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Long-term changes in circulation conditions over southern Poland for the period 1874–2020

Abstract
The study presents the long-term and annual trends in atmospheric circulation over southern Poland for the period 1874–2020. The analysis takes into account both the type of atmospheric circulation, and the types of air mass and atmospheric fronts. The study showed that there has been a noticeable decrease in the frequency of anticyclonic types of circulation and of air advection from the west and east, and a slight increase in advection from the south, as well as the presence of anticyclonic centres and cyclonic troughs. The research also found considerable changes in the frequency of the presence of polar air and of stationary and occluded fronts, as well as of days with several fronts moving over the study area.

Keywords
Circulation types • air masses • atmospheric fronts • Poland

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Introduction

Atmospheric circulation is one of the key factors determining climatic conditions in Europe. Its effect is particularly important during the cold half of the year, when it is responsible for supplying energy from lower latitudes and mitigating the energy balance deficit. One of the key aspects underlying the impact of atmospheric circulation on climatic conditions consists of the frequency at which its characteristic elements (types of circulation, air masses, and atmospheric fronts) occur and the persistence of the types of synoptic situations (Kyselý & Domonkos 2006). Both the long-term and annual changes in the occurrence of these components are responsible for the associated changes in climatic characteristics (Bárdossy & Caspary 1990), including the most important ones: cloudiness (Matuszko & Węglarczyk 2018; Sfica et al. 2021), temperature (Fleig et al. 2015; Bartoszek & Matuszko 2021), precipitation (Twardosz 2005; Hofstatter et al. 2018), and snow cover (Ye& Lau 2017; Szyga-Pluta 2022). For the above reasons, the problem of circulation has been addressed by numerous climatological studies; overviews of key Polish studies can be found, inter alia, in papers by Kaszewski (2001), and Niedźwiedź and Łupikasza (2019).

Studies devoted to the occurrence of the individual elements of circulation constitute a separate group of studies. Most of these concern pressure systems, circulation types and indices (Niedźwiedź 1978; Ustrnul 1997; Piotrowski 2012; Bartoszek 2017a), and air mass (Buchert 2006; Kierklo 2012; Kotas et al. 2013). Studies on atmospheric fronts are much less numerous (Buchert 1994, Niedźwiedź 2000, Więcław 2013), and most of these focus on changes over the period of a year, or on their multi-year variability over short observation periods.

This study presents the most important features of atmosphere circulation over southern Poland. Owing to the complex nature of the interrelationships between all of its elements and their cumulative impact on the climate of the area, the analysis addressed both the frequency of the occurrence of circulation types, and the types of air masses and atmospheric fronts. Particular attention was paid to their long-term variability, in particular, variations in the frequency of the atmospheric fronts that entail a range of dangerous meteorological phenomena. The most important of these include strong winds (Leckebusch & Ulbrich 2004; Jania & Zwoliński 2011), intense rainfall or blizzards (Twardosz et al. 2011; Bernas & Kolendowicz 2013; Degirmendžić et al. 2014), and storms and accompanying hailstorms (Bielec-Bąkowska 2002 and 2010; Twardosz et al. 2010; Taszarek & Suwała 2015; Piotrowicz et al. 2020).

Materials and research methods

This study uses the calendar of synoptic situations developed by Niedźwiedź for the years 1874–2020 (Niedźwiedź 2021). The types of synoptic situations identified characterise the atmospheric conditions found in southern Poland. They describe both the direction of advection and the type of pressure system that prevails over that part of the country, and the types of air masses and atmospheric fronts that cross the area on a given day. The calendar distinguishes between 16 types of circulation, where the description of the direction of advection is marked with a capital letter, while the index “a” or “c” stands for anticyclonic or cyclonic situations, respectively (e.g. Wa and Wc would mean advection of air from the west associated with an anticyclonic and cyclonic system, respectively). Additionally, the typology identifies four situations with no clear advection: Ca and Cc – a central anticyclonic or cyclonic situation respectively, Ka – anticyclonic wedge or ridge of high pressure, Bc – trough of low pressure, and X – unclassified situations or a pressure col. The types of air masses and atmospheric fronts are determined for a shorter period of time, 1951–2020. These are identified by the author’s own designations: A – Arctic air masses, mP – maritime polar air (fresh), wmP – warm maritime polar air, omP – old maritime polar air (transformed), cP – continental polar air, T – tropical, and vAm – various air masses

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Table 1. The frequency [%] of the directions of air mass advection and the occurrence of types of anticyclonic and cyclonic situations in southern Poland during the years 1874–2020

Seasons	Frequency [%]										
	The direction of advection								Anticyclonic situations	Cyclonic situations	Unclassified situations
	N	NE	E	SE	S	SW	W	NW	A	C	X
Spring	7.0	7.5	10.8	9.3	6.7	8.3	14.0	9.5	49.0	49.0	2.0
Summer	8.4	7.5	6.0	3.6	3.4	4.9	19.7	13.5	54.3	44.3	1.3
Autumn	4.3	3.4	6.7	8.7	8.5	12.5	22.2	9.4	59.5	38.9	1.6
Winter	4.1	3.5	8.1	9.8	6.5	12.0	26.4	10.1	57.3	41.1	1.6
Year	6.0	5.5	7.9	7.8	6.3	9.4	20.5	10.7	55.0	43.3	1.6

Source: own study

occurring within a day. The typology of atmospheric fronts is as follows: wF – warm front, cF – cold, oF – occluded, sF – stationary, and vf – various fronts. Both types of synoptic situations, as well as air masses and atmospheric fronts, were defined by the author of the *Calendar of Circulation Types for Southern Poland*, based on the analysis of synoptic maps of Poland and Europe from 00.00 and 12.00 UTC (prepared by Polish, Austrian, German, and Czech Meteorological Services), and maps of the 700 hPa isobaric surfaces' height (Niedźwiedź 1981 and 1996).

The data used in this study has already been analysed in other research for shorter periods of time for the region under consideration. However, the most important goal of this study was to present the "comprehensive" nature of the changes taking place in the circulation over southern Poland. This is especially important in the context of macroscale changes in circulation and the accompanying climate changes. In addition, the long-term changes in the frequency of atmospheric fronts, which have been described least often in the literature on the subject, were found to be exceptionally interesting.

The trends for long-term changes in the frequency of synoptic situations, as well as air masses and atmospheric fronts, were determined using an equation of a line, whereas the trend significances were calculated using the Mann-Kendall test (Mann 1945; Kendall 1975).

Long-term variability of the occurrence of synoptic situations

During the multi-year period under study, the weather in southern Poland, as elsewhere in the country (Woś 2010), was slightly more frequently modelled by synoptic situations associated with anticyclonic systems (on average, 55.0% of all days of the year), and this situation occurred especially in autumn and winter (57.3% and 59.5% of days in the season, respectively; Tab. 1). Corresponding to a westerly flow, which prevails in the temperate zone, most of the air masses entered the region from the west: 10.7% from the northwest (NW), 9.4% from the southwest (SW), and 20.5% from the west (W) (Tab. 1), which cumulatively accounted for about 40% of all days analysed. The inflows of air from the north (N), northeast (NE), and south (S) were the least frequent: on average only about 5.5–6.3% of days annually. One noteworthy fact was the exceptionally large range of variation in the frequency of air advection from the west and south: 19.2% (S) and 23.2% (W). This is particularly important in the case of the relatively rare advection of air from the south, which brings in warm and often dry air masses. The years 1950–1980 stood out in this respect, since, over this period, advection from this direction occurred on more than 10% of days, and in 1959 it even reached 20.8%.

As regards the types of synoptic situations, four of these clearly predominated. The anticyclonic wedge (Ka - 11.9%) and the advection of air from the west (Wc - 10.2% and Wa - 10.3% of all cases) were the most common situations for the study area (Tab. 2). Troughs of low pressure (Bc) were slightly less frequent (9.2%). The frequency of the other types ranged from about 2% to about 6%. The movement of the cyclonic centre was the least frequent (Cc - 1.0%), although central anticyclones (Ca) also occurred infrequently, on only 2.2% of days.

The frequency of individual synoptic situations also changed throughout the year (Tab. 3). The groups of situations that stood out noticeably were those most frequent in late spring and summer, i.e., those associated with the presence of a high pressure system over Scandinavia or Western Europe (Na, NEa, and Ka), or an active cyclone whose centre was located east or southeast of Poland (Nc, NEc, and Ec), as well as advection of air from the northwest (NWc), cyclonic troughs (Bc), and cyclone centres (Cc). It is also worth paying attention to the situations accompanying high pressure systems that had their centre located east or southeast of Poland (Ea, SEa, Sa, and SWa), and advection of air from the south associated with a low-pressure system (SEc, Sc, and SWc), which were usually observed during the transitional seasons of the year.

When analysing the long-term variability of the occurrence of the types of circulation under study, it can be noted that statistically significant changes predominantly concern those situations that involved advection from the south and east, and the occurrence of an anticyclonic centre and a cyclonic trough (Ca and Bc; Tab. 4, 5). These changes were usually relatively small, and varied from season to season. The increasing occurrence of anticyclonic centres (Ca) and cyclonic troughs (Bc), and the decrease in air advection from the west during anticyclonic situations (Wa) were the most noticeable trends.

There was also a noticeable decline in the number of days when the weather over the study area was under the influence of situations associated with high pressure systems. Over the period under study, it was 0.67% per 10 years (Tab. 5), which means that from 1874, the frequency of this type of situation decreased by over 10%. A particularly strong decline was seen during 1960–1980, when the average frequency of anticyclonic situations was 46.7%, with a long-term average of 55.0%. In 1970, this dropped to as low as 35.1%. Against this background, the last 37 years have been characterized by a clear increase in the frequency

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Table 2. The annual and seasonal frequency [%] of occurrence of synoptic situations in southern Poland during the years 1874–2020

Characteristics	Frequency [%] of synoptic situations																			
	Na	NEa	Ea	SEa	Sa	SWa	Wa	NWa	Ca	Ka	Nc	NEc	Ec	SEc	Sc	SWc	Wc	NWc	Cc	Bc	X
Year																					
Lowest	0.5	0.8	1.6	0.5	0.3	1.1	2.5	1.4	0.3	0.5	0.3	0.0	0.0	0.5	0.3	0.5	3.6	1.1	0.0	1.4	0.0
Average	3.4	3.5	5.6	5.2	3.3	4.3	10.3	5.5	2.2	11.8	2.6	2.1	2.3	2.7	3.0	5.2	10.2	5.2	1.0	9.2	1.7
Highest	9.9	7.4	12.9	12.8	11.5	10.1	18.9	12.6	13.4	21.3	6.6	5.7	7.4	8.2	9.6	9.6	18.9	10.4	5.2	17.2	6.0
Range	9.3	6.6	11.2	12.3	11.2	9.0	16.4	11.2	13.2	20.8	6.3	5.7	7.4	7.7	9.3	9.0	15.4	9.3	5.2	15.8	6.0
Seasons																					
Spring	3.8	4.7	7.0	5.2	2.9	2.7	5.8	4.4	1.5	10.8	3.2	2.9	3.7	4.0	3.8	5.6	8.2	5.1	1.3	11.1	2.0
Summer	4.7	4.7	4.3	2.1	1.9	2.3	9.9	6.9	2.1	15.4	3.7	2.8	1.8	1.6	1.6	2.6	9.7	6.7	1.1	12.8	1.4
Autumn	2.7	2.2	4.9	6.4	5.0	6.7	11.7	5.4	2.9	11.8	1.6	1.3	1.8	2.3	3.5	5.9	10.3	4.0	0.8	7.3	1.6
Winter	2.4	2.2	6.0	7.0	3.3	5.6	13.9	5.3	2.4	9.2	1.8	1.3	2.0	2.7	3.2	6.5	12.5	4.9	0.6	5.7	1.6

Source: own study

Table 3. The annual course of the frequency [%] of occurrence of individual synoptic situations in southern Poland during the years 1874–2020; 100% is all cases of a given type of synoptic situation

Synoptic situation	Frequency [%]												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Na	5.4	6.5	8.6	8.1	11.9	12.9	13.3	8.3	7.8	6.8	4.8	5.5	100
NEa	5.3	5.7	8.0	9.7	16.7	12.0	11.1	11.2	7.7	4.4	3.5	4.7	100
Ea	9.4	9.6	10.4	9.0	12.3	6.2	5.6	7.5	7.1	8.4	6.7	7.9	100
SEa	11.9	11.6	11.3	7.3	6.9	3.2	1.9	5.1	8.4	12.0	10.4	10.1	100
Sa	7.5	8.3	9.3	6.9	6.2	4.1	3.5	6.6	9.8	13.9	14.5	9.3	100
SWa	12.2	7.5	6.4	5.3	4.4	3.8	3.4	6.4	9.8	15.0	13.6	12.3	100
Wa	12.7	8.9	6.6	4.0	3.5	5.8	8.4	9.8	9.0	9.7	9.6	11.9	100
NWa	8.5	8.0	8.6	5.6	6.2	10.4	11.6	9.2	10.2	7.2	7.1	7.5	100
Ca	10.4	7.1	6.7	4.5	5.9	6.9	6.3	10.3	13.2	11.9	7.7	9.0	100
Ka	7.0	5.5	6.6	7.9	8.6	10.0	11.3	11.5	10.1	8.1	6.9	6.6	100
Nc	5.4	6.8	8.1	11.9	11.4	13.3	13.4	9.3	6.7	4.6	4.3	4.8	100
NEc	4.6	6.1	7.4	13.8	13.9	15.0	9.9	9.5	6.4	4.9	4.1	4.4	100
Ec	6.8	7.3	11.0	14.3	15.0	10.6	5.1	3.9	5.8	7.0	6.3	6.9	100
SEc	7.7	9.3	11.6	15.0	11.4	6.4	4.0	4.7	5.8	6.3	9.5	8.4	100
Sc	7.3	9.2	9.8	12.2	10.0	4.6	4.1	4.3	6.3	9.2	13.4	9.6	100
SWc	9.6	10.0	11.0	9.0	7.2	3.9	4.3	4.6	6.3	10.7	11.8	11.6	100
Wc	10.3	8.6	8.8	6.6	5.0	6.3	9.5	8.2	7.7	8.2	9.4	11.3	100
NWc	8.6	7.2	9.1	8.1	7.8	11.0	12.7	8.5	7.1	5.8	6.4	7.7	100
Cc	4.6	6.5	7.1	14.1	13.9	12.6	7.6	8.2	5.7	7.3	7.4	5.0	100
Bc	4.4	5.2	7.6	10.4	12.4	12.6	11.3	10.8	7.7	6.4	5.6	5.7	100
X	8.4	8.4	10.9	10.4	9.2	7.2	5.9	7.7	8.1	8.2	7.7	7.8	100

Source: own study

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Table 4. The tendency [%/10 years] of changes in the frequency of the occurrence of particular types of synoptic situations in southern Poland during the years 1874–2020

Tendency [%/10 years]																			
Na	**NEa**	**Ea**	**SEa**	**Sa**	**SWa**	**Wa**	**NWa**	**Ca**	**Ka**	**Nc**	**NEc**	**Ec**	**SEc**	**Sc**	**SWc**	**Wc**	**NWc**	**Cc**	**Bc**	**X**
Year																				
-0.05	**-0.05**	**-0.15**	**-0.10**	**0.11**	-0.02	**-0.45**	-0.04	**0.16**	-0.08	**0.08**	**0.04**	0.02	-0.01	**0.09**	**0.07**	-0.02	**0.07**	0.01	**0.25**	**0.08**
Spring																				
-0.02	-0.03	**-0.21**	0.02	0.07	0.01	**-0.33**	-0.05	**0.12**	0.04	**0.10**	0.03	-0.07	-0.07	0.05	0.02	-0.03	0.04	0.02	**0.21**	**0.08**
Summer																				
-0.07	-0.08	0.11	**0.13**	**0.20**	0.05	**-0.76**	-0.12	**0.16**	-0.13	0.05	0.01	0.04	0.03	**0.12**	**0.09**	**-0.27**	-0.03	0.00	**0.41**	**0.07**
Autumn																				
-0.07	-0.07	**-0.30**	-0.09	0.14	-0.02	**-0.39**	-0.06	**0.23**	-0.18	**0.08**	**0.06**	0.04	0.02	**0.12**	0.01	0.05	**0.17**	0.00	**0.17**	0.06
Winter																				
-0.04	-0.04	**-0.19**	**-0.43**	0.04	-0.12	**-0.32**	0.04	**0.13**	-0.06	**0.08**	**0.07**	0.07	-0.03	0.04	**0.15**	0.19	0.08	0.03	**0.19**	**0.12**

bold text – statistically significant at the level of 0.05
Source: own study

Table 5. The tendency [%/10 years] of changes in the frequency of occurrence of air advection in southern Poland during the years 1874–2020

Tendency [%/10 years]										
N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Anticyclonic situations (A)**	**Cyclonic situations (C)**	**Unclassified situations**
Year										
0.03	-0.01	**-0.14**	**-0.11**	**0.20**	0.06	**-0.47**	0.03	**-0.67**	**0.60**	**0.08**
Spring										
0.08	0.00	**-0.28**	-0.05	0.13	0.03	**-0.36**	-0.01	-0.38	0.31	**0.08**
Summer										
-0.02	-0.07	0.15	**0.16**	**0.32**	**0.14**	**-1.04**	-0.14	**-0.52**	**0.46**	**0.07**
Autumn										
0.01	0.00	**-0.25**	-0.07	**0.26**	-0.01	**-0.34**	0.12	**-0.79**	**0.73**	0.06
Winter										
0.04	0.04	-0.12	**-0.47**	0.08	0.03	-0.13	0.13	**-0.99**	**0.87**	**0.12**

bold text – statistically significant at the level of 0.05
Source: own study

of such situations, although not as large as in the first half of the study period. The average for the years 1874–1945 reached as high as 58.3%, with the highest frequency recorded for 1920 and 1921: 74.6% and 75.1%, respectively. The most significant variations occurred in winter and autumn: 0.79% and 0.99% per 10 years, respectively (approximately 13–14% over the entire study period). In this context, spring stood out for its more even values for the frequency of both types of synoptic situations and alternating periods of increased frequency. Notably, spring months were the only season when cyclonic types prevailed during 1960–1980 (Fig. 1).

Long-term variability of the occurrence of air masses

During 1951–2020, almost all known types of air mass entered the area under investigation, with old maritime polar (transformed) air (omP - 32.2%) and polar-continental air (cP - 20.7%) entering most often; while tropical (T - 3.3%) and Arctic air (A - 7.7%) entered least often. Quite often (on average

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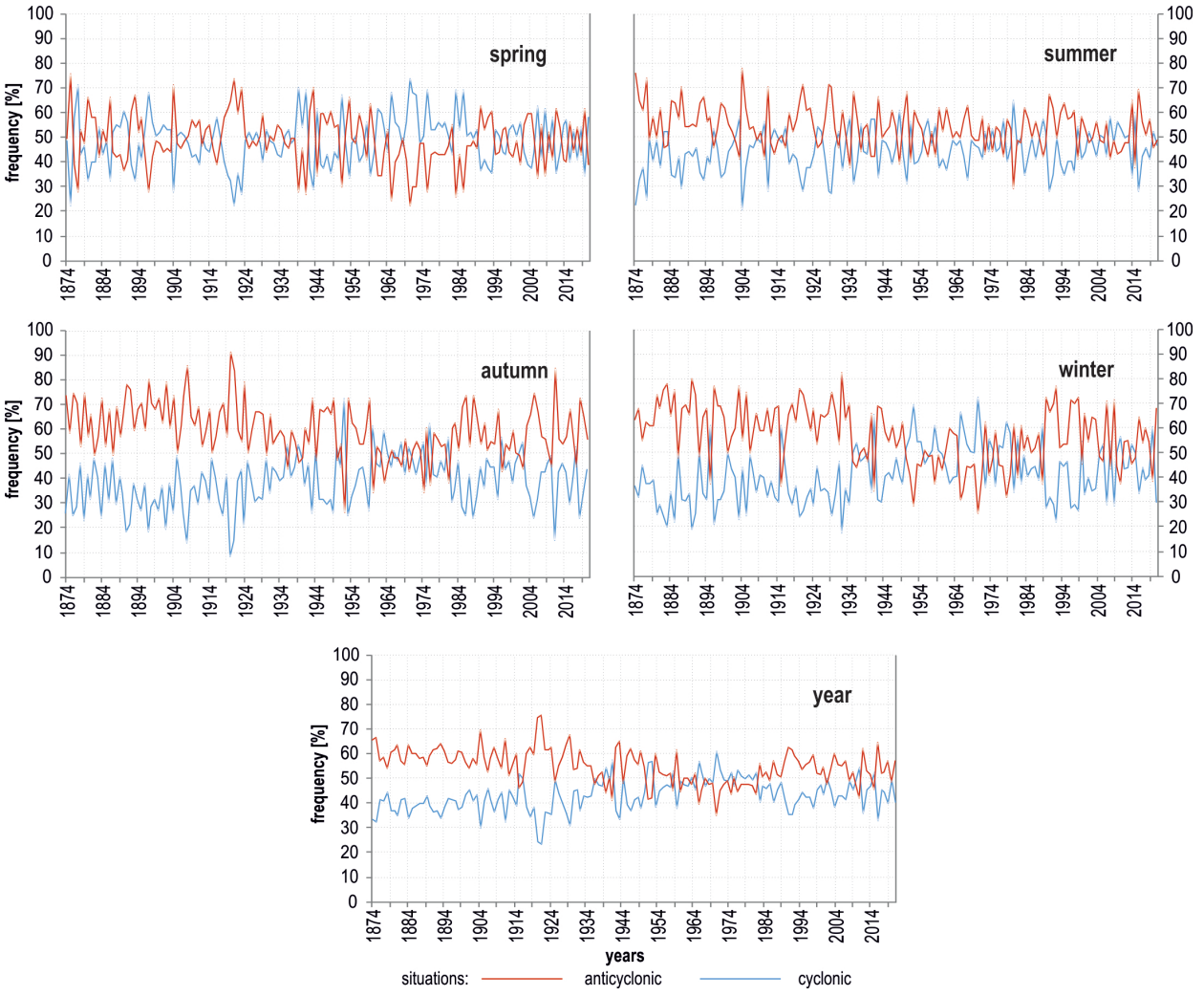


Figure 1. Annual and seasonal frequency of occurrence of cyclonic and anticyclonic types of synoptic situation in southern Poland during the years 1874–2020
Source: own study

Table 6. The frequency [%] of air mass occurrence in southern Poland during the years 1951–2020

Characteristics	Frequency [%] of air masses						
	A	mP	omP	wmP	cP	T	vAm
Lowest	2.5	10.4	19.7	0.8	8.8	0.0	0.0
Average	7.7	17.3	32.2	8.6	20.7	3.3	10.3
Highest	16.4	29.0	53.7	20.8	38.6	10.1	26.0
Range	14.0	18.6	34.0	20.0	29.9	10.1	26.0

Source: own study

10.3% of all days in the year; Tab. 6), there were also cases where several types of air mass (vAm) crossed the region being analysed during one day. Such situations typically occurred when a dynamic low-pressure system with accompanying atmospheric fronts passed over Poland.

The weather in the region under study was most often influenced by polar air masses, which is typical for temperate latitudes. During the period analysed, these accounted for 86.5% of all cases (Tab. 7; Fig. 2). A significant proportion of the air was polar maritime, which was observed over the study area on 58.1% of days annually. Its impact on meteorological conditions depended on whether they were fresh, transformed, or the least frequent incoming warm air masses from the southern part of the North Atlantic.

As in other regions of Poland (Martyn 1987; Woś 2010), the highest frequency of polar maritime air advection was recorded in the summer (64.8%), with the maximum in July (67.8%), while the lowest was recorded in the of transitional season months (with a minimum of 49.5% in March; Tab. 7, Fig. 2). However, due to the different origins of the various types of polar maritime air and a clear shift of air masses in the northern hemisphere towards the pole in the warm season, the annual trends in occurrence differed slightly. The above mainly applies to mwP advection, which was predominantly observed in autumn (11.7%) and at the turn of winter and spring, and demonstrated its lowest frequency in summer (only 4.6%; Fig. 2), with the minimum in

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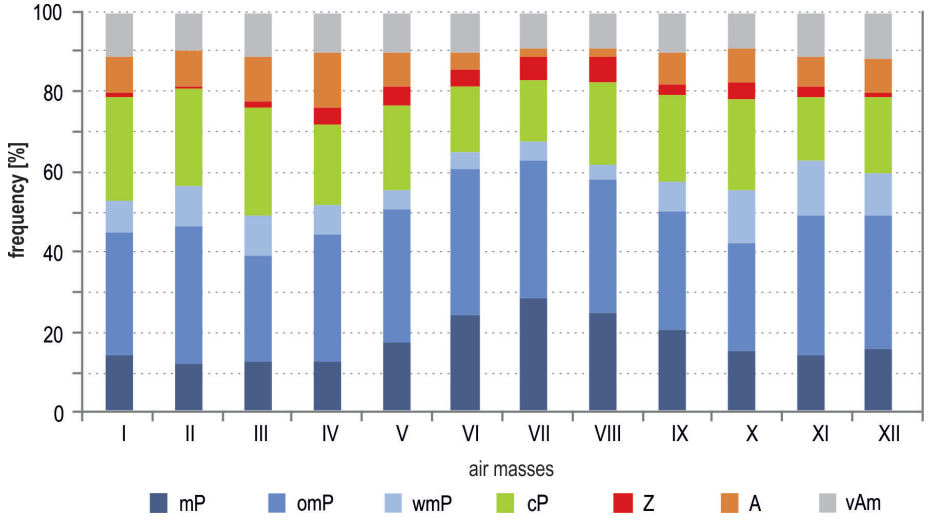


Figure 2. Average monthly frequency [%] of particular air mass occurrence in southern Poland during the years 1951–2020 (descriptions in the text)
Source: own study

Table 7. Average seasonal frequency [%] of types of air mass occurrence in southern Poland during the years 1951–2020

Type of air mass	Frequency [%] of air masses				
	Spring	Summer	Autumn	Winter	Year
A	11.4	2.7	8.0	8.8	7.7
mP	13.9	25.3	16.2	13.6	17.3
omP	30.5	34.9	30.9	32.1	32.2
wmP	7.9	4.6	11.7	9.8	8.6
mP+omP+wmP	52.3	64.8	58.7	55.5	58.1
cP	22.6	17.5	20.0	22.4	20.7
mP+omP+wmP +cP	74.9	82.3	78.8	78.0	86.5
T	3.4	5.6	3.1	1.0	3.3
vAm	10.3	9.4	10.2	11.3	10.3
Sum	100.0	100.0	100.0	100.0	100.0

Source: own study

August (4.1%). In turn, on average, dry polar-continental air from Asia and Eastern Europe moved into the study area on about 21% of the days in the year. The proportion changed slightly from one season and month to another, peaking at 26.6% in March. It was only in summer that its frequency was slightly lower, mainly due to the less frequent advection of these air masses in June and July (Fig. 2).

On average, on 7.7% of days in the year, Arctic air masses entered Poland, particularly from Greenland, the Svalbard region and the surrounding seas (moving over the Scandinavian peninsula), and the northwest part of Russia (Tab. 7). The annual course of these air masses is somewhat similar to the frequency of mwP. During the multi-year analysed period, they most often reached southern Poland in spring (11.4% of days), especially in March and April (11.4% and 13.8%, respectively; Fig. 2), and in late autumn; and were least frequent in July and August (1.8% and 2.4%, respectively). The region receives tropical air masses from the south, which are very warm and usually characterised by low transparency. This type of air mass was least frequent and did not represent more than 3.3% of all the cases studied over the multi-year analysed period. These masses were observed most frequently from April to August (reaching 6.0% of cases in August), and least frequently in January and February (0.8% each; Fig. 2).

When analysing the long-term variability of the types of air mass occurrence, it was found that in the case of Arctic (A) and tropical (T) air masses, their annual values did not reveal strong trends in change over the period 1951–2020. It was only possible to identify certain periods distinguished by an increased number of days with the abovementioned air masses (Tab. 8; Fig. 3).

A slight decrease in the frequency was observed for cP (0.90% per 10 years), and for mP and omP, approximately 0.54% and 0.99% per 10 years, respectively. This was the result of a noticeable decrease in the frequency of transformed air masses after 1980 and of fresh air masses from around 1975. As regards cP, the number of days with these air masses decreased gradually from the beginning of the period under study. This went hand in hand with an increase in the frequency of influxes of wmP into the study area: about 1.03% per 10 years. Also, the movement of various air masses (vAm) over the study area during the same day was recorded more frequently than at the beginning of the second half of the twentieth century (1.42%/10 years). The years 1976–1996 stood out distinctly in this respect, which may provide evidence of the highly dynamic atmospheric circulation for that period. It must also be emphasised that the value and long-term changes in the occurrence of vAm were very similar across the seasons of the year (Tab. 8).

When looking at the long-term variability of the number of days studied for the various seasons, it can be observed that, apart from vAm, the same trend across the seasons was only observed for omP (decrease in frequency) and wmP (increase). A more thorough analysis of the aforementioned variability in individual months mainly confirmed an increase in the frequency of wmP and vAm masses and a decrease for cP and omP (Tab. 8).

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Table 8. The tendency [%/10 years] of changes in the frequency of types of air mass occurrence in southern Poland during the years 1951–2020

Type of air mass	Tendency [%/10 years]																
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Spring	Summer	Autumn	Winter	Year
A	0.76	0.24	1.17	-0.36	-0.56	-0.42	-0.21	-0.17	-0.43	0.40	0.26	**0.88**	0.09	**-0.27**	0.08	**0.52**	0.13
mP	-0.71	-0.29	0.51	-0.07	-0.03	-0.56	-0.26	-0.46	**-1.46**	-1.07	-0.93	**-1.14**	0.14	-0.43	**-1.15**	**-0.74**	**-0.54**
omP	0.03	0.27	-0.57	-1.04	-1.35	-0.01	**-1.87**	**-1.97**	-0.92	-0.92	**-2.01**	**-1.46**	**-0.98**	**-1.30**	**-1.28**	-0.29	**-0.99**
wmP	0.46	0.49	0.77	**1.57**	**1.30**	**0.86**	**0.81**	0.58	**1.30**	1.24	**1.76**	1.18	**1.21**	**0.75**	**1.43**	**0.69**	**1.03**
cP	-2.14	-2.32	**-3.37**	0.14	-0.12	**-2.69**	-0.36	0.55	0.96	-0.18	-0.40	-0.97	**-1.13**	**-0.81**	0.12	**-2.10**	**-0.90**
T	**-0.29**	-0.42	**-0.49**	**-1.24**	-0.54	**1.30**	0.92	0.75	**-0.48**	-0.56	-0.34	**-0.44**	**-0.75**	**0.99**	**-0.46**	**-0.39**	-0.15
vAm	**1.90**	**2.00**	**1.98**	**1.00**	**1.30**	**1.51**	**0.96**	0.72	**1.04**	**1.08**	**1.66**	**1.95**	**1.43**	**1.06**	**1.26**	**1.98**	**1.42**

bold text – statistically significant at the level of 0.05
Source: own study

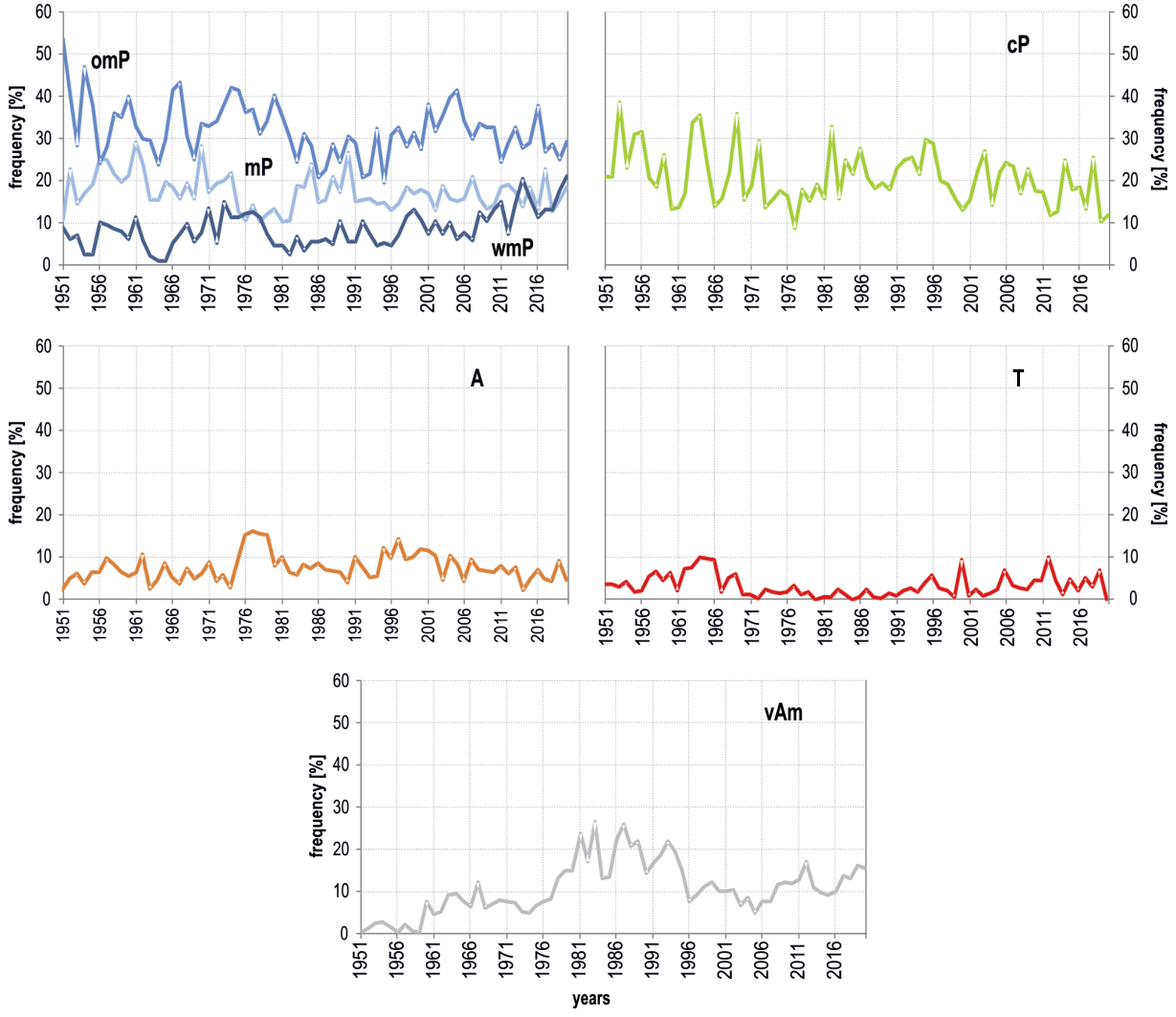


Figure 3. Frequency [%] of particular types of air mass occurrence in southern Poland during the years 1951–2020 (descriptions in the text)
Source: own study

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Long-term variability of the occurrence of atmospheric fronts

Air masses moving into a given area are separated by atmospheric fronts. The area they influence will experience very intense changes in meteorological conditions, which has a strong effect on both the various elements of the environment and the activity and well-being of humans. In the study period (1951–2020), the weather in southern Poland was predominantly determined by a homogeneous air mass, on as many as 59.7% of all days in the year, on average (Tab. 9). Cold fronts (cF - 15.9% on average, i.e., about 58 days a year) crossed the area much less frequently and were most often associated with active low pressure systems moving from the Atlantic Ocean. On average, warm fronts (wF), which brought about an increase in temperature, occurred on 8.4% of days per year (approx. 30 days), while occluded fronts (oF), which were accompanied by an extensive precipitation area, occurred on 5.5% of days (approx. 20 days). Stationary fronts modelled the weather over the area in question least frequently (sF - 2.7%, about 10 days).

Seasonal differentiation in the occurrence of the fronts in question was not large (Tab. 10). The main changes in the frequency of individual types of atmospheric front occurred in the summer and winter seasons. Over the whole study period, for the summer months, the frequency of days with cold fronts increased at the expense of warm fronts, occluded fronts, and days with various front types. The reverse relationship was observed in the winter.

Table 9. The frequency [%] of the types of atmospheric front occurrence in southern Poland during the years 1951–2020

Characteristics	Frequency [%] of atmospheric fronts					
	Lack	wF	cF	oF	sF	vf
Lowest	42.9	3.3	8.7	1.1	0.0	2.7
Average	59.7	8.4	15.9	5.5	2.7	7.7
Highest	73.7	13.4	26.3	12.3	10.9	15.9
Range	30.8	10.1	17.6	11.2	10.9	13.2

Source: own study

These regularities resulted from seasonal changes in atmospheric circulation and the shift in the tracks of dynamic low-pressure systems towards the north in the summer months and towards the south in the cold season. These changes were not very significant (usually 1–3 days a month) and they were most clearly visible in the case of the frequency of warm and cold atmospheric fronts. However, it should be noted that the lowest variability in weather was found at the end of summer and in the autumn, especially October and August (62.6% and 62.9% days without atmospheric fronts, respectively). The regularities described were related to the seasonal equalisation of the temperature difference over the surface of the continents and the surface of the Atlantic waters (Parczewski 1965). This weakened the processes of cyclogenesis and increased the frequency of the extent of anticyclonic systems.

The long-term variability of the occurrence of atmospheric fronts moving over the study area can be characterised by two main features. The first is the direction and magnitude of changes depending on the type of front. The second is the division of the multi-annual period into two periods of more or less equal duration, characterised by a range of changes in the frequency of fronts of different magnitudes from year to year or during shorter periods of the multi-annual period.

The occurrence of "frontless" weather, and days with a warm front (wF), had the least pronounced change and an absence of discernible tendencies in long-term variability (Tab. 11, Fig. 4). The first half of the 1951–2020 period also experienced periods of several years with similar numbers of days without atmospheric fronts, separated by sudden changes in their number. From the 1980s, the changes were much less noticeable, and the decrease in the range of change for the number of days under consideration was also visible in the case of days with a warm front (wF).

The long-term variability showed a different trend for the frequency of cold atmospheric fronts (cF; Fig. 4). For the period under study, the years 1976–1990 clearly stand out. This period had a much greater frequency of cold fronts moving over southern Poland. For those years, they averaged 20.3%, while the average for the period 1951–2020 was around 16.0%. The abovementioned increase in frequency was observable for all seasons, although it was weakest in the winter. This change accompanied increased dynamics in the atmosphere, which occurred during that period.

Table 10. Average frequency [%] of the types of atmospheric front occurrence in southern Poland during 1951–2020

Type of front	Frequency [%] of atmospheric fronts																
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Spring	Summer	Autumn	Winter	Year
without fronts	58.9	56.3	58.8	58.9	59.4	59.6	59.7	62.9	62.0	62.6	59.2	58.0	59.1	60.7	61.3	57.1	59.7
wF	8.8	11.0	9.6	9.9	7.2	6.9	5.9	5.2	6.0	8.7	11.1	10.3	8.9	6.0	8.6	9.9	8.3
cF	13.5	13.1	13.7	14.4	17.7	18.6	19.4	17.7	18.8	15.6	13.9	14.5	15.3	18.6	16.1	13.7	16.0
oF	8.2	8.7	6.4	5.4	4.9	4.1	5.3	4.1	3.9	4.8	4.9	6.2	5.6	4.5	4.5	7.6	5.6
sF	1.9	2.4	2.4	3.4	3.2	3.5	3.4	4.0	2.5	2.4	2.0	1.7	3.0	3.6	2.3	2.0	2.6
vf	8.8	8.3	9.1	8.0	7.6	7.3	6.4	6.1	7.0	5.9	9.0	9.3	8.2	6.6	7.3	8.6	7.8
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: own study

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Table 11. The tendency [%/10 years] of changes in the frequency of occurrence of the types of atmospheric fronts in southern Poland during the years 1951–2020

Type of front	Tendency [%/10 years]																
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Spring	Summer	Autumn	Winter	Year
without fronts	-0.27	1.01	-0.29	**1.17**	0.30	-0.70	0.05	0.28	0.28	-0.56	0.13	-0.12	0.38	-0.12	-0.05	-0.60	0.10
wF	0.17	-0.24	-0.20	-0.44	-0.12	**0.90**	0.34	-0.07	-0.19	0.07	-0.28	0.29	-0.25	**0.39**	-0.13	0.00	0.02
cF	0.08	0.32	0.44	0.55	-0.11	-0.09	0.03	**-1.02**	**-0.95**	0.06	0.36	0.18	0.29	-0.36	-0.17	0.00	-0.01
oF	0.05	-0.45	-0.52	**-0.87**	-0.41	-0.72	**-1.05**	**0.00**	-0.01	-0.15	0.20	0.01	**-0.60**	**-0.59**	0.01	-0.23	**-0.33**
sF	**0.59**	0.34	**0.86**	**1.22**	**1.60**	**1.59**	**1.36**	**1.47**	**0.98**	**0.96**	**0.45**	**0.50**	**1.23**	**1.47**	**0.80**	**0.48**	**1.00**
vf	-0.61	**-1.10**	-0.28	**-1.64**	**-1.26**	**-0.98**	**-0.74**	-0.66	-0.12	-0.38	**-0.88**	-0.86	**-1.05**	**-0.79**	-0.46	**-0.82**	**-0.79**

bold text – statistically significant at the level of 0.05
Source: own study

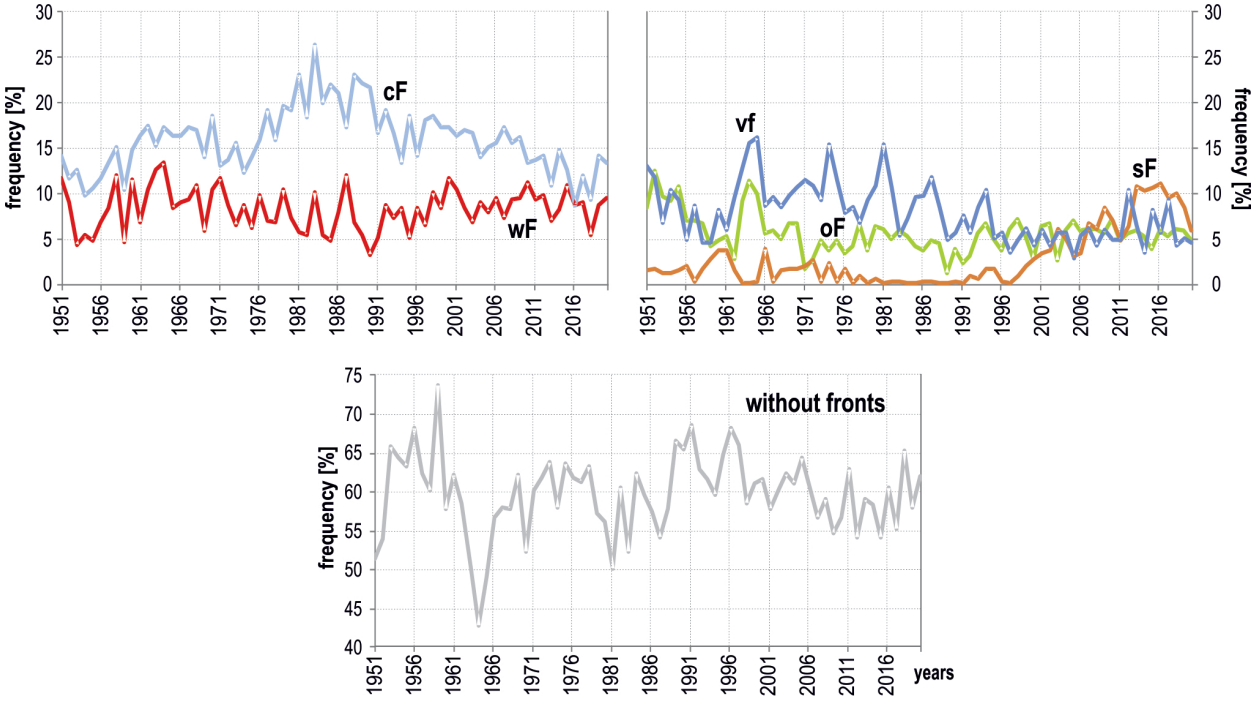


Figure 4. Frequency [%] of particular types of atmospheric front occurrence in southern Poland during the years 1951–2020 (descriptions in the text)
Source: own study

This was confirmed by a distinct increase in the frequency of days with various air masses (vAm), which was almost twice as high as in the remaining years of the whole study period (Fig. 3). The rapid and significant decrease in the number of cold atmospheric fronts over the area under consideration after 1983 means that the positive trend in changes to their frequency for the entire multi-year period (1951–2020) cannot be considered significant (Tab. 11).

In the case of the number of days with occluded (oF), stationary (sF), or various front types (vf), it was found that their frequency decreased from the 1950s until the end of the study period, or, in the case of stationary fronts, until the 1990s (Fig. 4). The post-1990 increase in frequency for various fronts (vf) and occluded fronts (oF) was too negligible to change the overall trend. However, the number increased significantly for stationary fronts. The result was a positive long-term trend in change, reflected by the annual, seasonal, and monthly values (Tab. 11).

Summary

The regularities in the occurrence of the elements that characterised the circulation of the atmosphere over southern Poland described above reveal that the elements vary greatly both intra-annually and in the long term. This also provides evidence for the complicated nature of their joint effect on the climate of the study area.

The analysis of the occurrence of the different types of atmospheric circulation has confirmed the prevalence in Poland

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(Osuchowska-Klein 1987; Bartoszek 2017a) and Europe (Chen 2000; Linderson 2001; Anagnostopoulou et al. 2004) of anticyclonic situations and air advection from the west. The study has also found that statistically significant changes in the occurrence of circulation types since 1874 mainly involved a decline in the frequency of anticyclonic situations when it comes to both their annual and seasonal values (except for spring), and the advection of air from the west (especially in summer). This is confirmed by a study by Niedźwiedź and Ustrnul (2021), which indicates a strong increase in the cyclonic index over southern Poland during the study period, and a decrease in the zonal circulation index (particularly strong in summer). A slight decline was also noticeable for the advection of air from the east, which may be related to the decrease in the frequency of advection from the east and southeast in the eastern part of Central Europe (Bartoszek 2017a). At the same time, there was a noticeable increase in the frequency of central anticyclones (Ca) and cyclonic troughs (Bc) and, especially in summer, advection of air from the south, which was partially confirmed by Bartoszek's research (2017b).

The results concerning the frequency of air masses and atmospheric fronts produced by the present study confirm the regularities behind their occurrence in Poland known from the literature (Więcław 2010; Kierklo 2012; Sykulski & Bielec-Bąkowska 2017); and they reveal some regional differences and variations caused by different study periods. However, attention should be drawn to long-term changes in the occurrence of the circulation elements being researched. In the case of air masses, the study has found a decrease in the share of mP and omP, as well as of cP (mainly in summer). This may be related to the observed decrease in the frequency of westerly circulation and air advection from the east and south (Bartoszek 2017a). In parallel, there is a noticeable increase in wmP (mainly in the last two decades) and the frequency of vAm (especially for the period 1975–1995). The trends in the changes described are attributable to supra-regional changes in circulation, which is confirmed by the results of research from other regions of the country (Bartoszek 2017c; Kaszewski et al. 2018). Changes in the occurrence of air masses go hand in hand with changes in the frequency of occurrence of atmospheric fronts. However, the only significant changes comprise a slight decrease in the frequency of occluded fronts and various fronts moving over the study area. A distinct change is represented by a strong increase in the number of days with stationary fronts. The frequency has increased from less than 2–3% annually to over 10% in the last two decades. An analysis of the changes in the total number of days with fronts has revealed that they depend on circulation conditions over shorter observation periods and on the region over which they occur (Niedźwiedź 2000; Więcław 2013; Sykulski & Bielec-Bąkowska 2017).

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