-maritime warm air (wmP). In the two earlier cases, a clear increase in the difference between the mean temperature in Kraków and the temperature characteristics of a given air mass started from the 1990s, and was particularly large for tropical air masses (T). The consequence was a strong increase in the average temperature of such air masses, reaching 1.44°C/decade, with a temperature increase in polar-maritime air of up to 0.38°C/decade and no major changes to continental and Arctic air. Considering the clear increase in the frequency of occurrence of warm air masses in Europe, including of dry ones, and the decrease in frequency of cold masses (Lee, 2020; Petrou et al., 2022), one should expect air temperature to continue growing in the study area, particularly in the summer and winter. This is also confirmed by the observed increase in the frequency of warm and exceptionally warm days (with temperature ≥ 50th, 75th or 90th percentile of all values), the number of which increases most in polar-marine air masses, primarily warm (wmP) and tropical (T) air masses. However, it is also worth paying attention to the more frequent occurrence of warm days (temperatures ≥ 50th percentile of all values) in Arctic air masses (A), which, in the absence of changes in the frequency of this type of air masses, may indicate a further increase in the temperature of the cold season.

Despite a clear increase in air temperature in the study region, thermal conditions of particular years, seasons, or months may differ significantly. This is due to the very high variability and unpredictability of circulation conditions in the region investigated (Bielec-Bąkowska & Twardosz, 2023). The research has also confirmed that it is difficult to clearly identify a frequency pattern of particular types of air mass in the warmest or coldest years. However, it turned out that the greatest influence on the thermal characteristics of a given period had the air masses wmP, omP and cP. This also confirms the results of previous studies, which indicated that changes in climatic conditions are not necessarily directly related to changes in the frequency of occurrence of particular types of circulation, but rather to changes in the thermal and moisture characteristics of the associated air masses (Brunner et al., 2017; Bartoszek & Matuszko, 2021).

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

References

Alekseev, G. W., Podgornyj, I. A., Swiaschchennikov, P. N. & Hrol, W. P. (1991). Osobennosti formirovanija klimata i ego izmennchivosti v poljarnoj klimaticheskoj sisteme atmosfera – morskoj led – okean. In B. A. Krutskich (Ed.), *Klimaticheskij rezhim Arktiki na rubezhe XX i XXI v.* (pp. 4-29). St. Petersburg: Gidromietieoizdat.

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*. https://doi.org/10.1016/j.atmosres.2020.105427

Bielec-Bąkowska, Z. (2014). *Silne wyże nad Europą (1951-2010)*. Katowice: Wydawnictwo Uniwersytetu Śląskiego.

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

Bielec-Bąkowska, Z., & Piotrowicz, K. (2021). Air pressure change. In M. Falarz (Ed.), *Climate Change in Poland: Past, Present and* Future (pp. 151-176). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-70328-8_7

Bielec-Bąkowska, Z., & Twardosz, R. (2023). Exceptionally cold and warm spring months in Kraków against the background of atmospheric circulation (1874-2022). *Pure and Applied Geophysics*, *180*, 3351-3370. https://doi.org/10.1007/s00024-023-03324-9

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

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., ... & Vera, C. (2020). Climate impacts of the El Niño–southern oscillation on South America. *Nature Reviews Earth & Environment*, *1*(4), 215-231. https://doi.org/10.1038/s43017-020-0040-3

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

Cattiaux, J., Vautard, R. & Yiou, P. (2011). North-Atlantic SST amplified recent wintertime European land temperature extremes and trends, *Climate Dynamics*, *36*, 2113-2128. https://doi.org/10.1007/s00382-010-0869-0

Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X. W., Xu, T. & Murray, D. (2011). Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, *38*(6). https://doi.org/10.1029/2010GL046582

Francis, J. A. & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*(6). https://doi.org/10.1029/2012GL051000

Gössling, S., Neger, C., Steiger, R., & Bell, R. (2023). Weather, climate change, and transport: A review. *Natural Hazards, 118*, 1341-1360. https://doi.org/10.1007/s11069-023-06054-2

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

IPCC. (2021). *Climate Change 2021*: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R.Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu,

& B. Zhou (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896

Kendall, M. G. (1975). *Rank correlation methods* (4th ed.). London: 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

Lee, C. C. (2020). Trends and variability in airmass frequencies: Indicators of a changing climate. *Journal of Climate*, *33*(19), 8603-8617. https://doi.org/10.1175/jcli-d-20-0094.1

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

Marosz, M., Miętus, M., & Biernacik, D. (2023). Features of multiannual air temperature variability in Poland (1951-2021). *Atmosphere*, *14*(2), *282*. https://doi.org/10.3390/atmos14020282

Martyn, D. (1992). *Climates of the world*. Amsterdam: Elsevier.

Met Office. (2022). *Unprecedented extreme heatwave, July 2022*. Met Office National Climate Information Centre. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2022/2022_03_july_heatwave_v1.pdf

Niedźwiedź, T. (1981). *Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły.* Kraków: Uniwersytet Jagielloński.

Niedźwiedź, T. (2024). *Calendar of Atmospheric Circulation Types for Southern Poland*. https://us.edu.pl/instytut/inoz/kalendarz-typow-cyrkulacji/

Niedźwiedź, T., & Ustrnul, Z. (2021). Change of atmospheric circulation. In M. Falarz (Ed.), *Climate Change in Poland: Past, Present and Future*. Cham, Switzerland: Springer, pp. 123-150. https://doi.org/10.1007/978-3-030-70328-8_6

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*(1810). https://doi.org/10.1098/rstb.2019.0505

Petrou, I., Kassomenos, P., & Lee, C.,C. (2022). Trends in air mass frequencies across Europe. *Theoretical and Applied Climatology*, *148*, 105-120. https://doi.org/10.1007/s00704-022-03921-z Pezza, A. B., Simmondsa, I., & Renwickb, J. A. (2007). Southern hemisphere cyclones and anticyclones: Recent trends and links with decadal variability in the Pacific Ocean. *International Journal of Climatology*, *27*(11), 1403-1419. https://doi.org/10.1002/joc.1477

Pfahl, S. (2014). Characterising the relationship between weather extremes in Europe and synoptic circulation features, *Natural Hazards and Earth System Sciences*, *14*, 1461-1475. https://doi.org/10.5194/nhess-14-1461-2014

Piotrowicz, K. & Ciaranek, D. (2020). A selection of weather type classification systems and examples of their application. *Theoretical and Applied Climatology*, *140*, 719-730. https://doi.org/10.1007/s00704-020-03118-2

Schemm, S., Sprenger, M., Martius, O., Wernli, H. & Zimmer, M. (2017). Increase in the number of extremely strong fronts over Europe? A study based on ERA-Interim reanalysis (1979-2014), *Geophysical Research Letters*, *44*, 553-561. https://doi.org/10.1002/2016GL071451

Screen, J. A. (2014). Arctic amplification decreases temperature variance in northern mid to high-latitudes. *Nature Climate Change*, *4*, 577-582. https://doi.org/10.1038/nclimate2268

Serreze, M. & Barry, R. (2011). Processes and impacts of Arctic amplification: a research synthesis. *Global and Planetary Change*, *77*(1-2), 85-96. https://doi.org/10.1016/j.gloplacha.2011.03.004

Serreze, M. C. & Francis, J. A. (2006). The Arctic amplification debate. *Climatic Change*, *76*, 241-264. https://doi.org/10.1007/s10584-005-9017-y

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

Sykulski, P. & Bielec-Bąkowska, Z. (2017). Atmospheric fronts over Poland (2006-2015). *Environmental & Socio-Economic Studies*, *5*(4), 29-39. https://doi.org/10.1515/environ-2017-0018

Trepińska, J. (Ed.). (1997). *Wahania klimatu w Krakowie*. Kraków: Instytut Geografii UJ.

Trigo, R. M., Osborn, T. J., & Corte-Real, J. M. (2002). The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Climate Research*, *20*(1), 9-17. http://www.jstor.org/stable/24866789

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., 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., Wypych, A. & Czekierda, D. (2021). Air temperature change. In M. Falarz (Ed.), *Climate Change in Poland: Past, Present and Future*. Cham, Switzerland: Springer, pp. 275-330. https://doi.org/10.1007/978-3-030-70328-8_11

Więcław, M. (2010). Przestrzenne i sezonowe zróżnicowanie częstości występowania mas powietrza w Europie Środkowej w latach 1996-2005. In L. Kolendowicz (Ed.), *Klimat Polski na tle klimatu Europy*: *Warunki cyrkulacyjne i radiacyjne* (pp. 9-21). Poznań: Bogucki Wydawnictwo Naukowe.

WMO. (2022). *State of the Climate in Europe 2021* (WMO-No. 1304). WMO: Geneva, Switzerland. https://digitallibrary.un.org/record/3994378?v=pdf

Zarrin, A., Ghaemi, H., Azadic, M., & Farajzadeh, M. (2010). The spatial pattern of summertime subtropical anticyclones over Asia and Africa: A climatological review. *International Journal of Climatology*, 30, 159-173. https://doi.org/10.1002/joc.1879

Zuo, J., Ren, H. & Li, W. (2015). Contrasting impacts of the Arctic oscillation on surface air temperature anomalies in Southern China between early and middle-to-late winter. *Journal of Climate*, *28*(10), 4015-4026. https://doi.org/10.1175/JCLI-D-14-00687.1

Zvyagintsev, A. M., Blum, O. B., Glazkova, A. A., Kotelnikov, S. N., Kuznetsova, I. N., Lapchenko, 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

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