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Impact of macro-scale circulation types on the occurrence of frosty days in Poland

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Abstract. The research aimed at determining the variability of occurrence of frosty days in Poland and defining the impact of macro-scale circulation types on the occurrence of these days from December to March. The study used daily data on the minimum, maximum and mean daily air temperature for 15 stations located in Poland from 40 winter seasons between 1970/71 and 2009/10. During that period, a decrease in the number of frosty days was noticed across the greater part of Poland; still, these changes were not statistically significant. The conducted research study showed that, of macro-scale circulation types, the North Atlantic Oscillation and Scandinavian type had the most significant impacts on the number of frosty days in Poland.

Key words:
winter,
frosty days,
macro-scale circulation types,
Poland

Introduction

The authors of the Fifth Report of the IPPC (2013) indicate with high probability that in the 21st century there is going to be an increase in frequency of extreme weather phenomena in many regions of the world, including heat waves and heavy precipitation events. Previous research on air temperature changes in many regions of Europe has shown an upward trend (Brázdil et al. 1996; Fortuniak et al. 2001; Wibig, Głowicki 2002; Klein Tank, Können 2003; Degirmendžić et al. 2004; Kürbis et al. 2009; Michalska 2011; Tylkowski 2013). One manifestation of warming is the increasingly frequent occurrence of hot days and heat waves (Kejna et al. 2009; Avotniece 2010; Kyselý 2010; Kossowska-Cezak, Skrzypczuk 2011; Lhotka, Kyselý 2014; Tomczyk, Bednorz 2014; Tomczyk 2014) and a decrease in the number of frosty and very frosty days (Cebulak, Limanówka 2007; Bielec-Bąkowska, Łupikasza 2009; Avotniece et al. 2010; Mužíková et al. 2011; Stěpánek et al. 2011; Bielec-Bąkowska, Piotrowicz 2013; Kossowska-Cezak 2014).

The climate of Europe is shaped by circulatory factors to a great extent—mainly through frequency of inflows of specific types of air masses (Więcław 2010). The Climate Prediction Center identifies four macro-scale circulation types in the Euro-Atlantic sector shaping the weather in Central Europe (Barnston, Livezey 1987):

1) North Atlantic Oscillation – NAO,
2) East Atlantic – EA,
3) East Atlantic/Western Russia – EA/WR,
4) Scandinavian – SC.

The most important of these is North Atlantic Oscillation (NAO), whose influence on the climate of Europe is considered to be powerful; especially in the winter season (Wibig 2001; Bednorz 2009).

Many studies have shown the significant impact of the North Atlantic Oscillation on the variability of temperature (Wibig 2000; Marsz, Styszyńska

2001; Huang et al. 2006; Ustrnul, Czekierda 2007; Kejna et al. 2009), on precipitation (Styszyńska 2001; Wibig 2001), on cloud cover (Adamczyk 2007) and on atmospheric pressure (Koźmiński, Michalska 2012). Additionally, Bednorz (2002, 2009) and Falarz (2007) showed a statistically significant impact of the NAO on the formation of snow cover, although, as the former of those authors indicated, this impact decreases eastward (Bednorz 2004). On top of this, Wrzesiński (2005, 2011) confirmed the strong influence of the NAO on the conditions of formation of the mouths of Polish and European rivers, while the research results of Wrzesiński et al. (2013) confirmed that changes in NAO intensity have an impact on parameters of ice phenomena (except their beginning) on selected Polish lakes. The influence of macro-scale circulation types other than the NAO on the weather and climate of Central Europe is undoubtedly weaker and requires further detailed research (Bednorz 2006, 2009).

The aim of the study was to determine the variability of occurrence of frosty days in Poland between 1970/71 and 2009/10 and to define the impact of macro-scale circulation types on the occurrence of these days from December to March.

Data and Methods

The study used daily data on the minimum, maximum and mean daily air temperature for 15 stations located in Poland (excluding mountain areas) from 40 winter seasons between 1970/71 and 2009/10 (Fig. 1). The data were obtained from the records of the Institute of Meteorology and Water Management's National Research Institute.

Fig. 1. Location of meteorological stations

On the basis of the obtained data, mean temperature values for particular winters were computed, and frosty days were distinguished. A frosty day was defined as a day with maximum temperature < 0°C. Subsequently, their variability in the analysed multiannual period was investigated and trends of change were determined. In the next stage, correlation coefficients between a monthly number of frosty days and monthly index of circulation type for winter (December-March) were defined. The methodology of distinguishing circulation types at a height of 500 hPa was based on principal component analysis with principal component rotation (Barnston and Livezey 1987; Bednorz 2009). The indices of circulation types were obtained from the Climate Prediction Centre and the National Oceanic and Atmospheric Administration (NOAA). The mean values of the above-mentioned characteristics for the analysed period were mapped by means of contour lines.

Results

Mean maximum, minimum and daily air temperature

The spatial distribution of mean air temperature in the winter season (December-March) shows that it declines from the west to the northeast. The lowest mean temperature in the analysed multiannual period was recorded in the Suwałki Region (< -2.0°C), while the highest was in north-western Poland (Świnoujście 1.5°C) (Fig. 2). In the analysed 40-year period, the coldest winter season was recorded in 1995/96 (-4.2°C), 1984/85 (-3.9°C) and 1986/87 (-3.8°C). On the other hand, the warmest winters were observed in 1989/90 (3.6°C) and 2006/07 (3.4°C). The course of mean winter air temperature shows considerable fluctuations from year to year; however, that changeability is similar across the investigated area, as proven by the insignificant diversity of standard deviation values, which range from 1.8 to 2.2°C. A similar spatial pattern and multi-year course is shown by the mean, maximum and minimum air temperature in the winter season. Their lowest values were recorded at the north-eastern ends (Suwałki, Tmax 0.5°C, Tmin -5.1°C), and their highest in the north-western part of Poland (Świnoujście, Tmax 4.0°C, Tmin -0.8°C) (Fig. 2). In the analysed period, there was an increase in the winter maximum, minimum and mean daily air temperature recorded in Poland; still, it was not statistically significant.

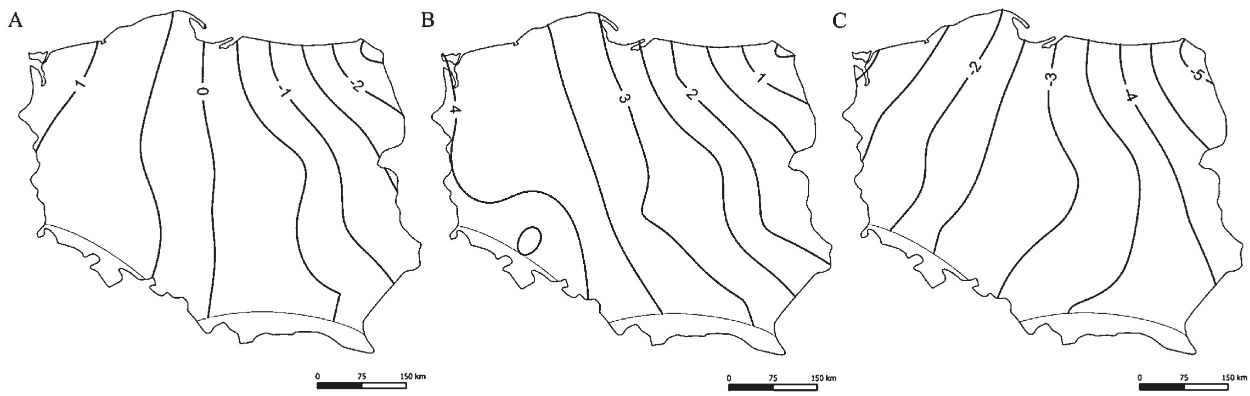

Fig. 2. Mean daily (A), maximum (B) and minimum (C) air temperature in the winter season (December-March)

Frosty days

The average number of frosty days in the analysed period in Poland was from less than 20 in the north-west to more than 50 in the north-east (Fig. 3). On average, the value of this index for the analysed area was 34 days. The annual number of frosty days increased from west to east; that is, in the direction of the weakening of the climate's oceanic characteristics and strengthening of continental features. The course of seasonal numbers of frost days in the particular stations shows considerable year-to-year fluctuations. Changeability of seasonal number of days within the country was diverse, which is shown the by diverse values of standard deviation amounting to 14-20 days. In eastern Poland, during frosty winters, there were over 90 days with Tmax < 0°C recorded, while during mild winters at the seaside and in the west of Poland, there were only a few frosty days (e.g. 1 day in Łeba). Winters with the lowest number of frosty days in the analysed 40-year period occurred in: 1974/75, 2006/07 and 1988/89 (Fig. 4). On the other hand, the seasons of 1995/96 and 1984/85 were extreme with regard to the number of these days. In the analysed period, no statistically significant changes in annual number of days with Tmax < 0°C were found. The variation coefficient reached its highest values within the area of the lowest average annual number of above-mentioned days (Świnoujście 78%, Łeba 72%). On the other hand, the most stable values of annual number of frosty days were recorded in north-eastern Poland where the variation coefficient was approximately 37%.

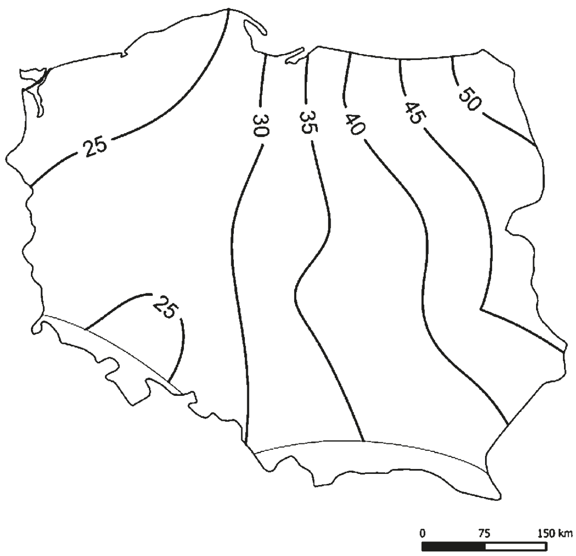

Fig. 3. Average number of frosty days in the winter season

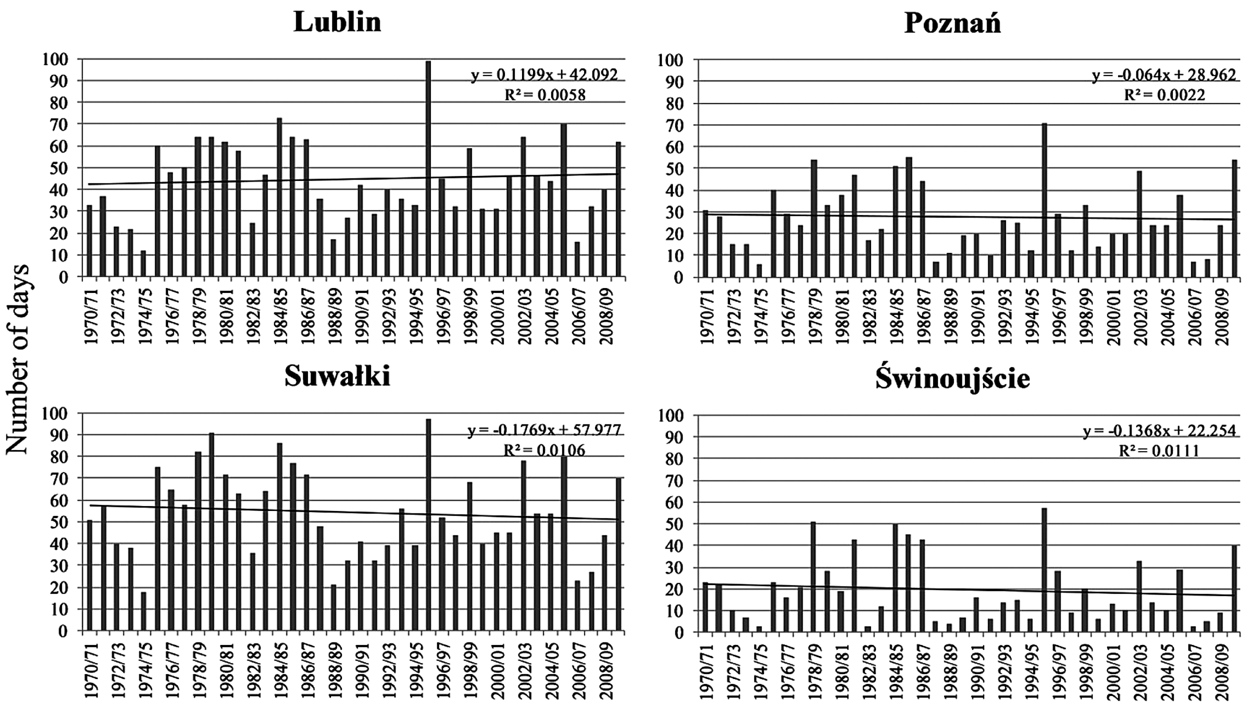

Fig. 4. Multiannual course of annual number of frosty days in selected stations

Frosty days in Poland in the analysed period occurred from October to April; still, in the outermost months of this period, these days were recorded only sporadically. In these particular months, the lowest number of frosty days was recorded in the north-west, and the highest number in the east of Poland. In all stations, the frostiest month was January, both with regard to air temperature and the number of frosty days. The average number of frosty days in January fluctuated between 7.9 (Świnoujście) and 16 (Suwałki). February was similarly frosty, with the average number of these days fluctuating from 5.1 to 14.1.

On average, the first frosty day in the winter season occurred on 20 November at the north-eastern ends (Suwałki, 16 November, Białystok, 19 November).

Till the end of November, frosty days were recorded mainly in eastern Poland, while till 10 December, they occurred within the whole area of Poland apart from the north-western extremities (Świnoujście, 16 December). The above-mentioned data showed that there was a monthly difference between the first occurrence of frosty days in the north-east and in the north-west. On the other hand, the last days with Tmax < 0°C were recorded earliest in the north-west (Świnoujście, 13 February). Across the majority of Poland, the last frosty day was recorded; on average, by the end of February, except for eastern Poland. At the north-eastern ends, the last frosty day was not recorded until mid-March (Suwałki, 14 March). As with the first frosty day, the last frosty day in the season saw a month's difference between the north-western and north-eastern ends of Poland.

The average duration of frosty periods (the time between the average dates of first and last frosty days) fluctuated between 60 days in Świnoujście and 119 days in Suwałki. On the other hand, the potential period of the occurrence of days with Tmax < 0°C (time between the earliest and the latest recording of a frosty day) was from 138 days in Gorzów Wielkopolski (from 3 November to 20 March) to 172 days (from 23 October to 12 April) in Suwałki.

Macro-scale circulation types and number of frosty days

North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is a bipolar circulation type resulting from interaction between the Azores High and the Icelandic Low. It stems from the pressure differential between these two pressure systems. NAO intensity is defined by the „NAO index", which is the normalized difference in atmospheric pressure between the Azores High and the Icelandic Low. The simultaneous occurrence of low atmospheric pressure at the centre of the Icelandic Low and high pressure in the Azores High is defined as the positive phase of the NAO. Conversely, co-occurrence of a pressure value higher than the mean value in the Icelandic Low and a pressure value lower than the mean value in the Azores High constitutes the negative phase of the NAO. During the positive phase of the NAO, there is a high pressure gradient between the above-mentioned pressure centres, which causes an inflow of air from the west, and a transport of humid and warm air masses over the northern part of the continent. On the other hand, a negative NAO index is associated with an inflow of dry and cool air masses from the north-west (Bednorz 2002, 2009; Nowosad 2005).

In the analysed multiannual period, the North Atlantic Oscillation significantly influenced the occurrence of frosty days from December to March (Fig. 5). The correlation was negative; therefore, the negative phase of the NAO saw an increase in the frequency of days with Tmax < 0°C. In December, the most significant relationship occurred at the north-eastern ends of the country ($r < -0.6$; $p \geq 95$). The strongest relationship between the North Atlantic Oscillation and the monthly number of frosty days was found in January. The above-mentioned relationship increased from the north-east to the north-west. Across the majority of Poland, the correlation was < -0.65 ($p \geq 95$), and the strongest relationship was found in Łeba (r -0.71; $p \geq 95$). In February, the correlation value was not very diverse within the whole of Poland, at approximately -0.5. On the other hand, at the end of winter; that is, in March, the NAO significantly determined the occurrence of frosty days, apart from in north-western Poland. The strongest correlation was found in Suwałki (r -0.46; $p \geq 95$). The above-mentioned data showed that within the majority of the country, NAO variability explains approximately 42% of variance in frequency of number of frosty days in January (near Łeba 50%), and 25% and 11% in February and March, respectively. In the analysed 40-year period, the mean value of the NAO index for winter changed from -1.9 to 1.2 (Fig. 6). The NAO index reached its highest values in the late 80s and early 90s of the 20th century, which was reflected in a decrease in the number of frosty days. On the other hand, the lowest value of the NAO index was recorded in the 2009/10 season, and resulted in an increase in the number of frosty days. During the winter with the highest number of frosty days – that is, in the 1995/96 season – the mean value of the NAO index was -0.9, while during the mildest winter (1974/75) it was -0.2. In the analysed period there were no statistically significant changes found in the NAO index.

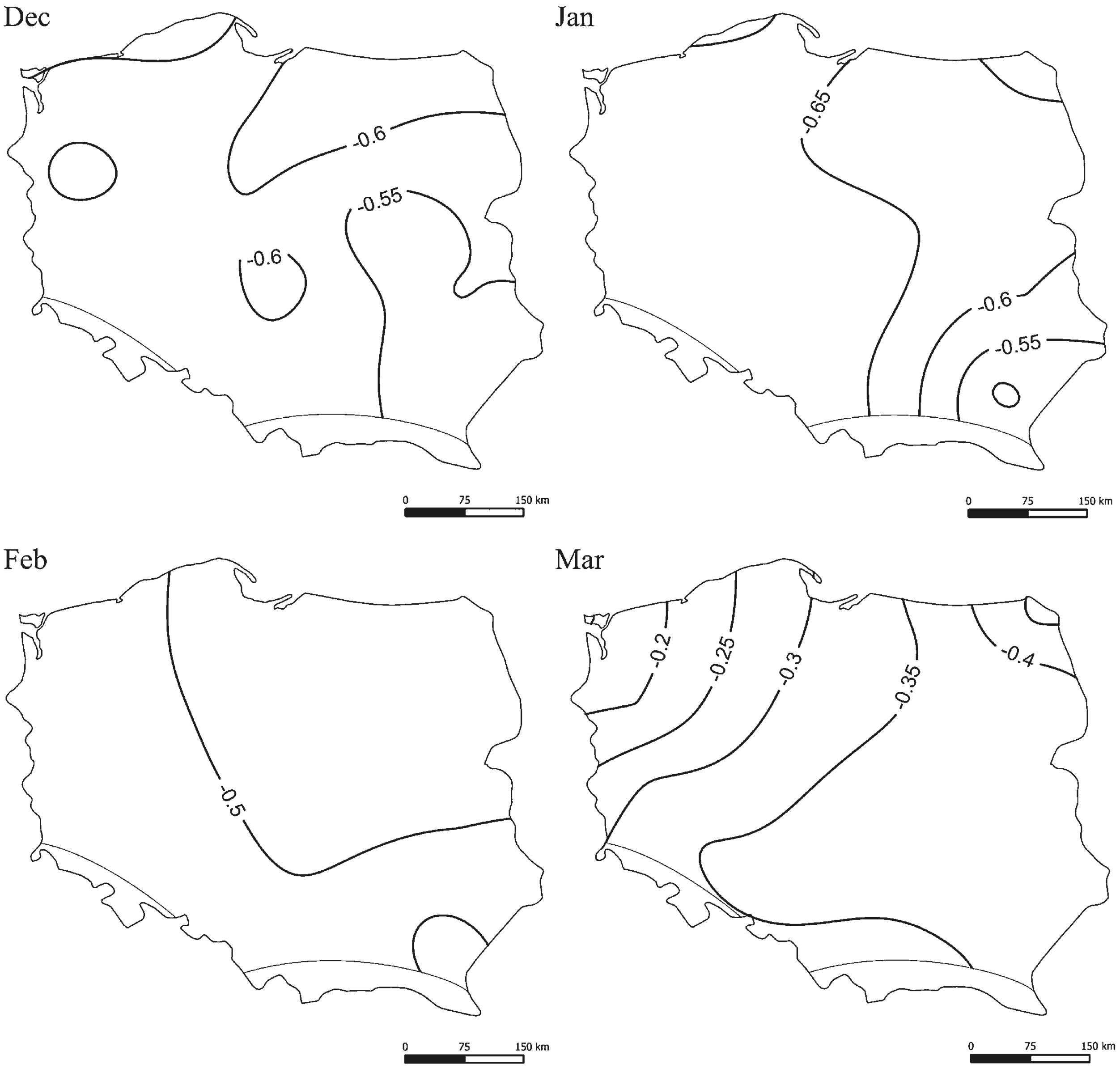

Fig. 5. Correlation coefficient of the monthly NAO index with monthly number of frosty days in the winter season

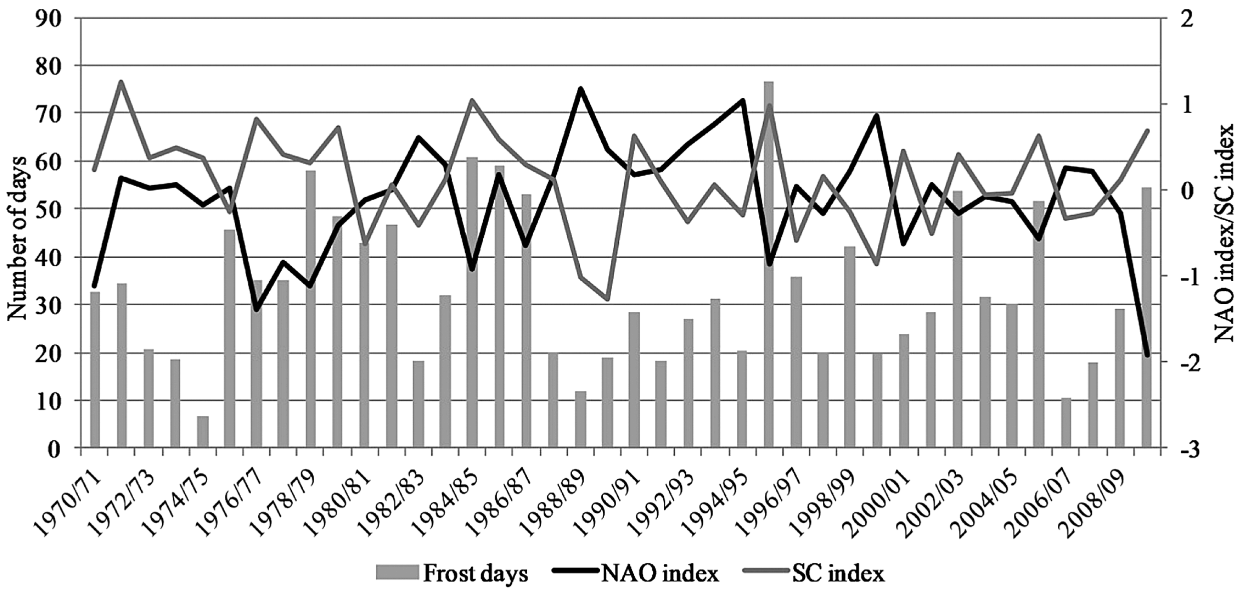

Fig. 6. Average number of frosty days in Poland in 1970/71-2009/10, with NAO index and SC index

Scandinavian

The second most significant circulation type in the Euro-Atlantic Sector was the Scandinavian type (SC). The SC is characterised by the occurrence of a strong high-pressure centre over the Scandinavian Peninsula, with its centre over Finland. A second, much weaker centre is located over south-western Europe. The pressure gradient is the strongest along the axis running southwest from Finland to the Iberian Peninsula. The Scandinavian type is characterised by great annual stability. Within the annual cycle, its impact is maximal in the winter and minimal in the summer (Wibig 2001).

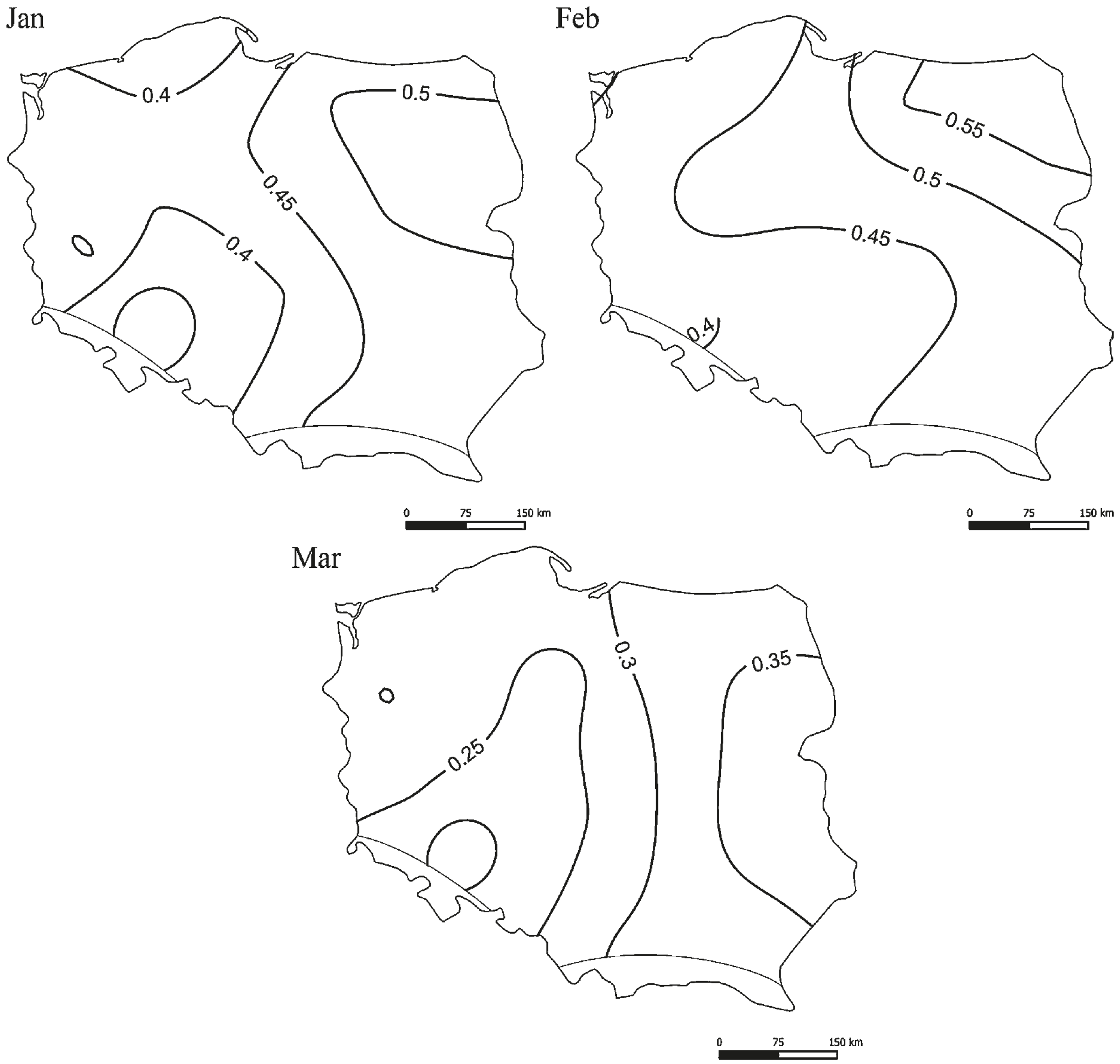

Fig. 7. Correlation coefficient of monthly SC index and monthly number of frosty days in winter

The SC is significant to the occurrence of frosty days in January, February and March (Fig. 7). The correlation was positive; therefore, during the positive phase of the SC there was an increase in frequency of days with Tmax < 0°C. In January, its impact increased eastward, and is most considerable in the Podlasie Lowland, where the correlation coefficient between monthly number of frosty days and the SC index exceeds 0.5. Across the majority of Poland, the value of correlation crossed the threshold of 0.4. In February, the strongest relationship occurred in north-eastern Poland ($r > 0.55$; Suwałki, 0.59). Apart from north-western ends of the country, the value of correlation was ≥ 0.4. In March, the impact of the Scandinavian type on number of frosty days was weaker; still, it was statistically significant in a large area of Poland, and was strongest in eastern Poland ($r > 0.35$). This means that, on average, within the area of the country, SC type variability explains approximately 20% of variance in frequency of number of frosty days in January, and 22% in February. In the analysed period, the value of the SC index fluctuated between -1.3 and 1.3. The lowest values of the SC index were recorded in the late 80s and early 90s of the 20th century. The research showed a statistically insignificant decrease in the value of SC index.

East Atlantic

The East Atlantic type (EA), similarly to the North Atlantic Oscillation, is a bipolar model of circulation shifted south-east in relation to the NAO. The southerly centre of the above-mentioned pressure system is strongly connected with tropical circulation (Bednorz 2006, 2009).

The correlation coefficient between the number of frosty days and the index of the EA circulation type from January to March was negative (Fig. 8). Only in January was this correlation statistically significant, and it covered eastern and north-eastern Poland. In February, the statistical significance of the correlation was nearly as high as in the majority of stations in the south of Poland.

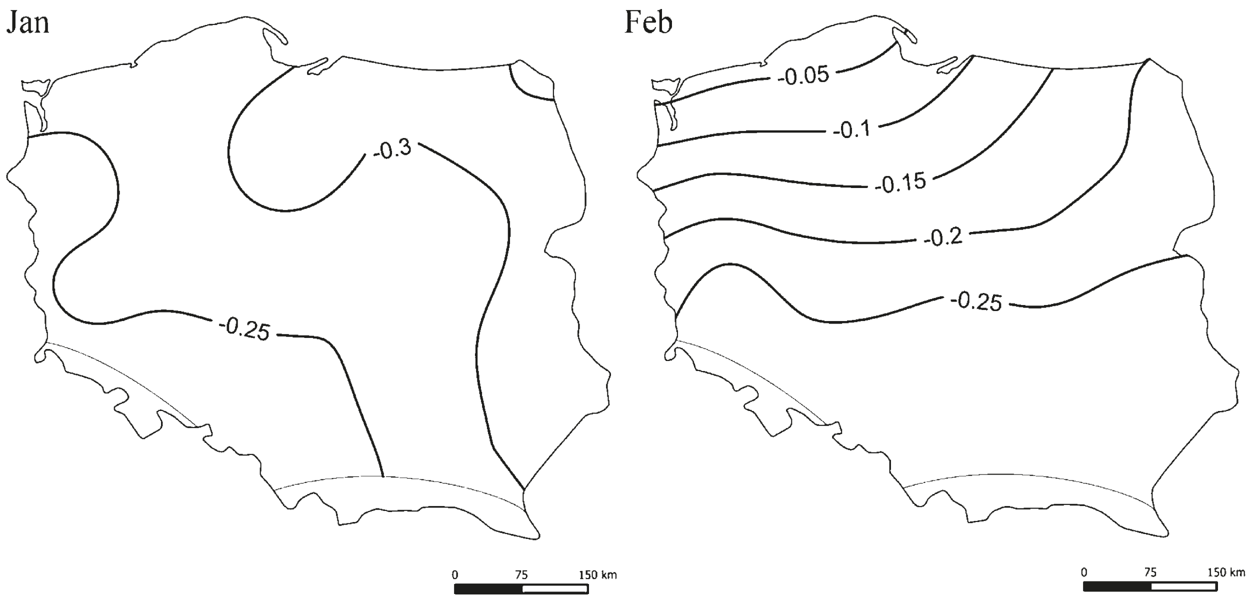

Fig. 8. Correlation coefficient of the monthly EA index with monthly number of frosty days in winter

East Atlantic/West Russia

It was shown that in winter the weakest circulation type was East Atlantic/West Russia, which was characterised by two centres located on the latitude line. In its positive phase, the centre of a southward-stretching low pressure area is located north of the Caspian Sea, while there is a high-pressure centre spanning the British Isles and Western Europe (Bednorz 2006, 2009).

The conducted research showed that the East Atlantic/West Russia type correlated negatively with the occurrence of frosty days in Poland; still, it did not have a significant impact on their occurrence from December to March. The highest correlations were found in December and March.

Discussion and Summary

The conducted research showed an increase in the maximum, minimum and mean daily air temperature in the winter season (December-March), although not statistically significant. Similar results were offered by Bielec-Bąkowska and Piotrowicz (2013), who analysed extreme temperatures in Poland between 1951 and 2006. The authors also confirmed an increase in temperature in winter (December-February), although statistically insignificant in most of the stations, at around 0.05. The highest increase in air temperature was recorded in March and May (Kożuchowski, Żmudzka 2001; Degirmendžić et al. 2004; Michalska 2011).

In the analysed multiannual period, across the majority of Poland, a decrease in number of frosty days was found; however, these changes were not statistically significant. Similar results were obtained by Kossowska-Cezak (2014), who described multiannual variation of thermal specific days in Warsaw; by Łupikasza et al. (2014), who analysed regional differentiation in the probability of occurrence of icy days in Poland and; Matuszko and Piotrowicz (2012), who analysed meteotropic situations in Kraków. More distinct changes have been observed in the frequency of occurrence of very frosty days, which are less and less frequent (Cebulak, Limanówka 2007; Bielec-Bąkowska, Łupikasza 2009; Bielec-Bąkowska, Piotrowicz 2013; Kossowska-Cezak 2014). As Bielec-Bąkowska and Piotrowicz (2013) emphasized, despite the fact that warming is visible, it is not considerable enough to be reflected in a distinct change of extreme conditions. A similar direction of changes has been shown; among others, in Czech Republic (Mužíková et al. 2011; Stěpánek et al. 2011) and in Latvia (Avotniece et al. 2010).

Of the four macro-scale circulation types, the North Atlantic Oscillation and the Scandinavian type had the strongest impact in determining number of frosty days in the winter season. The NAO correlated negatively with the number of days with Tmax < 0°C. Similar results were obtained by Cebulak and Limanówka (2007) when analysing correlation between the NAO index and a number of very frosty days (Tmin < -15°C). The authors showed that a considerable number of frosty days most often occurred with the negative phase of the NAO. As Wibig (2001) showed, variability of air temperature in winter is most strongly connected with the variability of the NAO type. In January, when the NAO has the strongest impact on mean monthly air temperature, the correlation coefficient between the discussed variables reaches 0.7 in a large portion of Central and Western Europe (Ustrnul and Czekierda 2007). A similarly strong impact of the NAO was found in relation to snow cover forming, and the highest values of correlation were recorded in January (Bednorz 2002, 2006, 2009).

Correlation between Scandinavian type and monthly number of days with Tmax < 0°C was positive; therefore, during the positive SC phase, there was an increase in the frequency of frosty days. As Wibig (2001) showed, SC type has the strongest influence on thermal conditions in winter. This is when almost the whole of Europe is within the eastern circulation, which is connected with the inflow of frosty, cool air masses from over the continent. In the cool season, the high over Scandinavia is sometimes the ridge of the Asian High, which is related to the occurrence of very low temperatures over Central Europe (Degirmendžić 1999; Wibig 2001).

The EA/WR type had the weakest impact on the occurrence of frosty days in the analysed multiannual period. Similarly, Bednorz (2009) showed a weak correlation between this type of circulation and number of days with snow cover, which was statistically significant only at the beginning and end of winter.

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