REGIONAL DIFFERENTIATION IN PROBABILITY OF ICE DAYS OCCURRENCE IN POLAND

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Abstract: This paper aims at recognizing spatial differentiation in probability of ice days occurrence with reference to atmospheric circulation, using regional classification of circulation types for Poland. Daily maximum air temperatures measured at nine meteorological stations were used to recognize the ice days occurrence in the period from January 1951 to March 2014. The relations between the ice days occurrence and atmospheric circulation were analysed using catalogues of circulation types compiled for nine grid boxes within Poland. Linkage between the frequency of ice days and atmospheric circulation was recognized in the period of January 2001 – March 2014. A decreasing tendency in the frequency of the occurrence of winter ice days was found. The occurrence of ice days in Poland is clearly related to atmospheric circulation. In the entire area of Poland their occurrence is favoured by eastern and south-eastern advection of air during anticyclonic conditions (types Ea nad SEa). Regional variability is also noticeable.

Key words: ice days, atmospheric circulation, circulation types, Poland

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Introduction

Ice days are 24-hour periods with the maximum air temperature remaining below 0°C (Niedźwiedź 2003). Ice days are a common feature in Polish weather conditions in the cold half-year. In Poland, days with maximum temperature never exceeding freezing point occur during at least five (Nov–Mar) or at most nine months (Sep–May) depending on location (Baranowski and Kirschenstein 2008, Błażejczyk at al. 2013). Being directly linked to daily air temperature, ice days are considered an indicator of current climate change**.** The frequency of ice days is also an important characteristic of bioclimatological conditions. Their occurrence has economic consequences (Piotrowicz 1998).

The frequency of ice days occurrence in Poland was rarely studied, usually as a part of climate characteristic of particular localities (Grabowska et al. 2007, Baranowski 2008, Baranowski and Kirschenstein 2008, Błażejczyk at al. 2013). Intensive studies of long-term variability in ice days frequency were performed by K. Piotrowicz (1998) in Cracow and Prague, by B. Głowicki (2008) in the Sudetes and by Bielec-Bąkowska and Łupikasza (2009) in Małopolska. As a result of these studies it appears that ice days occurrence is strongly influenced by altitude (Głowicki 2008, Bielec-Bąkowska and Łupikasza 2009) and atmospheric circulation (Piotrowicz 1998, Bielec-Bąkowska and Łupikasza 2009). Decreasing trends in the frequency of ice days were dominant (Piotrowicz 1998, Cebulak and Limanówka

2007, Głowicki 2008, Bielec-Bąkowską and Łupikasza 2009).

This paper aims at recognizing spatial differentiation in the probability of ice days occurrence with reference to atmospheric circulation, using regional classification of circulation types for Poland. The paper consists of 3 analytical chapters. Regional differentiation in the frequency of particular synoptic types is discussed in chapter 3 as a background for further analysis. Chapter 4 is devoted to the intra-annual occurrence of ice days. It also deals with the temporal variability of the aforementioned days. The probability of ice days occurrence with relation to atmospheric circulation is described in chapter 5.

Data and methods

Daily maximum air temperatures measured at nine meteorological stations were used to recognize the ice days occurrence. At the majority of the stations chronological series cover the period from January 1951 to March 2014. The series for Rzeszów starts in January 1952. The data comes from the Meteorological Yearbooks (1954–1965). The archival data (1951–2006) were provided by the Institute of Meteorology and Water Management – State Research Institute (IMGW – PIB) and latest data (2000–2014) was taken from the synoptic database OGIMET (Valor 2014).

The relations between the ice days occurrence and atmospheric circulation were analysed using catalogues of circulation types compiled for nine grid boxes within Poland (Fig. 1). The grid boxes cover an area limited by the meridians of 14°E and 25°E and by the parallels of 49°N and 55°N. Each of the meteorological stations used in the study represents one of the grid boxes and is located in or in the vicinity of its center as the circulation types are determined for the center points of the grid boxes. The catalogue distinguishes 21 synoptic types which are described by the direction of air advection (e.g. N – northern, S – southern, NE – north-eastern, etc.) and the type of baric center (a – anticyclonic, c – cyclonic). Apart from the directional types which are characterized by distinct air advection (Na, NEa, Ea, SEa, Sa, SWa, Wa, NWa, Nc, NEc, Ec, SEc, Sc, SWc, Wc, NWc), four further types are included into the classification: Ca – central anticyclone situation (high centre), Ka – anticyclonic wedge or ridge of high pressure, Cc – central cyclonic (centre of low), Bc – trough of low pressure (different directions of air flow and frontal system in the axis of trough). Unclassifiable situations are marked with an 'x'.

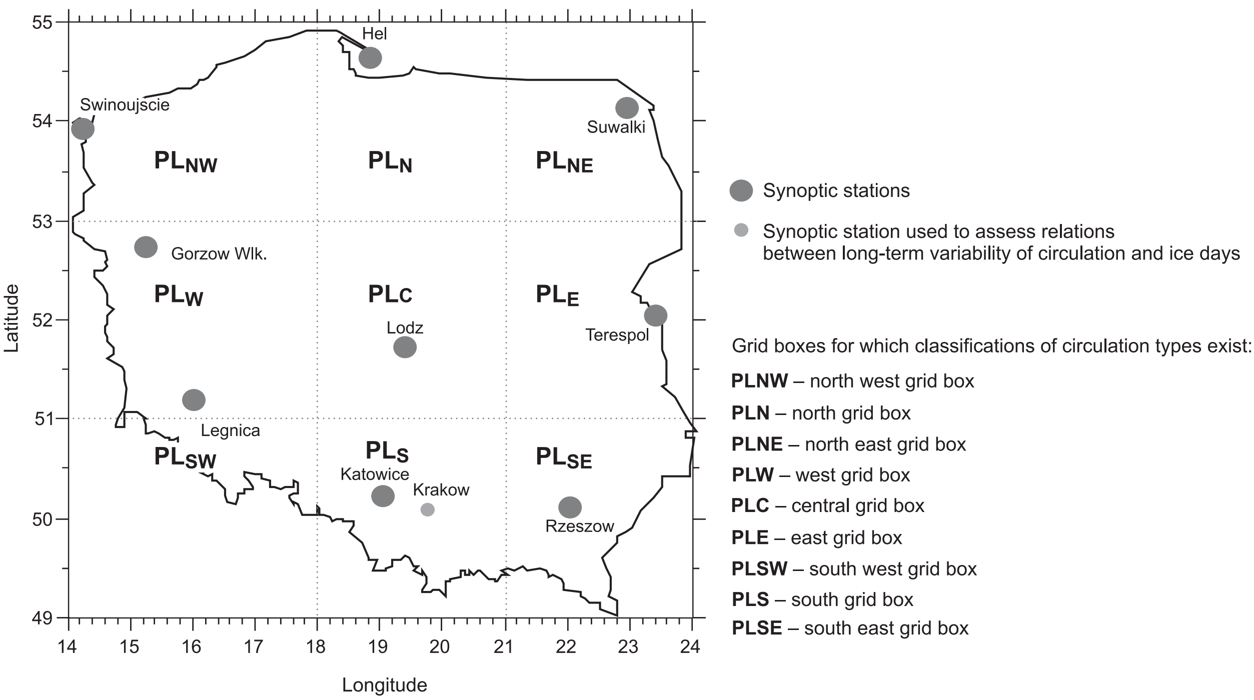

Fig. 1. Location of meteorological stations and grid boxes for which the classifications of circulation types exist

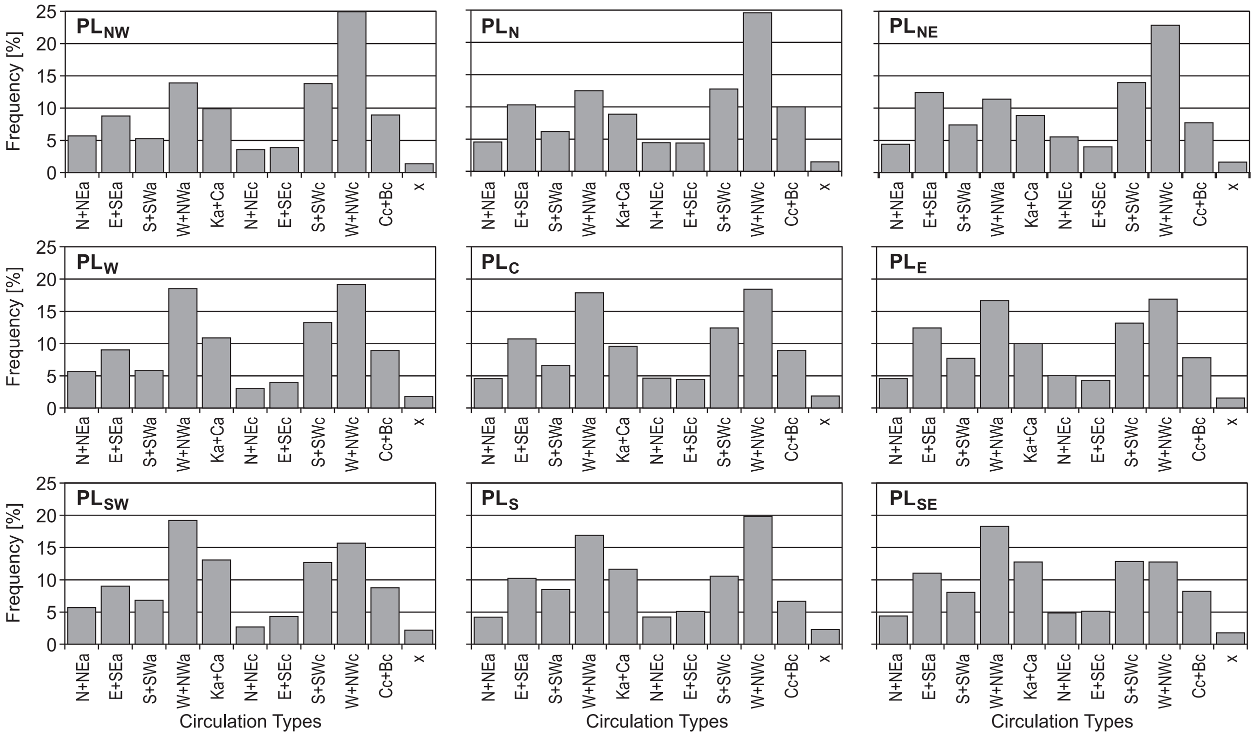

Fig. 2. Frequency of circulation types in winter (DJF) for grid box within Poland. PL_{NW}, PL_N, … etc. – grid box within Poland, e.g.: PL_{NW} – North-western grid box (see Fig. 1)

The series of circulation types start on January 1, 2001 with an exception of PL_S grid point, for which the catalogue begins on September 1, 1873. The catalogues have been created manually on the basis of synoptic charts by German Weather Service (DWD) published in "Tägliche Wetterbericht" and "Europäischer Wetterbericht" in the period of 1951–2002 and by Institute of Meteorology and Water Management (IMGW) published in "Daily Meteorological Bulletin" in the period of 1980–2007. The German synoptic charts from 2003 are available on the Internet (http://www.wetter3.de/Archiv/archiv_dwd.html).

In order to assess spatial variability of atmospheric circulation over Poland, the frequencies of the synoptic types for each grid box were calculated. The calculations were performed for winter, which is the peak season of the ice days occurrence in Poland. In that part of the study, joined circulation types were used (Fig. 2).

Spatial variability in the ice days occurrence in Poland and their annual course were recognized on the basis of arithmetical averages calculated for each month, for winter (DJF) and for the season of the ice days occurrence (from October to April) in the period from January 1951 to March 2014. The decadal and 30-year averages for the DJF and Oct–Apr were also calculated. Statistical significance of the differences between the decadal averages and between the 30-year averages was checked with the Mann-Whitney nonparametric test (Wilks 2006).

Probability of the ice days occurrence and conditional probability of their occurrence in particular synoptic types were calculated for winter to recognize a linkage between the frequency of ice days and atmospheric circulation. The time-frame for this analysis is limited (January 2001–March 2014) by the availability of the circulation data, with an exception of PL_S grid box with the longest series of the synoptic types (January 1951–March 2014). Afterwards the differences between the probability of the ice days occurrence in winter and the conditional probabilities were calculated. The types with differences reaching at least 25% were recognized as favourable to the ice days occurrence whereas the types with the differences below –25% were recognized as unfavourable.

Trends in the frequencies of those circulation types which are significantly correlated with the ice days occurrence deliver information on possible directions of future tendencies in the occurrence of ice days. Such analyses were performed using the data for PL_S grid box with the longest series of the circulation types. Spearman correlation coefficients between the frequency of circulation types for PL_S grid box and the frequency of ice days in Katowice and Kraków in the winters of 1951/52–2013/14 were calculated. The magnitude of trends in the circulation types was calculated with the least square method, whereas their statistical significance was checked with the Mann-Kendall test (Mann 1945, Kendall 1975). The significance level adopted for both the trends and the correlation coefficients is $\alpha<0.05$

Regional differentiation of circulation types in Poland

Regional variation in the atmospheric circulation over Poland in winter (DJF) expressed as the frequencies of synoptic types for each of the grid boxes is shown in Figure 2. Little spatial variability in the pattern of the circulation types frequencies was found in winter, when the westerlies are the most pronounced (Kożuchowski 2011). The summarised frequency of the synoptic types with western component (S+SWa, W+NWa, S+SWc, W+NWc) constitutes more than 50% of all circulation types. In the western grid boxes it decreases from 58% in PL_{NW} grid box to 54% in PL_{SW} grid box. In the eastern grid boxes it is slightly lower and diminishes from 56% in PL_E grid box to 52% in PL_{SE} grid box. The north-south changes in the frequency of W+NWc type and W+NWa type are the exact opposite. In northern Poland as well as in the central part of southern Poland W+NWc type occurs most often. Its frequency in PL_{NW} and PL_N grid boxes reaches almost 25%. On the other hand, northern Poland is characterized by the least frequency of W+NWa type which decreases when moving from the west (14% for PL_{NW}) to the east (11% for PL_{NE}) (Fig. 2).

In the middle grid boxes the anicyclonic type of W+NWa occurs almost as often as the cyclonic type of W+NWc. In southern Poland (PL_{SW} and PL_{SE} grid boxes) the air advection from W and NW during anticyclonic conditions is more frequent than during cyclonic ones (Fig. 2). A gradual decrease in the occurrence of eastern and south-eastern advection during the anticyclonic conditions (E+SEa type) was found in the east-west direction (Fig. 2). In western grid boxes E+-SEa type accounts for 9% of winter days (PL_{NW}, PL_W and PL_{SW} grid boxes). In the eastern part of the country it reaches 11% (PL_{SE} grid box) and 12% (PL_E and PL_{NE} grid boxes) of winter days. In the entire Poland the rarest are N+NEa or N+NEc types.

The jointed frequency of all anticyclonic and cyclonic types is shown in Figure 3. It is clearly evident that in winter in the northern part of Poland the frequency of cyclonic conditions is about 10% higher than of anticyclonic ones (Fig. 3). In this season the track of the Atlantic depressions crosses the Baltic Sea territory (Paszyński and Niedźwiedź 1999) whereupon the occurrence of cyclonic types increases.

Intra-annual ice days occurrence in Poland

In Poland ice days occur from October to April. In that time maximum daily air temper-

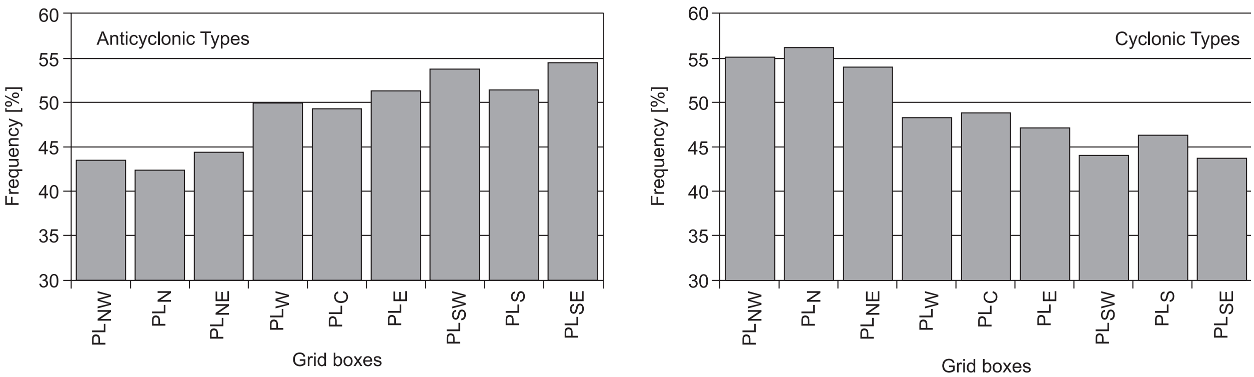

Fig. 3. Frequency of antycyclonic and cyclonic circulation types in winter (DJF) for grid box within Poland. PL_{NW}, PL_N, … etc. – grid box within Poland, e.g.: PL_{NW} – north-western grid box

ature falls below the freezing point during 36 days, as indicated by the average value for the period of 1951/52–2012/13 calculated from the nine stations considered here. Spatial distribution of ice days results from the changes in the degree of continentality – the further to the east the station is located the higher number of ice days occurs. The rate of west-east increase reaches 37 days in northern Poland and 14 days in southern Poland. In western Poland the number of ice days changes from 23 ice days in Szczecin to 29 ice days in Gorzów, whereas in eastern Poland it is substantially higher, reaching 59 ice days in Suwałki and 47 ice days in Terespol. The lowest number of ice days in Szczecin and Hel is an indication of the moderating influences of the Baltic Sea on the climate of coastal regions (Table 1).

Table 1. Average monthly and seasonal number of ice days in the period January 1951–March 2014 at stations representing each grid box for which circulation classification exists

stations	index	Jan.	Feb.	Mar.	Apr.	Oct.	Nov.	Dec.	Oct.–Apr.	Dec.–Feb.
Świnoujście	Avg.	8.4	6.7	1.6	0.0	0.0	0.7	5.2	23	20
	St. Dev.	7.1	6.8	2.7	0.0	0.0	1.8	5.3	16	15
	max	25.0	27.0	14.0	0.0	0.0	9.0	23.0	73	67
	year	1963	1963	1987	–	–	1965	1969	1962/63	1962/63
Hel	Avg.	9.8	8.6	2.4	0.0	0.0	0.9	4.8	26	23
	St. Dev.	7.1	7.4	3.2	0.1	0.0	2.2	5.1	17	15
	max	27.0	27.0	11.0	1.0	0.0	10.0	22.0	68	64
	year	1987[1]	1986	1964	1986	–	1965[2]	2010	1962/63	1969/70
Suwałki	Avg.	17.0	15.4	7.4	0.1	0.1	5.0	13.8	59	47
	St. Dev.	7.8	7.6	6.4	0.5	0.5	4.8	6.8	21	17
	max	31.0	28.0	24.0	3.0	3.0	20.0	31.0	97	83
	year	2010	1963	1952	2003	1979	1993	1969	1995/96	1969/70
Gorzów	Avg.	10.7	7.6	1.6	0.0	0.0	1.6	7.6	29	26
	St. Dev.	7.2	7.1	2.4	0.0	0.0	2.8	6.3	17	15
	max	28.0	27.0	10.0	0.0	0.0	11.0	28.0	76	72
	year	1963	1963	1987	–	–	1965[3]	1969	1962/63	1962/63
Łódź	Avg.	12.9	10.3	3.7	0.1	0.0	2.5	9.4	39	33
	St. Dev.	7.2	7.3	4.4	0.2	0.2	3.6	6.2	17	15
	max	29.0	28.0	16.0	1.0	1.0	17.0	28.0	80	70
	year	2010	1963	1958	1955[4]	1956	1965	1969	1995/96	1962/63
Terespol	Avg.	15.2	12.3	4.6	0.1	0.1	3.3	10.9	47	39
	St. Dev.	7.4	7.6	5.0	0.2	0.3	4.2	7.0	19	16
	max	30.0	28.0	16.0	1.0	2.0	20.0	28.0	92	74
	year	1972	1986	1952	1956[5]	1979	1965	1969	1995/96	1962/63
Legnica	Avg.	9.0	7.5	2.0	0.0	0.0	1.3	6.2	26	23
	St. Dev.	6.9	6.6	3.0	0.2	0.0	2.6	5.5	15	14
	max	26.0	27.0	12.0	1.0	0.0	13.0	28.0	68	65
	year	1963	1956	1964	1978	–	1965	1969	1962/63	1962/63
Katowice	Avg.	12.5	8.7	3.1	0.0	0.0	2.2	8.8	36	30
	St. Dev.	6.7	6.7	3.9	0.2	0.2	3.3	6.1	15	14
	max	27.0	27.0	14.0	1.0	1.0	13.0	29.0	69	63
	year	1963	1986	1958	1958[6]	1980	1965	1969	1962/63	1962/63
Rzeszów	Avg.	14.0	10.3	3.5	0.0	0.0	2.8	9.8	40	34
	St. Dev.	7.0	7.4	4.4	0.3	0.2	3.8	6.4	16	15
	max	28.0	27.0	16.0	2.0	1.0	18.0	27.0	82	66
	year	1963	1956	1952	2003	1979	1993	2001	1995/96	1995/96

Avg. – average from 1951/52-2013/14, St. Dev.–Standard deviation, max – maximum number of ice days in the research period, year – a year with the maximum number of ice days. The upper index at the year means that particular maximum value occurred more than once in the research period. The further years of its occurrence are as follow: [1]2012; [2]1993, 1998; [3]1985, 1993, [4]1970, 1986, 2003; [5]1960, 1986, 2003; [6]1970, 2003.

Considering October – April season, the highest frequencies of ice days at particular stations have been registered in 1962/63 or 1995/96 depending on the station (Table 1). The majority of ice days fall in winter (85% on average). The number of winter ice days varies from 20 days in Swinoujście to 47 days in Suwałki. Spatial distribution of these days in winter resembles the pattern for October-April season (Table 1).

The maximum monthly number of ice days falls in January (from 8 days in Świnoujście to 14 days in Suwałki). In the other winter months it reaches on average 10 days in February (from 7 to 15 ice days) and 9 days in December (from 5 to 14 ice days). All of the monthly extremes were noted in Świnoujście (minimum number) and in Suwałki (maximum number). January 1963 and December 1969 were very cold in the research period. At five of the nine stations the maximum number of January ice days was noted in 1963, and at seven stations the maximum frequency of December ice days was noted in 1969. In March the maximum air temperature falls below 0°C during 6 days on average. At particular stations this number varies from 2 days in Świnoujście to 7 days in Suwałki. In November ice days occur more rarely (2 days less) than in March (on average 4 ice days). However, at the majority of the stations no more than 2 ice days are observed in November. The ice days occur sporadically in April and October. At three stations located in the north-eastern sector of Poland (Swinoujście, Hel, Gorzów), no ice days were noted in October and April. The exception is Hel, where one ice day occurred in April 1986. The highest number of ice days both in April and October characterizes the Suwałki station where 3 ice days occurred in both April 1986 and October 1979. In Suwałki the total number of ice days within the entire research period equals 9 days in each of these months.

The tendencies in the number of winter ice days were analysed by calculating the statistical significance of differences (Mann-Withney test) between averages for selected multiyear periods. These average frequencies for 30-year periods, for decades and for the periods of 1951/52–1999/2000 and 2001/01–2013/14 are presented in Table 2. At the majority of the stations the average number of ice days for the period of 1951/52–1999/2000 is higher than for the period of 2000/01–2013/14, except for the two stations located in the south-eastern part of Poland (Katowice and Rzeszów). These averages are significantly different only at two stations (Suwałki and Terespol), which indicates decrease in the number of ice days in the last decade.

Table 2. Average number of ice days for various periods at stations representing each grid box for which circulation classification exists

Periods	Świno-ujście	Hel	Suwałki	Gorzów	Łódź	Terespol	Legnica	Kato-wice	Rzeszów
a. 1951/52–1999/00	21	23	47^{b}	26	33	39^{b}	23	30	34
b. 2000/01–2013/14	18	22	**43^{a}**	25	33	**37^{a}**	22	30	35
c. 1951/52–1979/80	23	26	51	28	35	42	24	32	36
d. 1961/62–1989/90	23	25	50	28	34	41	25	31	35
e. 1971/72–1999/00	18	21	43	23	29	35	20	26	30
f. 1981/82–2009/10	17	20	42	23	31	35	21	28	31
g. 1951/52–1960/61	20	23	47	27	33	38^{h}	22	32	33
h. 1961/62–1970/71	30	**33^{k}**	**58^{k}**	**36^{k}**	**42^{k}**	**51^{gjk}**	**32^{ki}**	**40^{ki}**	**44^{k}**
i. 1971/72–1980/81	18	21	47	22	29	37	19^{h}	24^{h}	31
j. 1981/82–1990/91	20	23	45	26	31	35^{h}	23	29	32
k. 1991/92–2000/01	16	**18^{h}**	**38^{h}**	**21^{h}**	**28^{h}**	**33^{h}**	**19^{h}**	**26^{h}**	**29^{h}**
l. 2001/02–2010/11	16	20	42	23	33	36	21	31	34

a, b, c … l – indications of the multiyear periods, bolded are averages with statistically significant differences (at $\alpha<0.05$) between the period given in the first column and the period indicated by a superscripts, e.g. at the Hel station the average number of ice days in the period 1991/92–2000/01 equalling 18 days is significantly different from the average for the period 1961/62–1970/71 which is marked by the h superscript. Superscripts refer to the indications of the multiyear periods in the first column.

At the majority of the stations the 30-year averages were highest in the period of 1951/52 –1979/80 (Table 2) and the lowest in the period of 1981/82–2009/10 or in the period of 1971/72–1999/2000. Gradual decrease in the frequency of ice days was found at the stations located in northern Poland (Świnoujście, Hel, Suwałki) and in Terespol. At the other stations the averages for the last 30-year period (1981/82–2009/10) are higher than for the previous 30-year period of 1971/72–1999/2000. At every station however, the average number of ice days in the last 30-year period of 1981/82–2009/10 was lower than in the first one (1951/52–1979/80). The differences between the 30-year averages are not statistically significant at any of the stations.

The decadal average number of ice days was the highest in the period of 1961/62–1970/71, which therefore may be considered the coolest decade in the research period. At the majority of the stations, with an exception of Katowice, the lowest frequency of ice days was found in the decade of 1991/92–2000/01 (Table 2). The differences between the averages for these decades are statistically significant. At Legnica and Katowice stations significant differences in the averages were also observed for the period of 1961/62–1970/71 and 1971/72–1980/81. The greatest variability in the decadal number of ice days characterises Terespol station, where the average number of ice days in the decade of 1961/62–1970/71 was significantly higher than the averages for the decades of 1951/52–1960/61, 1981/82–1990/91 and 1991/92–2000/01. The signs of the differences between a given decade and the preceding decade are various, therefore it is not possible to identity a clear direction of the tendencies in the frequency of ice days. However, the difference calculated between the decade of 1951/52–1960/61 and any previous decade (e.g. the average for 1991/92–2000/01 minus the average for 1951/52–1960/61) is usually negative, which is compatible with the results coming from the analysis of 30-year averages. Generally the statistically insignificant decreasing tendency in the frequency of the ice days occurrence is found at the analysed stations. Similar results were found by Limanówka (1999), Cebulak, Limanówka (2007) and Bielec-Bąkowska, Łupikasza (2009).

Probability of the occurrence of ice days in circulation types

The frequency of ice days in Poland is clearly related to atmospheric circulation. The character of these relations is shown in figure 4 presenting the differences between the probability of the ice days occurrence in winter and its probability in a particular circulation type in the same season. All the types with differences crossing the black line are recognised to influence the frequency of ice days.

Air advection from eastern and south-eastern direction during anticyclonic conditions (types Ea and SEa) favours the ice days occurrence in the entire Poland (Fig. 4). Its probability in Ea type is very high in eastern Poland, reaching 96%, 95% and 78% of days with Ea type respectively in Suwałki, Terespol and Rzeszów. These numbers decrease considerably to the west (57% in Swinoujście, 69% in Gorzów, 64% in Legnica). The probability of ice days in SEa type varies from 84% in Suwałki to 62% in Legnica. At the majority of the stations, Ea type is more conducive to the ice days occurrence than SEa type except for Świnoujście (64% of ice days with SEa type) and Gorzów (75% of days with SEa type).

Regional variability is also noticeable in the dependence of ice days upon atmospheric circulation. In south-eastern Poland (Terespol, Rzeszów, Katowice) ice days can be expected during an inflow of air from the North-East under anticyclonic conditions (NEa type). There, the maximum temperature is lower than 0°C during more than 70% of days with NEa type (72% in Legnica, 74% in Terespol, 77% in Rzeszów). In the northern part of the country ice days occur during the majority of days with Ca type, which results in great differences between the probabilities (Fig. 4). This, however, arises from a very low frequency of Ca type at these stations (5 days in Świnoujście and Hel, 4 days in Suwałki).

Ice days are also related to air inflow from the east sector during cyclonic conditions (NEc, Ec, SEc types). Except for Swinoujście (no connection was found), ice days occupy from 57% (Hel) to 80% (Terespol) of days with Ec type. In southern and eastern Poland the share of these days in the overall number of days with Ec type exceeds

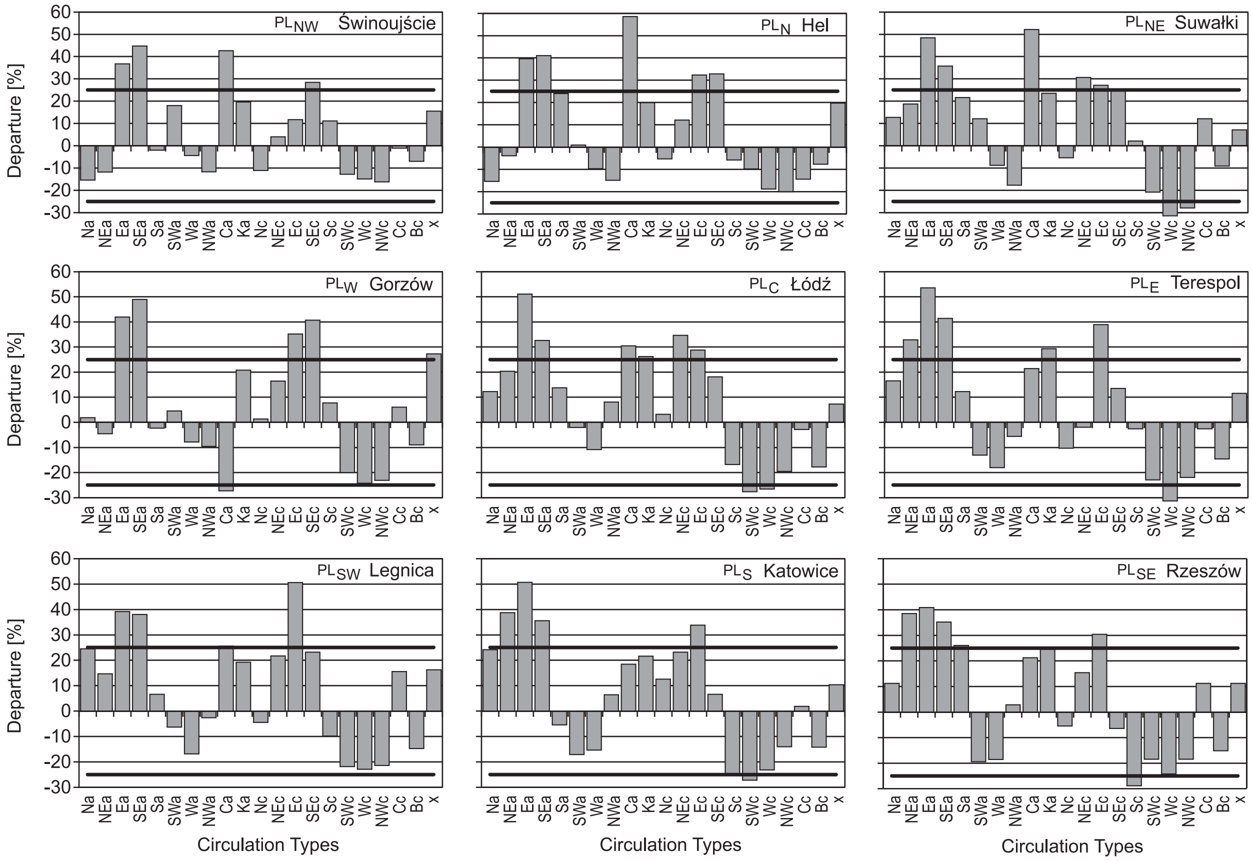

Fig. 4. Departures of the probability of the ice days occurrence in circulation types from the probability of the ice days occurrence in winter (DJF) for grid boxes within Poland. PL_{NW}, PL_N, … etc. – grid box within Poland, e.g.: PL_{NW} – north-western grid box (bold lines mean departures greater than 25%)

65%. In the central and north-eastern part of the country NEc type is most characteristic (71% of ice days in Łódź and 79% of ice days in Suwałki). In the north-eastern sector, days with T_{max}<0°C are also associated with SEc type – 48% (Świnoujście), 58% (Hel) and 68% (Gorzów) of days with this type.

At the stations located in the middle and eastern part of Poland (Gorzów, Łódź, Suwałki, Terespol, Katowice, Rzeszów) some cyclonic types were found to be negatively related to the ice days occurrence, as evidenced by a low conditional probability. At the majority of these stations (except for Katowice), maximum tem-

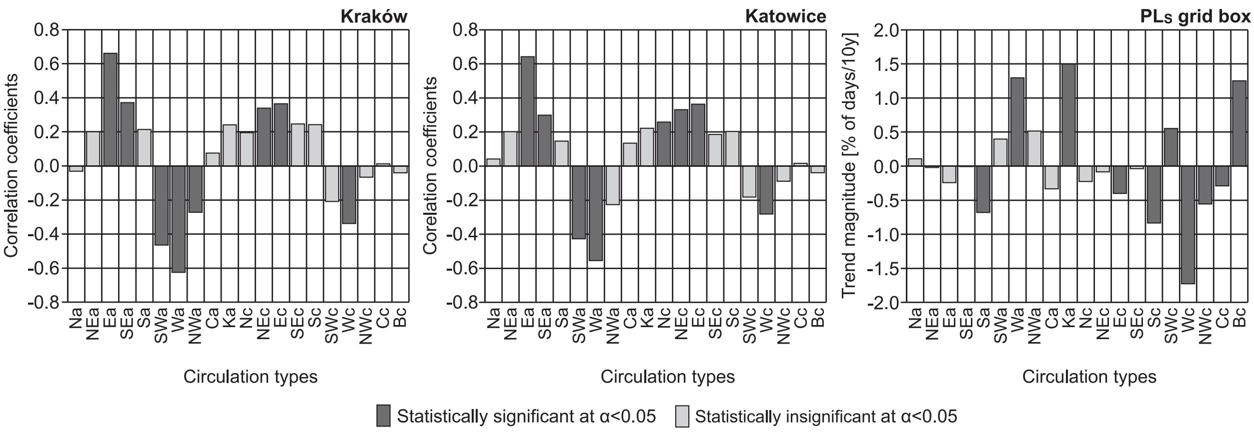

Fig. 5. Correlation coefficients between the ice days frequency (Kraków and Katowice) and the frequency of circulation types for PL_S grid box and linear trends in the frequency of circulation types for PL_S grid box in winters (1951/52–2013/14)

Table 3. Conditional probability of the ice days occurrence in circulation types at stations representing each grid box for which circulation classification exists

Circulation types	Świnoujście PL_{NW}	Hel PL_{N}	Suwałki PL_{NE}	Gorzów PL_{W}	Łódź PL_{C}	Terespol PL_{E}	Legnica PL_{SW}	Katowice PL_{S}	Rzeszów PL_{SE}
Na	4	9	61	29	39	58	49	57	50
NEa	8	21	67	23	61	74	39	72	77
Ea	57	64	96	69	80	95	64	84	80
SEa	65	66	84	76	75	82	63	69	74
Sa	18	49	70	25	65	53	31	28	65
SWa	38	26	60	32	34	28	18	16	19
Wa	15	15	39	19	22	23	8	18	20
NWa	8	10	30	18	37	35	22	40	42
Ca	63	83	100	0	56	63	50	52	60
Ka	39	45	71	48	65	70	44	55	63
Nc	9	19	43	29	36	31	20	46	33
NEc	24	37	79	44	67	39	46	56	54
Ec	32	57	75	63	75	80	75	67	69
SEc	48	58	73	68	66	55	48	40	32
Sc	31	19	50	35	25	38	15	8	10
SWc	7	15	27	7	14	18	3	6	20
Wc	5	6	16	3	8	9	2	10	15
NWc	4	5	20	4	11	19	3	19	20
Cc	19	10	60	33	33	38	40	35	50
Bc	13	17	39	18	26	27	10	19	24
x	35	44	55	55	57	53	41	44	50

perature rarely falls below freezing point during the air advection from the West (Wc type). The other types with a low probability of the ice days occurrence are of NWc type (Suwałki), SWc type (Łodź, Katowice) and Sc type (Katowice, Rzeszów) (Table 3).

Spatial variability in the frequency of ice days in Poland is related to the synoptic scale of atmospheric circulation, as evidenced above. In order to assess the linkage between the temporal variability in the frequencies of ice days and circulation types, the correlations between these variables were calculated using the longest series of the circulation data (PL_S grid box) and the frequency of ice days in Katowice and additionally in Kraków. At both stations long-term variability in the frequency of ice days is positively correlated with Ea and then with SEa, Ec and NEc types (Fig. 5). The variability in Ea type frequency explains 43.5% of ice days variability in Katowice and 45.4% of ice days variability in Kraków, as assessed by the coefficient of determination. Strong negative correlation was found between the frequencies of ice days and Wa, SWa and Wc types. Wa type explains 30% of the variability in ice days in Katowice and 34% in Kraków. In the case of the other types, the coefficient of determination does not exceed 23%.

The analysis of linear trends in the frequency of circulation types does not provide clear information about possible future changes in the ice days frequency. Both significant decreasing trends in Ec type (+0.4day/10y) and significant increasing trends in the frequency of Wa type may suggest a possible decrease in the occurrence of days with Tmax<0°C. This, however, may be strongly weakened by a decrease in the frequency of Wc type (–1.7 days/10y) (Fig. 5).

Discussion and conclusions

In Poland ice days occur from October to April (36 days on average) but the majority of these days occur in winter months (85% of these days). The maximum monthly number of ice days falls in January (13 ice days). In the other winter months it reaches on average 10 days in February and 9 days in December. Spatial variability in the frequency of ice days results from local conditions, the most relevant of which are degree of continentality, distance from the Baltic Sea and altitude. The average frequency of winter ice days at the stations located in Western Poland equals 23 days, whereas at the stations located in Eastern Poland it reaches 40 days. The lowest number of ice days in north-western and northern Poland results from the moderating influences of the Baltic Sea upon the climate of these localities.

The analysis of the 30-year and decadal averages at particular stations indicates a decreasing tendency in the frequency of the ice days occurrence. However, the differences between the 30-year averages are not statistically significant. In the case of decadal averages, the significant differences were found between the coolest decade of 1961/62–1970/71 with the highest number of winter ice days and the warmest decade of 1991/92–2000/01 with the lowest number of these days. An insignificant decreasing trend in the annual number of ice days was also observed in the Sudety in the period of 1951–2007 (Głowicki 2008), in Małopolska in the period of 1951–2000 (Bielec-Bąkowska 2009) and at particular stations in Poland (Cebulak, Limanówka 2007).

The occurrence of ice days in Poland is clearly related to atmospheric circulation. In the entire Poland the ice days occurrence is favoured by eastern and south-eastern advection of air during anticyclonic conditions (types Ea nad SEa). Regional variability is also noticeable in the dependence of ice days upon atmospheric circulation. In south-eastern Poland (Terespol, Rzeszów, Katowice) ice days can be expected during an inflow of air from a north-eastern direction under anticyclonic conditions (NEa type). In the northern part of the country, ice days appear during the majority of days with Ca type. However, days with Ca type are very rare. Bielec-Bąkowska and Łupikasza (2009) similarly concluded that in Małopolska ice days are more probable during advection from the east, southeast and the northern sector.

Atmospheric circulation is also an important driver of long-term variability in the frequency of winter ice days. Positive correlations were found between the frequencies of ice days and the frequencies of Ea, SEa, Ec and NEc types. The opposite relations concern ice days and Wa, SWa and Wc types. Statistically significant growing trends in the frequency of Ec type and decreasing trends in the frequency of Wa type suggest a possible future decrease in the occurrence of ice days. On the other hand, a decrease evidenced in the frequency of Wc may lead to an increase in the number of ice days. Due to complicated linkages between ice days and atmospheric circulation, an increase in the winter air temperature cannot be directly translated as a decrease in the frequency of ice days.

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