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THE VARIABILITY OF ATMOSPHERIC CIRCULATION OVER POLAND IN THE YEARS 1950–2021

PIOTR PIOTROWSKI[1]

Abstract. The Jenkinson and Collison method, originally used to automate the weather type classification developed by Lamb for the British Isles, was used to develop a catalog of atmospheric circulation types in Poland. Sixteen directional atmospheric circulation types (ACTs) from this method were used for the characterization of circulation conditions in Poland. They were determined based on the direction of the geostrophic wind and the distinction between cyclonic and anticyclonic circulation based on shear vorticity. Both circulation indices were calculated based on data from ERA5 reanalysis, namely the 850 hPa geopotential height. Atmospheric circulation types were determined for a total of 195 grid points, including 109 located in Poland. The study presents an analysis of spatial and temporal changes in circulation conditions in the years 1950–2021 in Poland, which indicates an increase in the frequency of anticyclonic circulation in Poland since the 1980s, notably W and NW advection. The Sc, SWc and Wc types stand out among the cyclonic types with the greatest decrease in frequency across the entire territory of Poland. The anticyclonic west circulation stands out for its statistically significant increase in frequency in winter throughout the analyzed area.

Key words: atmospheric circulation, automatic method of determination of atmospheric circulation, spatial and temporal variability of atmospheric circulation, Poland

Introduction

Atmospheric circulation is undoubtedly an important factor in shaping the weather and, in the long run, also the climate. The territory of Poland is in the central part of Europe; in this part of Europe, the direction of the inflow of air masses changes quite often, which is reflected in the high dynamics of changing weather conditions over Poland. The frequency of the inflow of air masses from certain directions may be subject to long-term changes. This may also result in changes in weather conditions and even, in the longer-term, a climate change.

The dominance of lowlands in Poland facilitates the zonal flow of air masses. Mountain ranges are found along the southern border of the country, modifying to some extent the Meridional air flow and the spatial distribution of precipitation total on the windward and leeward sides of mountains. Similar effects of landforms on precipitation can also be observed in and near the lakeland belt in the north of the country and upland areas in the south.

The study uses geopotential height of 850 hPa level to describe circulation conditions. This choice was selected with the intention of minimizing the effect of friction on the direction of air flow and omitting small-scale deformations of the pressure field at a lower level. Ojrzyńska (2012) draws attention to the possibility of a problem in determining the lower cyclonicity in mountainous areas when considering data from the 950 hPa level, so in her study she uses data from the 850 hPa level.

Multiannual variability of atmospheric circulation in Poland and Central Europe have been studied using different methods of description of atmospheric circulation by Osuchowska-Klein

[1] University of Lodz, Faculty of Geographical Sciences, Department of Meteorology and Climatology, Narutowicza 88, 90-139 Lodz; e-mail: piotr.piotrowski@geo.uni.lodz.pl, ORCID: 0000-0003-2168-1645

(1986, 1987), Niedźwiedź (1995), Piotrowski (2007, 2009), Przybylak and Maszewski (2009), Filipiuk and Kaszewski (2010), Bartoszek (2017), Kożuchowski and Degirmendžić (2018) and Niedźwiedź and Ustrnul (2021). All the analyses conducted by Niedźwiedź and Ustrnul (2021) confirmed that Poland is significantly affected by westerly circulation, which has a major influence on the formation of the climate. From the end of the nineteenth century to the present day, it has been found to exhibit large fluctuations and a generally weak increasing trend.

The analysis of atmospheric circulation variability in Poland (Piotrowski 2017) showed that significant changes in conditions can occur over a relatively small area. Therefore, an analysis of the variability of conditions over Poland was made based on data from 109 points evenly distributed across the country. The variability of circulation conditions in the form of climatic fluctuations has prompted many researchers to try to distinguish circulation epochs (including Osuchowska-Klein 1986, 1987; Degirmendžić *et al.* 2000). Kożuchowski (1989), for example, detected tendencies to deviations in 6-, 8- and 10-year periods. Kożuchowski (1993) also attempted to assess the links between the frequencies of the macrotypes distinguished by Girs (1948) with Osuchowska-Klein atmospheric circulation types and noted the recurrence of multi-year trends in the course of frequencies of certain atmospheric circulation patterns. An example of the analysis of atmospheric circulation variability in the annual cycle can be found in the studies of Osuchowska-Klein (1973) and Kaszewski (1983). Kaszewski distinguished, based on Lityński classification, eight periods of the year that differ in terms of atmospheric circulation. Nowosad (1998, 2004) also conducted similar analyses.

In this paper, the objective scheme classification of atmospheric circulation types offered by Jenkinson and Collison (1977) issued. Previously, some circulation indices from this method (air flow direction and shear vorticity) were used by Dessouky and Jenkinson (1975) to create an objective daily catalog of surface pressure, flow and vorticity indices for Egypt to be used in monthly rainfall forecasting. Jenkinson and Collison (1977) automated the circulation weather types (CWTs) that had been distinguished by Lamb (1972) for the British Isles. Lamb original classification distinguished 27 circulation weather types based on daily sea-level pressure. To this end, two circulation indices were used: geostrophic wind and shear vorticity. The Jenkinson and Collison method is quite simple to calculate and has been widely used to analyze circulation conditions in various parts of Europe (Jones *et al.* 1993; Chen 2000; Spellman 2000; Trigo, DaCamara 2000; Linderson 2001; Goodess, Jones 2002; Post *et al.* 2002) and other parts of the world (Sarricolea *et al.* 2018).

The main objective of the analysis is to check the multiannual variability in frequency of the atmospheric circulation types in the years 1950–2021 in Poland. For this purpose, the multiannual variability in the frequency of ACTs was checked at five selected points in Poland and trends for the whole of Poland. In addition, the differences in annual frequency of ACTs between the five selected points in Poland were checked. Statistics relating to the annual, seasonal and monthly frequency of ACTs in selected points in Poland were also presented.

Data and methods

Circulation conditions were analyzed based on 16 directional types determined using the Jenkinson and Collison method (1977). The number of types distinguished is subjective. A similar division into 16 types was proposed by Lamb (1972) with a possible extension to hybrid and unclassified types. According to Bogucki (1992), on a regional scale, such the division seems to be the most appropriate. The method of determination of circulation types used in this paper is based on two circulation indices – geostrophic wind and shear vorticity. The direction of geostrophic wind and shear vorticity were calculated for 195 points (Fig. 1) based on geopotential height of the 850 hPa level from 32 grid points. In the original paper (Jenkinson, Collison 1977), 16 grid points with a resolution of 5×5 degrees latitude and longitude were used. For the purposes of this study, the same resolution of points was used, while the total number of points was increased to 32 in order to increase the sample of pressure-field data. The same number of points was considered, but with lower spatial resolution, in Goodess and Palutikof (1998) and Goodess (2000). The studies by Piotrowski and Jędruszkiewicz (2013) and Bartoszek (2017) present the method used to calculate the mentioned circulation indices and the distribution of grid points. Data come from the ECMWF reanalysis (CDS 2022). In this study, data are used from the ERA5

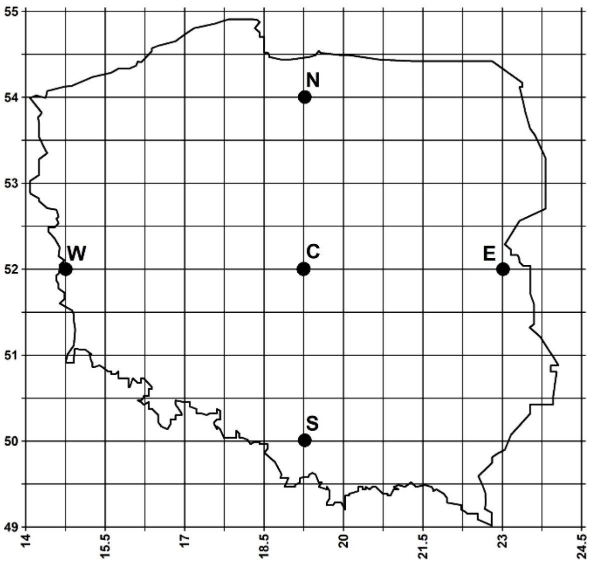

Fig. 1. Grid points (at the intersection of parallels and meridians) used to determine atmospheric circulation types
Points C, W, E, N, S were used to analyze temporal and spatial variability of the types of circulation

reanalysis for 1950 to 1978 in a preliminary version (Bell *et al.* 2021), as well as data for the years 1979–2021 (Hersbach *et al.* 2020). In this study, the 850 hPa level is chosen to analyze the circulation conditions over Poland because this level represents the middle atmospheric pattern where surface friction has little or no impact on flow direction.

The data used in the calculations of circulation indices have a spatial resolution of 0.25°× ×0.25°. The data of geopotential height of 850 hPa level cover years from 1950 to 2021. The 16 atmospheric circulation types were determined for: 00:00, 06:00, 12:00 and 18:00 UTC. The choice of four terms in a day, instead of daily average values used in the original study by Jenkinson and Collison (1977), is motivated by the possibility of using the data for, e.g., circulation dynamics analyses. The signature of 16 circulation types refers to the direction of geostrophic wind and cyclonic or anticyclonic circulation (e.g., Wa – – a westerly flow and anticyclonic circulation). Atmospheric circulation types were determined for 195 points (among them 109 points in the area of Poland) with a resolution of 0.50° latitude and 0.75° longitude (Fig.1). This choice of resolution was preceded by spatial analysis of the compatibility of atmospheric circulation types (Piotrowski 2017). Out of 109 points located in Poland, five points were selected whose coordinates are indicated by the letters: W, N, S, E and C (Fig. 1), and these were used for a more detailed analysis of multiannual variability of ACTs frequency.

The frequency of ACTs was calculated using data for all four terms in a day without considering the sequence of circulation types.

A linear trend was used to analyse variability of ACTs frequency in Poland in the years 1950– –2021. The statistical significance of annual trends in the frequency of individual types of atmospheric circulation was checked at a significance level of α=0.05 using the Mann–Kendall test.

The frequency of atmospheric circulation types

Zonal circulation dominates over Poland in all seasons of the year; it appears least frequently in spring (Fig. 2, 3). Over the center of Poland, in all seasons of the year, anticyclonic circulation from the W, NW and SW directions occurs most often. Throughout the year, the total frequency of advection from these directions reaches 40%. In winter and spring, advection of air masses from SW during cyclonic circulation occurs quite often. The frequencies of advection from the S and N directions are similar to one another for each season, during cyclonic and anticyclonic circulation alike. The advection of air masses from the east, north-east and south-east appears least frequently – – 5.5%, 5.9% and 6.1%, respectively. The share of anticyclonic circulation is greater than that of cyclonic circulation in all seasons. Anticyclonic circulation occurs most often in summer and autumn.

The dominant type of Wa circulation occurs most often in August and September (Fig. 3). The distinct dominance of the Wa, NWa and SWa types persists from June to January. From February, other types of circulation begin to appear more frequently. It can therefore be concluded that spring is the most unpredictable season in terms of circulation. During cyclonic circulation, as with anticyclonic circulation, advections from the W, NW and SW directions prevail in all months. Among the remaining cyclonic types, the Nc and Sc types stand out. The Nc type most often appears in February and between April and July. The Sc type occurs most often in November, which is associated with the shift of the polar front to the south of Europe. In this month, there

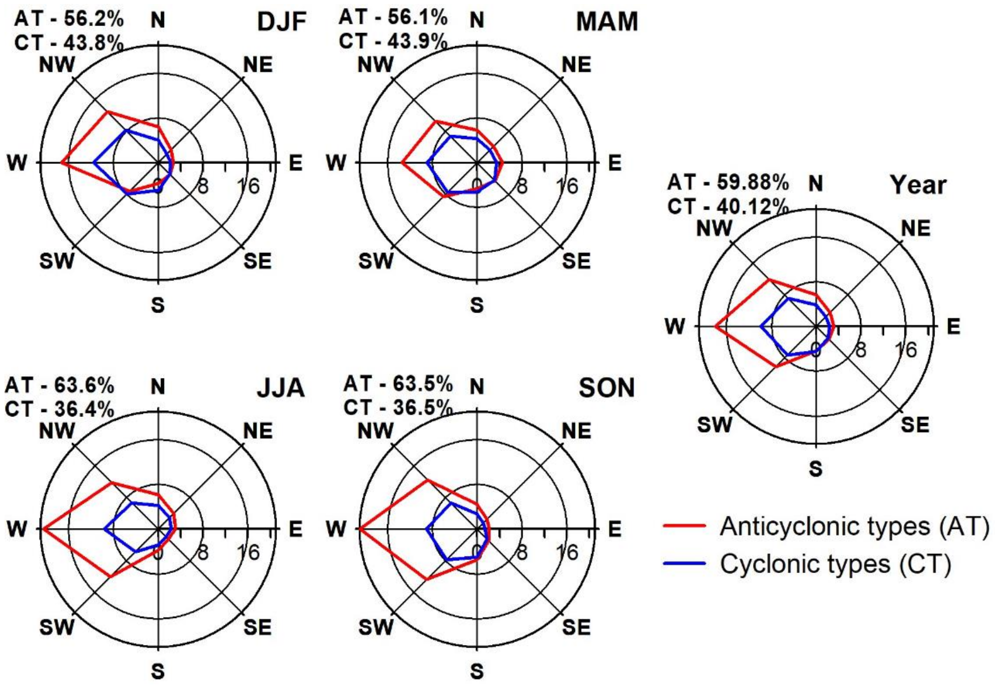

Fig. 2. Seasonal and yearly relative frequency of atmospheric circulation types in the center of Poland (point C)
AT – anticyclonic types, CT – cyclonic types, DJF – winter, MAM – spring, JJA – summer, SON – autumn

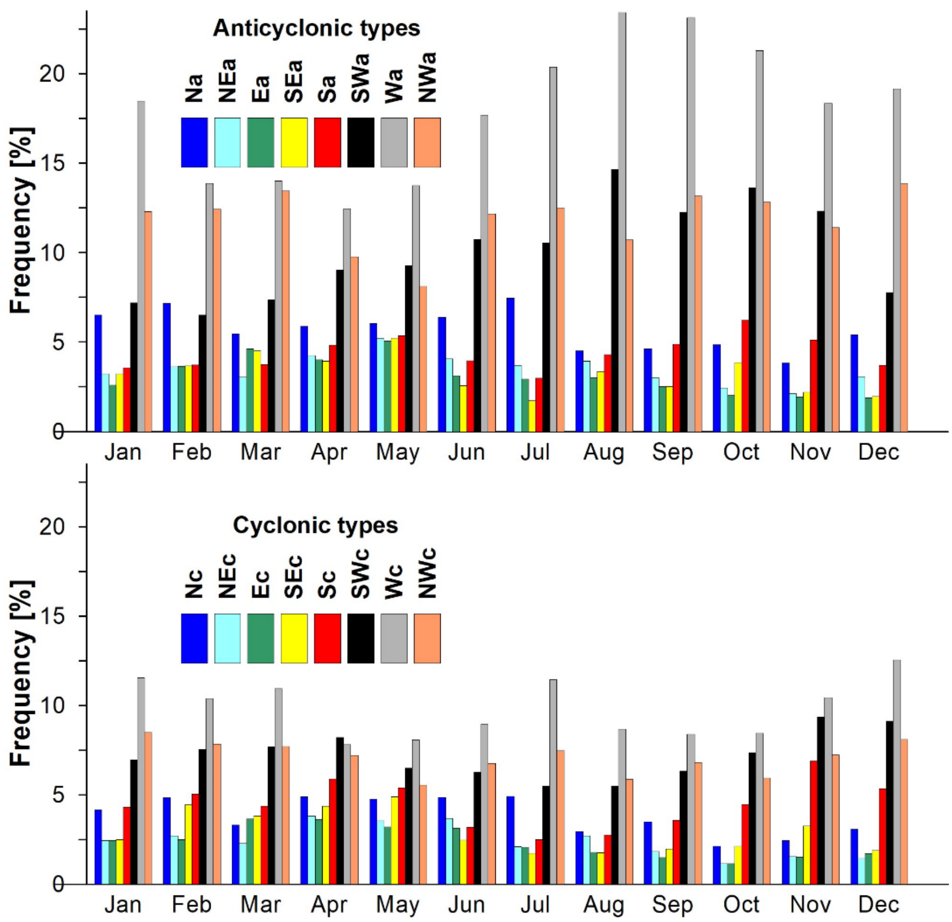

Fig. 3. Monthly frequency of atmospheric circulation types in the center of Poland (point C)

is also an increase in the incidence of the SEc type. A similar situation appears in April and May.

The variability of atmospheric circulation types in the years 1950–2021

Cumulative deviations from multiannual average were used to analyze the frequency variability of individual types of atmospheric circulation (Fig. 4, 5). This simple method makes it possible to capture the moment of a more pronounced change in the frequency in the analyzed period relative to the multiannual average. To analyze the variability of the frequencies of atmospheric circulation types, data from point C located more or less in the center of Poland and four points located near the northern, southern, western and eastern border of the country were used (Fig. 1).

A significant increase in the frequency of anticyclonic circulation from the W and NW directions has been visible since the beginning of the 1980s, whereas since the beginning of the 1990s there has been a slightly smaller increase from the E and NE directions. Somewhat later, in the late 1990s, the incidence of the SWa type also increased. Almost all types of cyclonic circulation have appeared progressively less often in the 21st century. Some types of cyclonic circulation have recorded a decrease in frequency since the end of the 1970s (NEc, Ec types). The patterns of cumulative frequency deviations are synchronous at all five analyzed points during all types of circulation. This synchronicity is somewhat disturbed between the end of the 1970s and the end of the 1980s only, and only for anticyclonic circulation from the N direction as recorded at the point representing the west of the country.

The differences in the frequency of ACTs between the five selected points are highest during

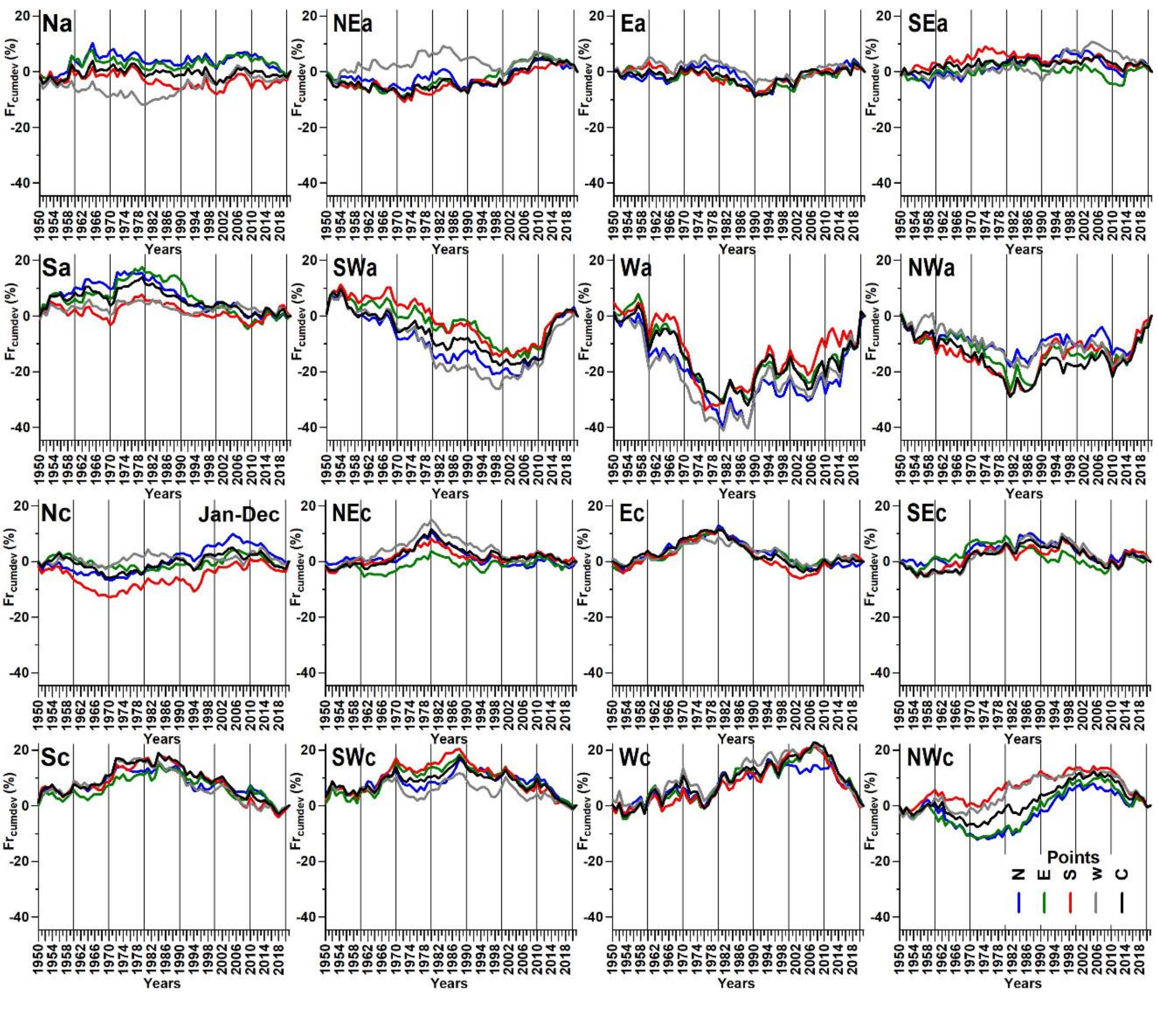

Fig. 4. Cumulative deviations from mean of the annual frequency and annual relative frequency (numerical values) of atmospheric circulation types in selected points (points C, W, E, N, S according to Fig. 1)

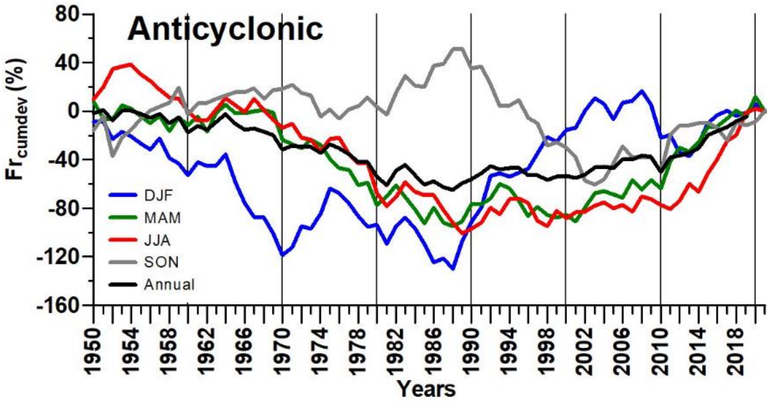

Fig. 5. Cumulative deviations from mean of the annual and seasonal frequency of anticyclonic circulation in the point C

DJF –winter, MAM – spring, JJA – summer, SON – autumn

western and north-western advection of air masses and lowest during eastern and north-eastern advection (Fig. 4).

An increase in the frequency of anticyclonic circulation on an annual basis has been visible since the mid-1980s, but a slightly greater increase has been visible for the last 11 analyzed years (Fig. 5). In spring and summer, the pattern of anticyclonic circulation frequency is very similar; its increase was slow from roughly the mid-1980s and has accelerated over the last 11–12 years. The increase in frequency in summer in the years 1986–2021 was 0.32% per year, whereas in spring it was lower (0.11% per year). In autumn, the increase in frequency of anticyclonic circulation appeared as late as in 2003; however, this increase has been interspersed with years in which its frequency has been below the multi-year average. Earlier, in the years 1989–2003, there had been a sharp decrease in the frequency of anticyclonic circulation by 0.29% per year. In winter, there was a persistent and marked increase in the frequency that prevailed for the years 1989–2008.

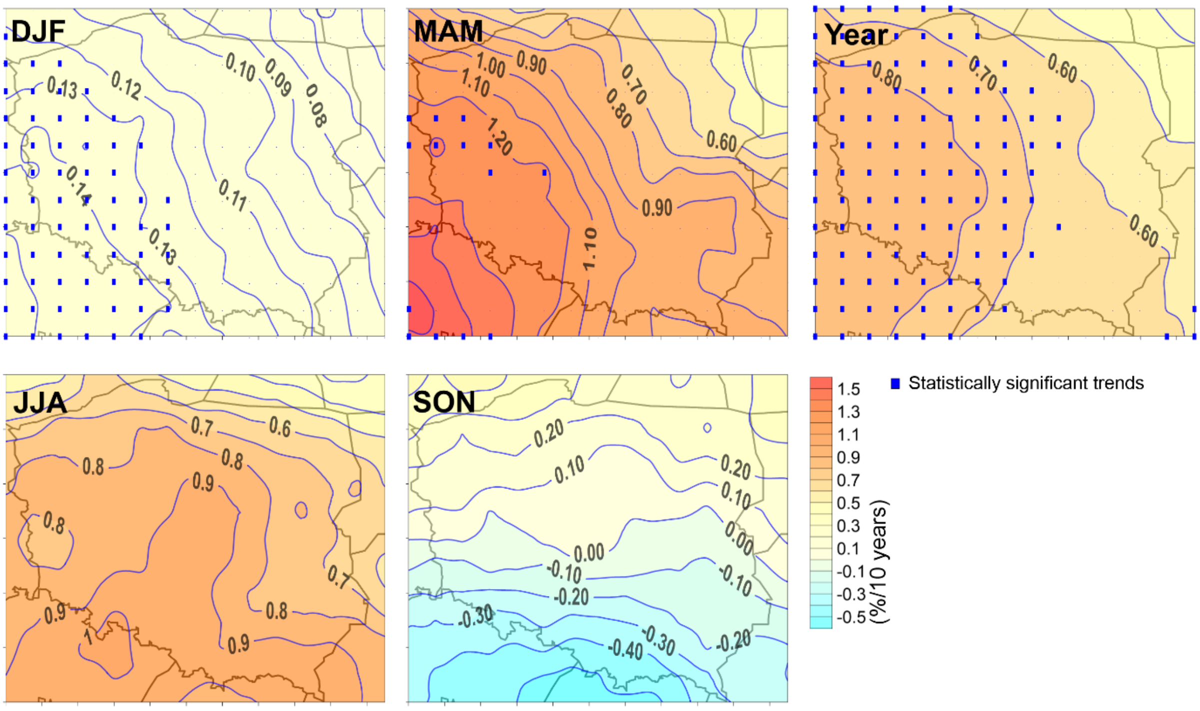

Fig. 6. Annual and seasonal trends of the frequency of the anticyclonic circulation types

DJF –winter, MAM – spring, JJA – summer, SON – autumn

A more detailed spatial analysis of the annual trends of changes in frequency allowed the pace of these changes in the analyzed area to be verified. The increase in the annual frequency of anticyclonic circulation is statistically significant across almost all of Poland, with the exception of its eastern parts (Fig. 6). The greatest increase in the frequency of anticyclonic circulation occurs in spring in the western and south-western part of the country; however, it is statistically significant only at a few points. A smaller increase in the frequency of anticyclonic circulation is recorded in winter, but it is statistically significant at more points in the above-mentioned parts of Poland. In summer, an upward trend in anticyclonic circulation is also visible throughout Poland, but it is statistically significant only at a few points in the south of the country. No significant statistical trends have been observed in autumn; no upward trends in the frequency of anticyclonic circulation have been observed in the southern half of Poland.

The largest area of Poland is subject to a significant downward trend in the annual frequency of Sc and SWc types (Fig. 7). Among anticyclonic types, the Wa type (northern part of the country) and the NWa type (in the central and south-eastern parts of the country) are distinguished by a significant increase in frequency in a large area of Poland.

For the analysis of statistical significance of frequency trends in seasonal terms, the types of atmospheric circulation selected were those whose number of points at which statistically significant changes were found is the highest in a given season (Fig. 8).

In winter, the increase in the frequency of the Wa type is statistically significant at all analyzed points. In spring, in the eastern half of the country, a significant decrease in the frequency of the Sa type is visible, while in summer most of Poland is subject to a significant decrease in the frequency of the NEc type. In autumn, significant decreases in the frequencies of Na, NEc and Wc types appear at only a few points.

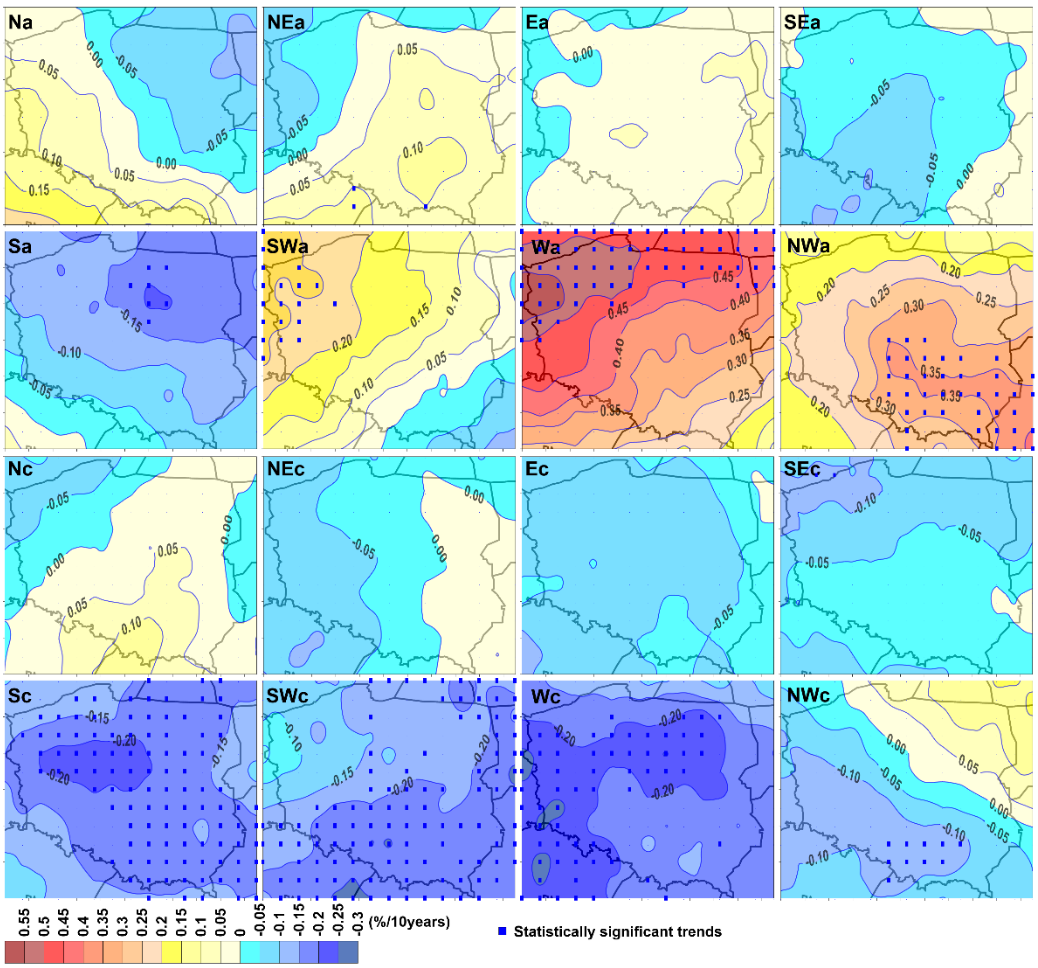

Fig. 7. Annual trends of the frequency of the atmospheric circulation types

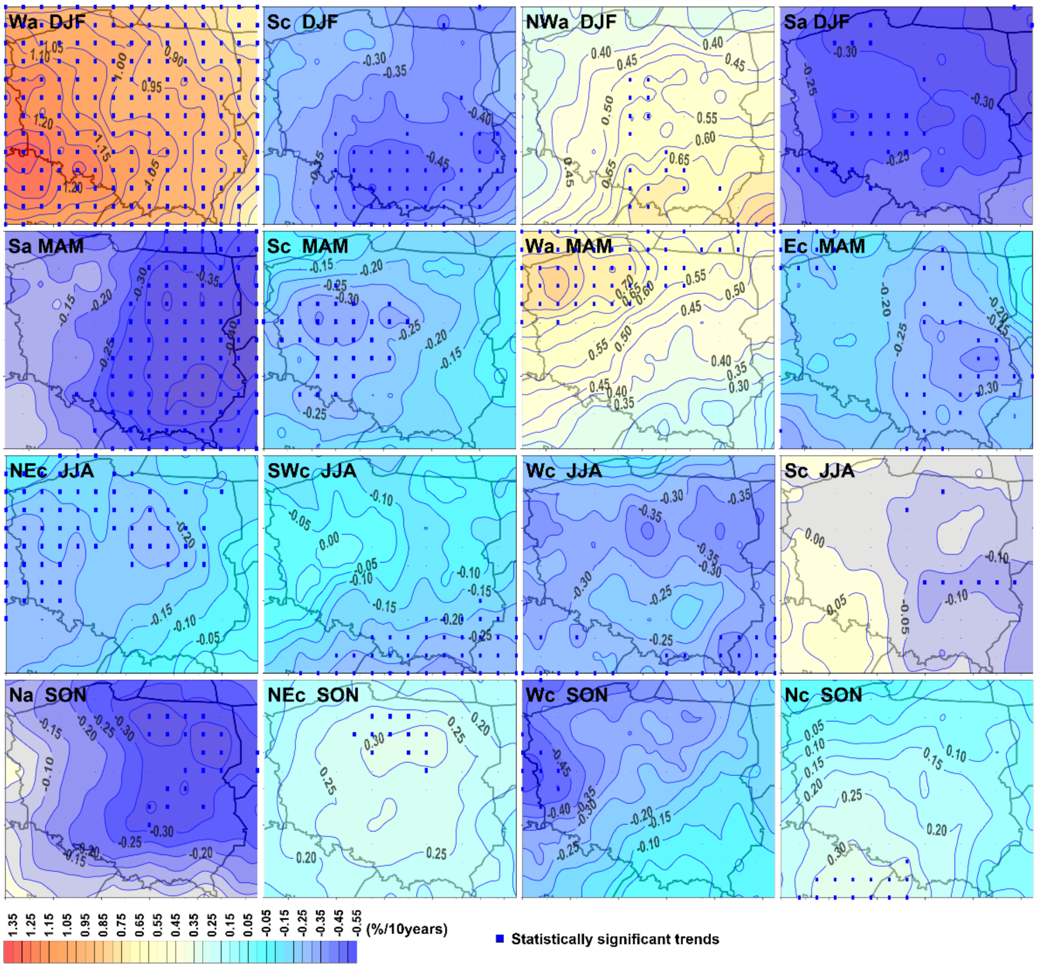

Fig. 8. Seasonal trends of the frequency of the selected the atmospheric circulation types
DJF – winter, MAM – spring, JJA – summer, SON – autumn

Conclusions and discussion

The results of the frequency analysis of atmospheric circulation types and their variability over time are difficult to compare against other studies due to differences in their typological criteria and numbers of types. For example, Niedźwiedź classification for the upper Vistula River basin comprises 21 types (1981). In his classification, the annual average frequency of occurrence of air advection from west in the period 1951–1990 is 6.6% lower (Nowosad 1998) compared to the frequency calculated in this study for the same period at point S (Fig. 1). On the other hand, a confirmation of the generalized patterns of atmospheric circulation over Poland, e.g. the domination of zonal circulation in winter and summer, can be found in the study by Kożuchowski (2003). Other examples of the influence that methodological differences, input data and length of analyzed period have on the frequency of atmospheric circulation types can be seen in the results of Piotrowski (2007) and Bartoszek (2017), whose analyses are based on the same Jenkinson and Collison method. Piotrowski used a method developed to automate the classification of atmospheric circulation types of Osuchowska-Klein (1978, 1991) and mean sea-level pressure (MSLP) data from NCEP-NCAR Reanalysis. This method differs from the classification of the number of circulation types presented in this paper, the methodological assumptions related to spatial coverage, the input data, and the period on which basis it was developed. For example, the course of frequency variability over the same period (1958–2005) of comparable types (Wa, Sc, SEc, SWc) is similar at 850 hPa and MSLP levels, despite different data sources.

Differences occur only in the frequency of types due to differences in typology. Bartoszek (2017) partially employs assumptions proposed by Lityński (1969) to describe atmospheric circulation for East-Central Europe based on 23 circulation types and data of daily mean obtained MSLP from The Twentieth Century Reanalysis version 2 (20CRv2). The distribution of the frequency directional circulation types in the present paper shows the dominance throughout the year of circulation from a westerly direction, while in the Bartoszek study it appears only in the winter months. Differences in frequency of circulation types are due to different the lengths of the analysis periods, pressure levels, the number of circulation types and perhaps also input data.

The lack of unification of the description of atmospheric circulation associated with the subjective approach to the description of atmospheric circulation can, on the one hand, promote the appearance of problems in comparative analysis, while on the other hand, it creates opportunities to seek the best possible typological solutions.

The progressing global warming poses new challenges for climatologists while also providing new material for research. The relationships between atmospheric circulation and weather bear the character of interdependencies. On the one hand, atmospheric circulation affects individual elements of weather, while, on the other hand, changes in the substrate temperature may affect the pressure field and, consequently, the frequency of the inflow of air masses from a specific direction (Czaja, Frankignou 1999; Zhao *et al.* 2001). An analysis of changes in the thermal and humidity characteristics of air masses flowing over the territory of Poland, especially air masses from the Arctic, where the temperature increase is the most visible, may also be an interesting direction for research.

There is statistically significant increase in the frequency of Wa type throughout the analysis area in winter. The reason for the more frequent occurrence of Wa type in winter can be seen in the shifting of the Azores High towards the European landmass (Falarz 2019). According to Marsz (2002), such a situation appears when pressure drops in the Icelandic Low and, at the same time, pressure rises in the Azores High. This situation often favors westerly anticyclonic circulation over Poland.

At point S, the increase in Wa type frequency over the last decade is invisible compared to the other points, while the Wc type frequency over the entire study area shows a marked decrease over this period. This course is very similar to those of Niedźwiedź and Ustrnul (2021) analysis. The authors noted that the annual decreasing trend in the westerly circulation index is an effect of significant weakening of the Wi index in summer months.

If the Gulf Stream does not significantly change its position in the Atlantic and the upward trend in the frequency of the most frequent Wa type continues, warm winters with a small proportion of snowfall should be expected in the near future. The impact of the Gulf Stream on air temperature in Poland is evidenced by a correlation analysis conducted by the Marsz (2007). Values of linear coefficients of the correlation between the index of climatic Gulf Stream activity proposed by Marsz and annual air temperature in Poland range from about 0.3 in the south-west of Poland to more than 0.4 in the north. The results of the analysis indicate that the correlation between index of climatic Gulf Stream activity and air temperature is unstable in time. The results presented by Marsz and Styszyńska (2021) indicate that the changes in the annual sea surface temperature values in the North Atlantic explain about 46% of the annual air temperature and sum of sunshine duration variance in Poland, 27–30% of the relative humidity and wind speed variance, and 12–23% of the annual variance of cloud cover, sum of precipitation and sea-level pressure.

In winter, a significant increase of warming in the period 2081–2100 is forecast (Filipiak *et al.* 2012). Another future projection (using data from the RACMO2 model for the period 2021–2050) indicates in winter far more frequent cyclonic circulation from the west and south-west (Jędruszkiewicz, Piotrowski 2012).

An increase in the frequency of anticyclonic circulation since the mid-1980s visible. The same period also exhibited an increase in air pressure at the station in Cracow (Bielec-Bąkowska, Piotrowicz 2019). The increasing trend of anticyclonic circulation in the western and central parts of Poland is a cause for concern, because anticyclonic circulation may contribute to a decrease in precipitation totals in areas where water scarcity is observed, especially in the growing season (Łabędzki, Ostrowski 2018).

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