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High atmospheric pressure and accompanying cold season weather types in Poland (1951–2010)

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ABSTRACT: Recent climate change manifests itself in changes to the properties and frequency of particular weather types. This study explores the statistical characteristics of weather types that accompanied strong high sea level pressure (≥1030 hPa 'SHP') over Poland during the period from 1951 to 2010. Sea level pressure NCEP/NCAR Reanalyses data of 2.5° × 2.5° resolution, as well as observed climatic data from 8 Polish weather stations, are used. There was a small increase in SHP frequency during the study period in the cold half-year (October to March), especially for synchronous SHP occurring over the entire territory of Poland. The dominant weather types accompanying SHPs were ground frost and frosty types, although cool and moderately warm types were also frequent. In most cases, days with SHPs were without sunshine and without precipitation. The long-term variability in the frequency of occurrence of particular weather types on days with SHP indicates an increase in the frequency of warmer weather after 1980 as compared to the period before that year. However, this warming demonstrates significant regional and seasonal variation.

KEY WORDS: Air pressure · Strong high pressure · Weather extremes · Weather types · Poland · Central Europe

1. INTRODUCTION

This study examines the relationship between an extreme positive air pressure anomaly (hereafter referred to as strong high pressure, SHP) and climate characteristics in Poland. Although mid-latitude continental SHP events may co-occur with various air mass and advection types, they represent a specific kind of disturbance of mean large scale circulation with some common effects on the local weather. During SHP, atmospheric stability is predominantly high, which reduces the frequency of rainy or snowy weather and favours the development of extreme thermal conditions.

Recent studies point to significant regional variability in long-term air pressure change in the European region. The key features of this change include an increase in pressure values to the south of approximately 55° N, a corresponding change in the location of major Atlantic highs and a decrease in air pressure in northern and eastern Europe (Davis et al. 1997, Piervitali et al. 1997, Schönwiese & Rapp 1997, Bhend 2005). The number of days with very high pressure in Central Europe gradually decreased throughout the 20th century (Bielec-Bąkowska & Piotrowicz 2011) and reached its lowest point between approximately 1960 and the late 1980s (Cahynová & Huth 2009, in press, Kyselý 2008). However, an increasing trend was recorded in the second half of the 20th century and at the beginning of the 21st century (Stefanicki et al. 1998, Kyselý & Huth 2006, Bielec-Bąkowska 2010b, 2014). This might explain why there was no marked decrease in the occurrence of cold weather types despite the

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increase in the frequency of mild winters in this part of Europe. An increased persistence of anticyclones and the accompanying cold spells has also been reported (Kyselý 2008).

We examined the frequency and variability of SHP events and their impact on the distribution of thermal weather types and cloudiness in Poland. We also looked at the possible links between the recent winter warming in Poland (Degirmendži et al. 2004, Piotrowski & Jędruszkiewicz 2013) and the temporal change in SHP events.

2. DATA AND METHODS

Our study is based on average daily air pressure values measured at sea level at 12 grid points from a 2.5° × 2.5° grid covering the territory of Poland (Fig. 1). The data, spanning the years 1951 to 2010, comes from the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalyses made available by the National Oceanic & Atmospheric Administration/Oceanic & Atmospheric Research/Earth System Research Laboratory Physical Sciences Division (NOAA/OAR/EARL PSD, Boulder, Colorado, USA; www.cdc.noaa.gov/). The data makes it possible to select days with SHP on which high pressure values persisted for most of the day and thus represented a suitable condition for the development of high atmospheric pressure in the region.

The definition of SHP as days with a pressure equal to or higher than 1030 hPa (Bielec-Bąkowska 2010a,b, 2014) has not changed with respect to previous research. Similar values can be found in literature, although some researchers prefer to use 1035 hPa as the threshold value (Kłysik 1995, Kożuchowski 1995). However, an analysis of air pressure values in the Euro-Atlantic sector has shown that over most of the territory of Europe the value of 1030 hPa is close to the 95th percentile of all the recorded values (Bielec-Bąkowska 2010b, Bielec-Bąkowska & Piotrowicz 2011), which supports its use as an extreme event threshold. SHP events of this magnitude are characterised by their large spatial extent, which normally substantially exceeds a radius of 1000 km. In this study, SHP events are understood as days when the mean daily sea level air pressure values exceed the given threshold. This definition is applied both locally (to 1 observation station and its nearest grid point) and to the entire region when the threshold is expected to be exceeded at all 12 grid points.

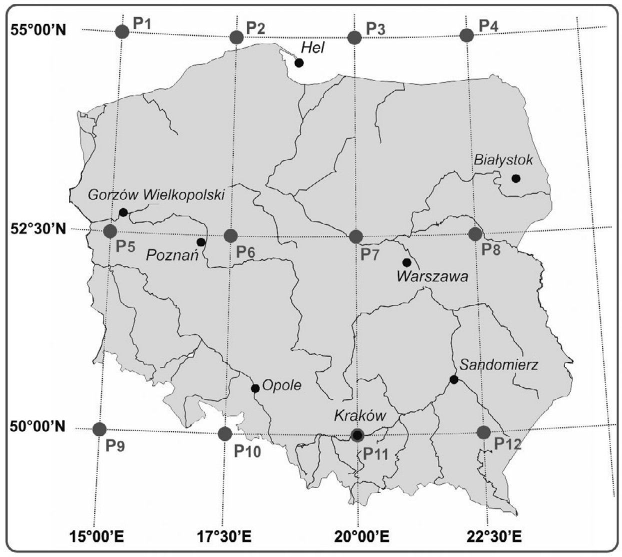

Fig. 1. Meteorological stations and grid points used in the study

Due to the seasonality of the occurrences of high air pressure (with peak values in winter and a minimum in summer), each year has been split into a warm half-year (April to September) and a cold half-year (October to March), and the annual values have been determined for a year lasting from 1 July to 30 June (e.g. from 1 July 1951 to 30 June 1952). The study mostly focuses on SHP events in the cold season (October to March), which were often examined in calendar order, e.g. from 1 October 1951 to 31 March 1952.

The study is based on observed climatic data from 8 weather stations (Hel, Gorzów Wielkopolski, Poznań, Warszawa, Białystok, Opole, Sandomierz and Kraków), sorted into 3 groups, according to their geographical location, i.e. Coast, East and West regions (Fig. 1, Table 1). They are characterized by different frequencies of the analysed weather types, resulting from different environmental conditions and atmospheric circulation over the areas where they are located.

Unlike most of the available studies of weather types, often confused with types of synoptic situation (Littmann 2000, Bissolli & Dittmann 2001, Post et al. 2002, Sheridan 2002, Brown 2004, Makra et al. 2009), this study goes beyond considering just a single isolated climatic element or indicator (e.g. Niedźwiedź 1983), and looks at a complex of meteorological elements which define the status of the atmosphere on a given day.

A wide range of methods for defining weather types has been published. The oldest of these include the method devised by Fedorov (1925), Nichols (1925), Switzer (1925) and Chubukov (1962). These authors

Table 1. Localisation of meteorological stations used in the study. a.s.l.: above sea level

Station	Latitude (N)	Longitude (E)	Altitude (m a.s.l.)
Coast			
Hel	54°36′	18°49′	3
West region			
Gorzów Wielkopolski	52°45′	15°17′	73
Pozna	52°25′	16°50′	92
Opole	50°40′	17°58′	178
Kraków	50°04′	19°58′	206
East region			
Warszawa	52°17′	20°58′	99
Białystok	53°06′	23°10′	151
Sandomierz	50°42′	21°43′	218

grouped the values of selected meteorological elements into daily intervals and assigned codes to them. This approach was largely followed in weather-type classification systems in Poland (Woś 1999, Piotrowicz 2010) and Greece (Maheras 1984). The only differences between these systems are in the number of the included weather elements and in the definition of their ranges. The latest classification systems have opted for cluster analysis (Kassomenos 2003, Michailidou et al. 2009), the percentile method or the '3 sigma' method (involving long-term averages with a standard deviation of ±0.5 to 2.5) for grouping weather elements (Ciaranek & Piotrowicz 2014).

In Poland, the best known and most commonly used system is the weather-type classification devised by Woś (1999). Its main advantage is that it takes into account maximum and minimum temperatures, as well as average daily values. The tight ranges used (5 to 10°C) enable a precision analysis and the division of thermal weather types into 3 main groups: warm (maximum [T_{max}] and minimum temperature [T_{min}] > 0°C), ground frost (T_{max} > 0°C and T_{min} < 0°C) and frosty (T_{max} and T_{min} < 0°C). Additionally, the system includes information on the cloud cover and total precipitation.

This study employs a slightly modified version of the thermal weather-type classification system introduced by Woś (1999), as well as a weather-subtype system developed by Piotrowicz (2010). The observational data is classified into weather types and weather subtypes as follows:

- average daily maximum and minimum temperatures determine thermal weather types
- relative sunshine duration and daily precipitation determine weather subtypes (detailed description in Section 4.1)

Weather-type analysis was mainly performed separately for each station, taking into consideration the threshold criterion (≥1030 hPa) at the grid point nearest to the station. Trend significances were calculated using the Mann-Kendall test (Mann 1945, Kendall 1975).

3. STRONG HIGH PRESSURE EVENTS OVER POLAND

There were 2058 days when the pressure was ≥1030 hPa at at least one (hereafter ≥) grid point during the study period. This means that, on average, there were 34.7 d yr^{-1} when at least a part of Poland was under the influence of a strong high pressure system. The highest number of such days (59) was recorded in 1988/89 and the lowest (8) in 1966/67 (Table 2, Fig. 2). There were only 415 days when the pressure threshold criterion was met at all 12 grid points, which is also referred to as synchronous SHP. The average annual number of occurrences was 7, and the extreme years included 1992/93 with 23 such days and 3 years with none (Table 2, Fig. 2).

Most SHP events occurred during the cold season (October to March), accounting for >80% of all occurrences in 54 years and >90% in 38 years. As a consequence, the cold season statistics are very similar to the annual statistics (Table 2, Fig. 2). SHP was very rare during the warm season, occurring with an average of approximately 2.7 d yr^{-1} for the ≥1 out of 12 grid points criterion, while synchronous SHP at all 12 grid points occurred on just 7 d yr^{-1} (Table 2, Fig. 3). For this reason, most of our examinations are limited to the analysis of SHP events in the cold half-year.

The occurrences of SHP (annual and cold season values) showed a slight increase in frequency, which only resulted in a statistically significant trend (about 0.8 days per 10 years; $p < 0.05$) for synchronous SHP (Table 2, Fig. 2). However, it is worth noting the occurrence of 2 periods when the number of high-pressure systems dropped substantially, i.e. in the 1960s and early 1970s (by half) and at the turn of the century.

We also examined how temporal changes affected the frequency of SHP in various parts of the year. The results obtained for individual months suggest very minor systematic long-term changes which can only be regarded as evidence of a slight growth tendency. They are mostly not statistically significant, except for strong highs covering the whole country in December. As the low frequency changes

Table 2. Number of days with air pressure ≥1030 hPa (strong high pressure days) at selected grid points (1951 to 2010). Tendency is given as number of days per 10 years. P1/12: pressure ≥1030 hPa occurred at ≥1 of 12 grid points; P 12/12: pressure ≥1030 hPa occurred at all 12 grid points synchronously; 'Year' is the period from 1st July to 30th June e.g. from 1 July 1951 to 30 June 1952; **bold:** statistically significant at $p < 0.05$; ***bold italics***: statistically significant at $p < 0.01$

Index	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P1/12	P12/12
Year														
Highest	41	40	39	38	35	37	32	33	41	42	41	39	59	23
Mean	19.0	18.3	18.6	19.5	17.7	18.6	18.4	18.6	18.7	20.2	19.0	18.6	34.7	7.0
Lowest	3	3	4	3	3	4	3	2	1	4	3	4	8	0
Tendency	0.65	0.61	0.60	0.77	**1.22**	0.97	0.92	0.83	***1.86***	1.36	1.00	0.96	1.41	**0.78**
October–March														
Highest	38	36	38	36	33	34	31	33	41	42	41	39	52	23
Mean	17.4	16.6	17.3	18.2	16.5	17.3	17.4	17.8	17.9	19.5	18.5	18.2	31.9	6.9
Lowest	3	3	4	3	2	3	2	2	1	3	2	4	8	0
Tendency	0.41	0.43	0.38	0.52	**1.10**	0.81	0.70	0.65	**1.69**	1.22	0.97	0.91	1.2	**0.76**
April–September														
Highest	7	7	8	7	4	5	6	6	5	4	4	4	8	2
Mean	1.6	1.7	1.4	1.2	1.2	1.2	1.0	0.8	0.9	0.7	0.5	0.4	2.7	0.1
Lowest	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tendency	**0.24**	0.19	**0.22**	**0.24**	0.12	0.15	**0.21**	0.16	0.16	0.13	0.02	0.04	0.21	0.02

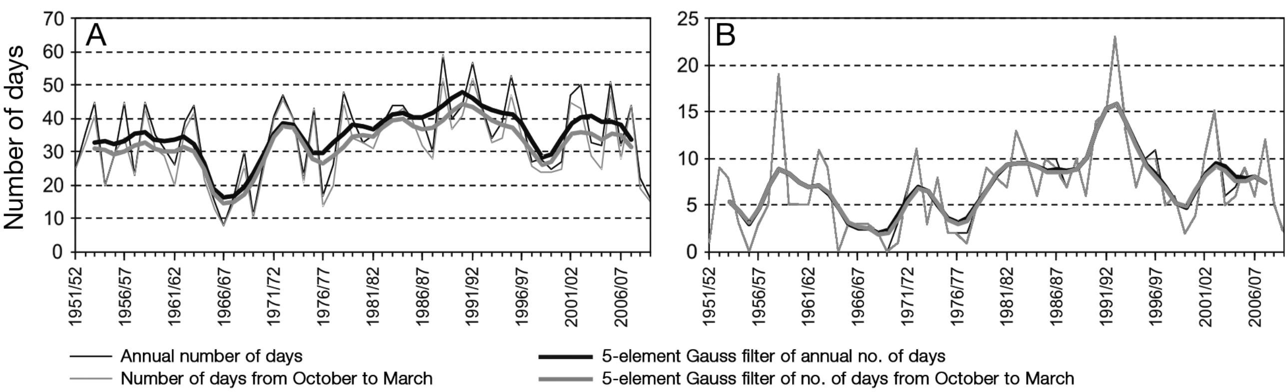

Fig. 2. Number of strong high pressure days: (A) at ≥1 grid point, (B) at all 12 grid points synchronously (1951 to 2010)

of the accompanying weather types differ notably between the early and late parts of the cold season (see Section 4.4), the trends for the first and second half of the winter season (i.e. for October to December and January to March, respectively) were also analysed. The increase in SHP was only noticeable for October to December (0.37 d decade^{-1}, $p < 0.05$; Fig. 4).

A detailed analysis showed that the frequency of SHP mainly increased around the middle of the examined period. Indeed, there was a much greater number of SHP events between 1981 and 2010 as compared to the preceding 30 yr (Table 3).

A spatial analysis of SHP events showed that both the number of occurrences and the long-term patterns were similar for individual grid points (Figs. 2 & 4). The values of correlation coefficients between SHP frequencies at particular grid points were usually very high (between 0.7 and 0.9). Larger differences were only found between the north and south of the country during warm seasons. It is worth noting, however, that the pattern of change in the north of the country was more gradual than elsewhere.

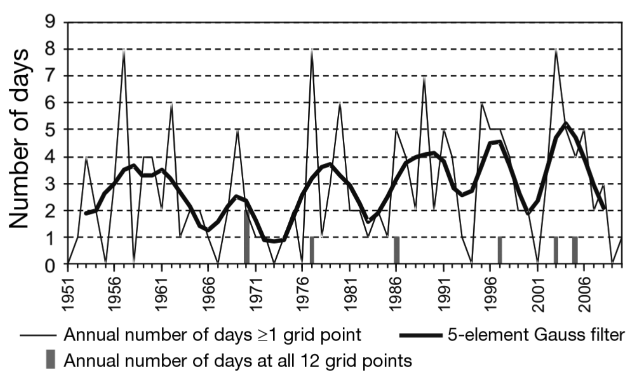

Fig. 3. Number of strong high pressure days in the warm half year (April to September) from 1951 to 2010

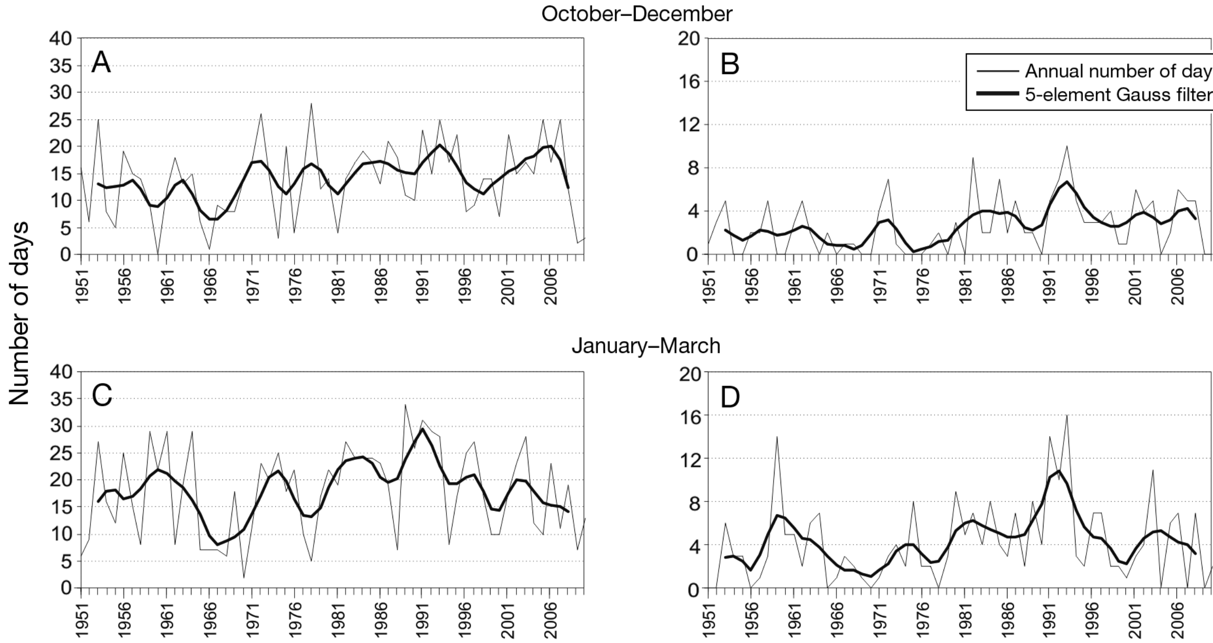

Fig. 4. Number of strong high pressure days: (A,C) at ≥1 grid point, (B,D) at all 12 grid points synchronously (A,B: October to December and C,D: January to March) from 1951 to 2010

The south of Poland experienced an exceptionally large number of strong anticyclones in the late 1980s and early 1990s. The increasing trend was only statistically significant ($p < 0.05$) at points P5 and P9 (1.2 and 1.9 d decade^{-1}, respectively).

During the warm season, SHP events occurred rarely and their long-term pattern was quite smooth. There were only 2 outstanding features in this pattern, i.e. a much lower frequency in the south of Poland and a slight, but statistically significant, rising trend in the north (Table 2).

The long-term variability in SHP events at individual grid points was similar to the overall trends for Poland. The number of days with SHP was generally higher in the second half of the study period than in the first 30 yr and this difference was especially considerable for December and January (60 % of SHP occurred in the second half-period). However, the linear trend for the entire period was only significant at P10 and only for December. The regional differences in the occurrences of SHP were larger in summer than in winter. In summer, the frequency of SHP events decreased from the northwest to the southeast.

4. CONNECTIONS BETWEEN SHP AND WEATHER TYPES

As most SHP events occur from autumn to spring, only the cold half-year (October to March) SHPs are considered in this analysis. This section consists of 4 subsections: first, the unconditional weather-type distribution is briefly described (Section 4.1), fol-

Table 3. Number of strong high pressure (SHP) days at ≥1 grid point and at all 12 grid points synchronously in the period from 1951 to 2010 (annual course)

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
SHP at ≥1 grid point													
1951–1980	175	156	143	22	13	8	1	0	28	105	120	150	921
1981–2010	246	204	143	34	24	2	3	1	29	120	119	212	1137
SHP at all 12 grid points													
1951–1980	35	50	11	0	0	0	0	0	3	7	18	25	149
1981–2010	63	60	33	2	0	0	0	0	2	20	21	65	266

Table 4. Frequency of weather type occurrence in particular regions from October to March (1951 to 2010). Coast: Hel; West: Gorzów Wielkopolski, Poznań, Opole, Kraków; East: Białystok, Warszawa, Sandomierz; SHP: strong high pressure; T_{mean}, T_{min}, T_{max}: mean, minimum and maximum air temperature, respectively; U: relative sunshine duration; P: sum of precipitation

Symbols	Partition	Weather types	Unconditional frequency (%)			Frequency (%) when SHP was noted at the nearest grid point			Frequency (%) when SHP was noted at all grid points		
			Coast	West	East	Coast	West	East	Coast	West	East
Thermal weather types											
T1	T_{mean} > 15.1°C; T_{min} and T_{max} > 0°C	Hot	0.2	0.9	0.5	–	–	–	–	–	–
T2	T_{mean} 5.1–15.0°C; T_{min} and T_{max} > 0°C	Warm	30.4	29.3	22.8	14.8	10.1	6.5	12.3	5.8	4.1
T3	T_{mean} 0.1–5.0°C; T_{min} and T_{max} > 0°C	Cool	27.4	17.7	16.0	19.1	12.1	8.5	17.8	9.2	6.4
T4	T_{mean} > 0.1°C; T_{min} ≤0°C; T_{max} > 0°C	Ground frost cool	15.8	20.6	19.7	19.3	20.0	16.4	19.7	13.0	12.6
T5	T_{mean} −5.1–0.0°C; T_{min} ≤0°C; T_{max} > 0°C	Ground frost cold	11.0	14.1	15.5	15.4	20.6	18.1	16.9	21.0	16.2
T6	T_{mean} −5.0–0.0°C; T_{min} ≤0°C; T_{max} ≤ 0°C	Cold	10.8	7.8	10.4	19.2	12.8	14.8	20.3	15.6	16.6
T7	T_{mean} < −5.1°C; T_{min} and T_{max} < 0°C	Frosty	4.4	9.6	15.1	12.2	24.4	35.7	13.0	35.4	44.1
Sum			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Weather subtypes											
00	U ≤33.0% and P < 0.1 mm	Without sunshine and precipitation	25.5	26.9	27.8	37.7	42.4	40.3	41.2	41.4	41.1
10	U = 33.1–67.0% and P < 0.1 mm	Sunny, without precipitation	11.2	14.3	12.5	18.0	20.3	17.7	18.2	21.5	19.4
20	U ≥67.1% and P < 0.1 mm	Very sunny, without precipitation	8.6	9.0	11.3	25.0	19.6	28.0	24.0	23.4	26.0
PP	U ≥0.0% and P ≥ 0.1 mm	With precipitation ≥0.1 mm	54.7	49.8	48.4	19.3	17.7	14.0	16.6	13.7	13.5
Sum			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

lowed by an analysis of weather types conditioned by the SHP at the nearest grid (Section 4.2) and those occurring during synchronous SHP over Poland (Section 4.3); and finally, the long-term variability of conditional and unconditional weather-type frequencies is discussed (Section 4.4).

4.1. Weather-type frequencies in Poland in the cold half-year

The majority of weather types occur in the cold half-year, the only exception being hot weather. At every weather station the group of warm weather types (T3 and T2) was dominant during the study period and accounted for between 35.2% (Białystok, East region) and 57.8% (Hel, Coast; Table 4). The frequency of weather types from the ground frost group (T4 and T5) varied from 26.8 to 35.2%. Days with frosty weather (T6 and T7) were the least frequent group amounting to between 15.2% at Hel and 28.6% at Białystok (25.5% in the East region; Table 4).

Considering sunshine duration and precipitation, the dominant weather types were those with precipitation ('PP'; from 48.4% in the East region to 54.7% at the Coast), as well as days without sunshine and without precipitation ('00'; from 25.5% at the Coast to 27.8% in the East region).

4.2. Weather on days with SHP at the nearest grid

Four weather types were dominant on days with air pressure ≥1030 hPa at the nearest grid point: 2 from the ground frost group (T4 and T5) and 2 from the frosty group (T6 and T7). Together, they accounted for approximately 80% of all SHP days (77.8% in the West and 85.0% in the East region) between 1951 and 2010 (Table 4). At Hel, 6 thermal weather types (T2 to T7) occurred with similar frequency. Warm group types occurred sporadically, apart from at the peninsular station at Hel. This is surrounded by the Baltic Sea, which moderates the winter cold.

SHP was most frequently associated with weather without sunshine and without precipitation at all stations. This subtype accounted for between 37.7% of SHP days at Hel (P3) and 43.2% at Krakow (P11) during the study period (42.4% in the West region; Table 4). The very sunny ('20') and sunny without precipitation ('10') subtypes together accounted for 40 to 45% of SHP days, and a con-

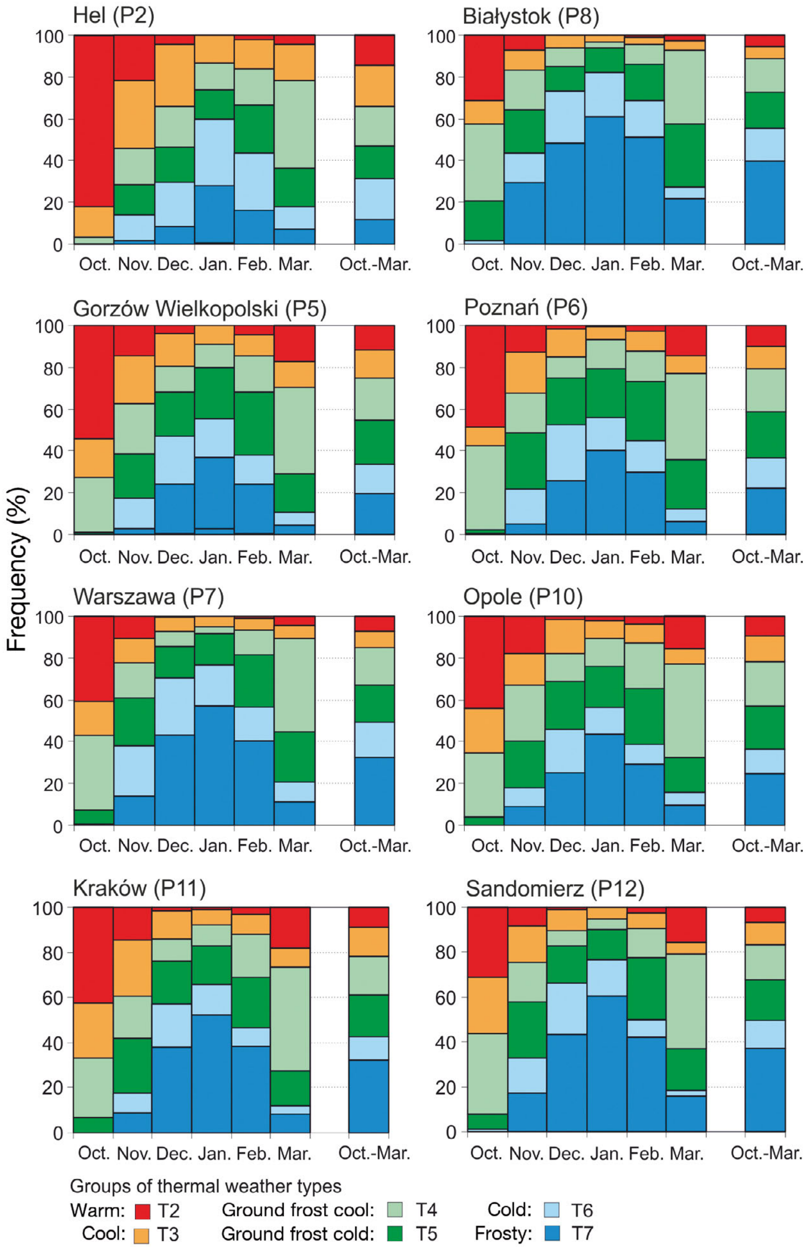

Fig. 5. Frequency of the occurrence of thermal weather types at particular stations on strong high pressure (SHP) days in the cold half year (October to March) from 1951 to 2010

siderable proportion of the days (14.0 to 19.3%) still had weather with precipitation.

An analysis of the monthly frequency of thermal weather types on SHP days in the cold half-year (Fig. 5) found that the warm weather group (T2 and T3) was dominant in October. It accounted for 96.9% of SHP days at Hel and 42.2 to 72.9% of SHP days elsewhere. Ground frost weather (T4 and T5) was the second most frequent group in this month. By contrast, the frosty weather group (T6 and T7) was most frequent in December, January and February. Generally, the eastern region was the coldest and the highest frequency of cold and frosty weather types with SHP was observed at Białystok (Fig. 5) with 73, 82 and 68% of such thermal conditions in December, January and February, respectively. In March, daily temperatures were generally substantially higher during SHP events than in the previous calendar months and therefore ground frost was the dominant weather type in this month (between 59.7% at Gorzów Wielkopolski and 69.3% at Warszawa).

An analysis of weather subtypes with SHP shows that weather without sunshine and without precipitation ('00') was generally the most frequent type, but in October and February, and especially in March, very sunny weather ('20') was also very frequent (Fig. 6).

Between November and January, sunny or very sunny weather was relatively rare and the frequency of the '00' type reached 40 to 50%. Precipitation with SHP was also more frequent in these months than in other parts of the year, although the amount of precipitation was mostly small or very small (not shown).

4.3. Weather on days with synchronous SHP over the entire territory of Poland

Synchronous SHP over the entire territory of Poland was much less frequent than regional SHP, occurring on only 415 days between 1951 and 2010. All the events were recorded between September and April, peaking in February with 110 days (Table 5). The total number of synchronous SHP days for the cold half-year (October to March) was 408.

One purpose of examining weather types with synchronous SHP was to reveal the degree of spatial uniformity of weather with uniform SHP over the country. Our results show that exactly the same thermal type was recorded at each weather station on only 24 out of 408 days. However, when adjacent thermal

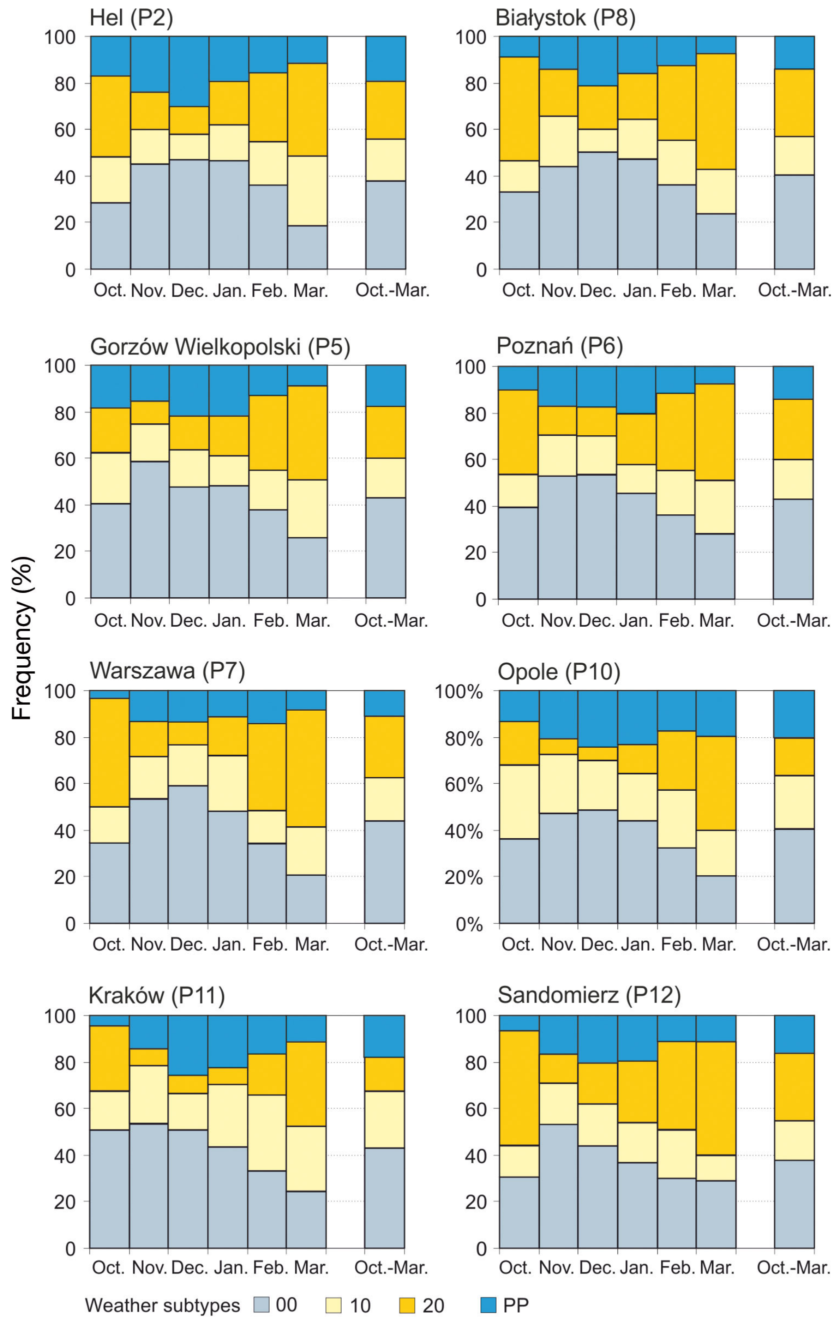

Fig. 6. Frequency of the occurrence of weather subtypes at particular stations on strong high pressure (SHP) days in the cold half year (October to March) from 1951 to 2010. See Table 4 for definitions of weather subtypes

Table 5. Number of synchronous strong high pressure (SHP) days with particular thermal weather types from October to March (1951 to 2010)

Weather type	Month						Sum
	Oct	Nov	Dec	Jan	Feb	Mar	
Number of days with strong highs	27	39	90	98	110	44	408
All 12 stations							
Warm group (T2, T3)	5	5	3	–	2	2	17
Ground frost group (T4, T5)	–	1	–	4	11	12	28
Frosty group (T6, T7)	–	4	22	43	32	3	104

types were examined together using the defined thermal groups, the picture was quite different. There were 104 days on which frosty group weather (T6 and T7) occurred at all weather stations, another 28 days with ground frost weather (T4 and T5) all over the country and another 17 days with warm group weather (T2 and T3) at all stations.

Weather-type frequencies and their seasonality show a picture similar to that of regional SHP events, with the only identifiable differences being higher uniformity (i.e. higher ratio of the occurrence of the dominant weather type) for particular months and clearer seasonal changes in the dominance of weather types (Table 5). The results show that the dominance of T6 and T7 types was overwhelming between December and February, ground frost weather (T4 and T5) dominated in March and warm group weather (T2 and T3) in October, while November and partly February were transitional months. However, a few exceptions were recorded when mild (T3) weather occurred in December and February.

The analysis of weather subtypes with synchronous SHP confirms the findings described in Section 4.2. SHP mostly favours '00' weather (ca. 41 %). In all regions, sunny ('10') and very sunny ('20') weather was recorded with similar frequencies and these 2 subtypes together accounted for approximately 42 to 45 % of all days with synchronous SHP. Precipitation with synchronous SHP had an even lower frequency than that with regional SHP. However, there were still 6 instances of precipitation >5 mm at 4 weather stations (Gorzów Wielkopolski, Poznań, Warszawa and Hel).

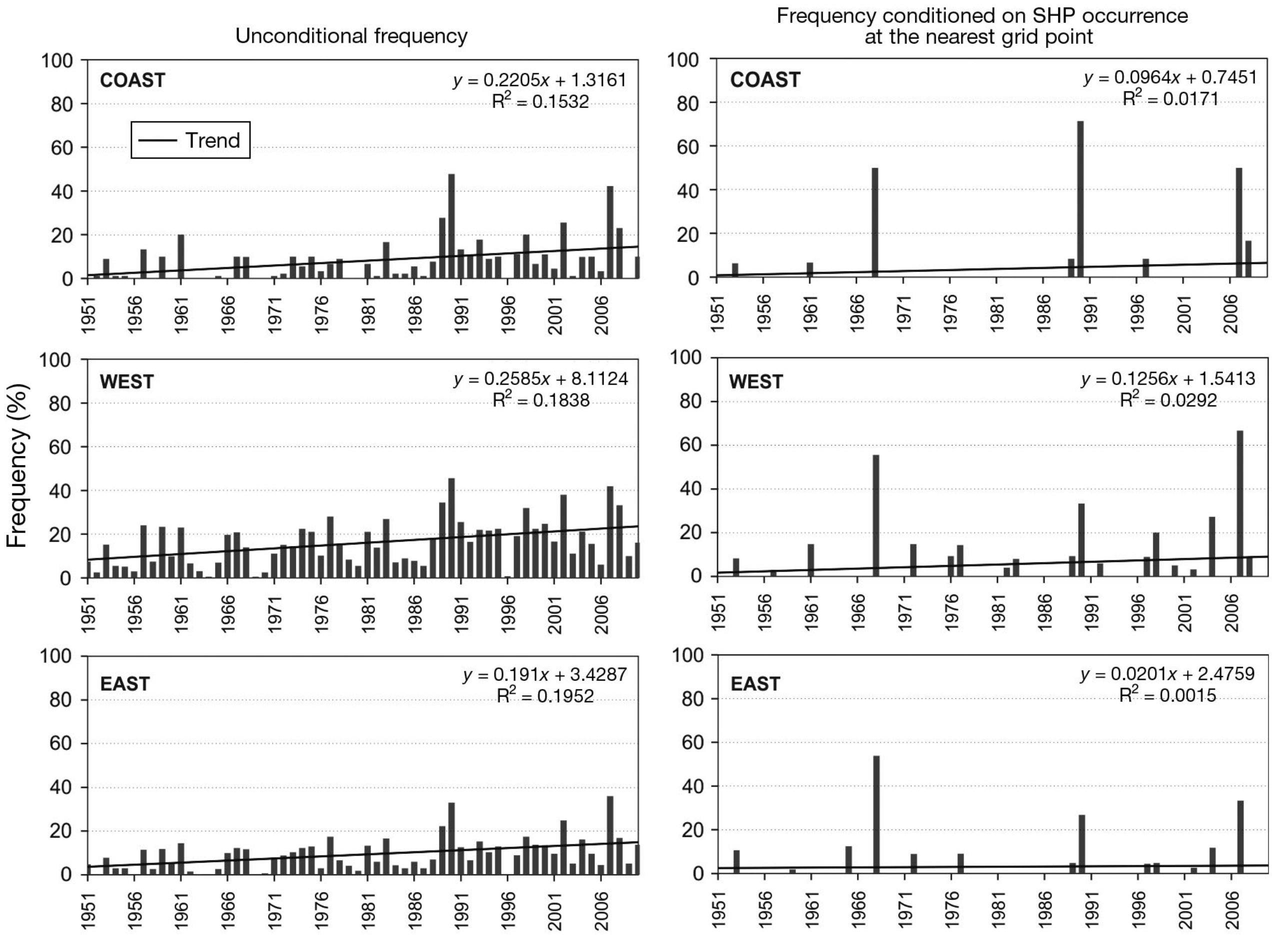

Fig. 7. Unconditional and conditional (strong high pressure [SHP] at the nearest grid point) frequency of days with warm weather types (T2) in 3 Polish regions (January to March, 1951 to 2010)

4.4. Long-term variability of weather type frequency related to SHP events

The results described in Section 3 showed a long-term increase in the frequency of SHP events. Therefore, it is particularly interesting to examine the long-term frequency changes in the related weather types. Cold half-year SHP events occurring at the grid point nearest to the weather station are considered in this analysis, along with long-term changes in unconditional frequencies of weather types. The results are broken down into 2 parts of the cold half-year, i.e. October to December and January to March. The reason for this division is that the results differ markedly between the first and the second half of the cold half-year. In a standard winter season (December to February), the analysed changes in weather-type frequency are similar but not so considerable as those recorded from January to March. Therefore, changes in the December-February season are not described in the following part of the paper.

As regards the frequency of warm group weather types, the trends for October to December during the study period were small and statistically insignificant. However, starting from the second half of the 1980s, these weather types started to occur with increased frequency between January and March (Fig. 7; the changes are statistically significant at 0.01 level). When warm group weather types occurred on days with SHP, the changes were less visible than those of the unconditional frequencies; however, greater changes were observed when the cool type (T3) was examined separately (Fig. 8). The increase in the frequency of SHP days with cool weather (T3) was only statistically significant at the Coast and amounted to 5.2 days per 10 years during the study period. In other cases, the increase in the number of days with T2 and T3, though notable, was not statistically significant. At Hel, in the second half of the analysed period (1981 to 2010), when SHP occurred at grid points P2 or P3 between January and March, the T2 weather type accounted for approximately 40 % on average.

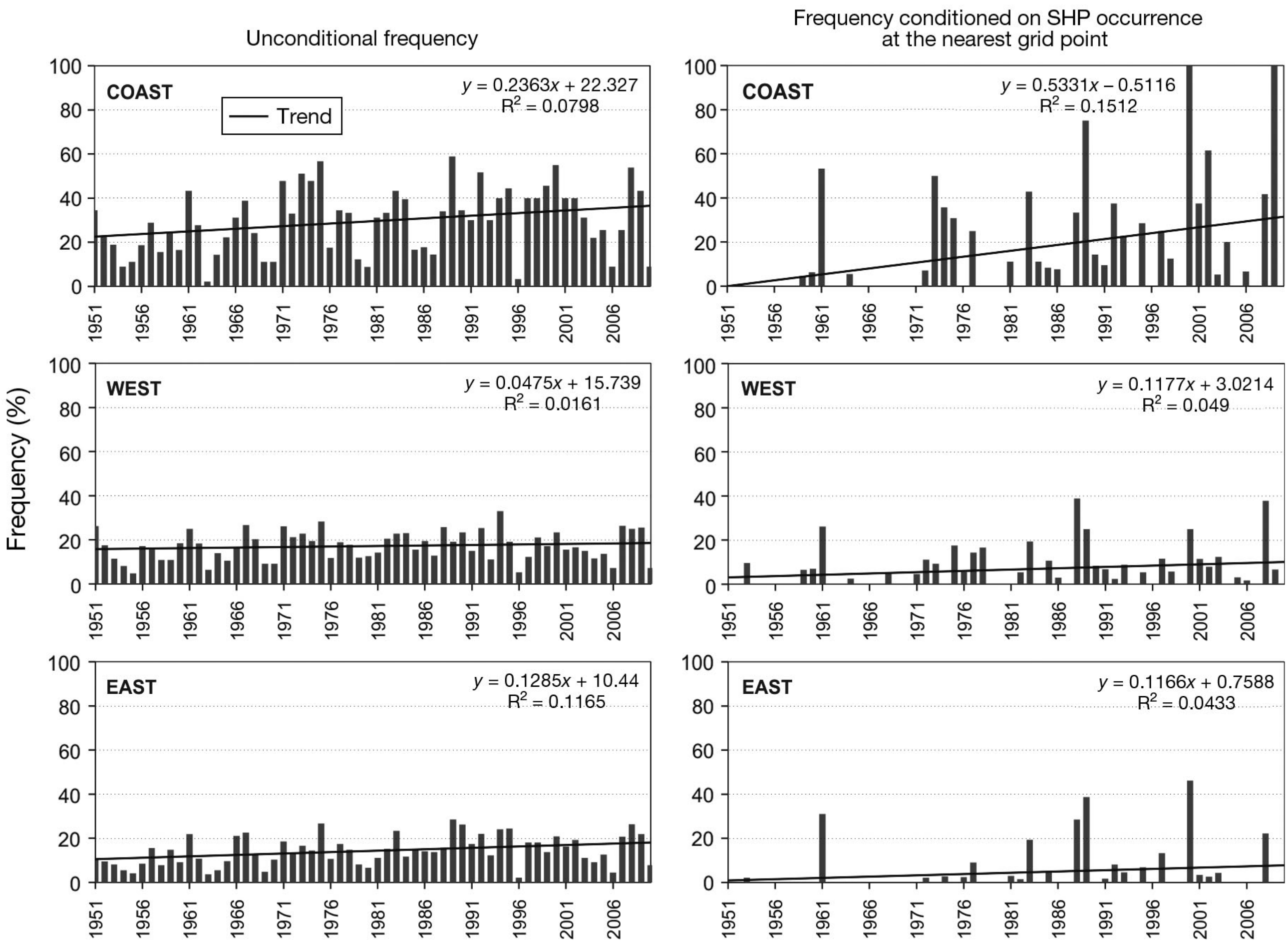

Fig. 8. Unconditional and conditional (strong high pressure [SHP] at the nearest grid point) frequency of days with cool weather types (T3) in 3 Polish regions (January to March, 1951 to 2010)

Days with ground frost weather (T4 and T5) were not associated with any significant frequency change during the study period, either within the entire October to March period or any of the sub-periods. The only noticeable trend was a slight decrease in their number after the second half of the 1990s, which was clearer in the East and West regions than at the Coast.

As regards the coldest weather types (T6 and T7), a clear decline both in the conditional and unconditional frequency could be seen in the January to March period, although the trends were not statistically significant. The decline was most notable for the coldest thermal weather type (T7). The greatest drop in the frequency of their occurrence was recorded in eastern Poland, i.e. in the region where days with this weather type most often accompany SHP (Fig. 9).

Considering the long-term variability of weather subtypes, an increase in the frequency of days with very sunny weather and without precipitation ('20') could be observed in all of the investigated regions. This change appeared both in the general climate of the cold half-year and during SHP events. The increase was particularly large in the second half of the cold half-year (January to March), and it was greatest in the West, where the change was statistically significant at the level of 0.01. The frequency of the other weather subtypes did not change significantly during the analysed period.

5. DISCUSSION AND CONCLUSIONS

The presented distribution of thermal weather types shows that winters in Poland are becoming less cold, both during anticyclonic situations and otherwise. Considering the period of 1951 to 2010, this warming was prominent only in the second half of the cold half-year (between January and March).

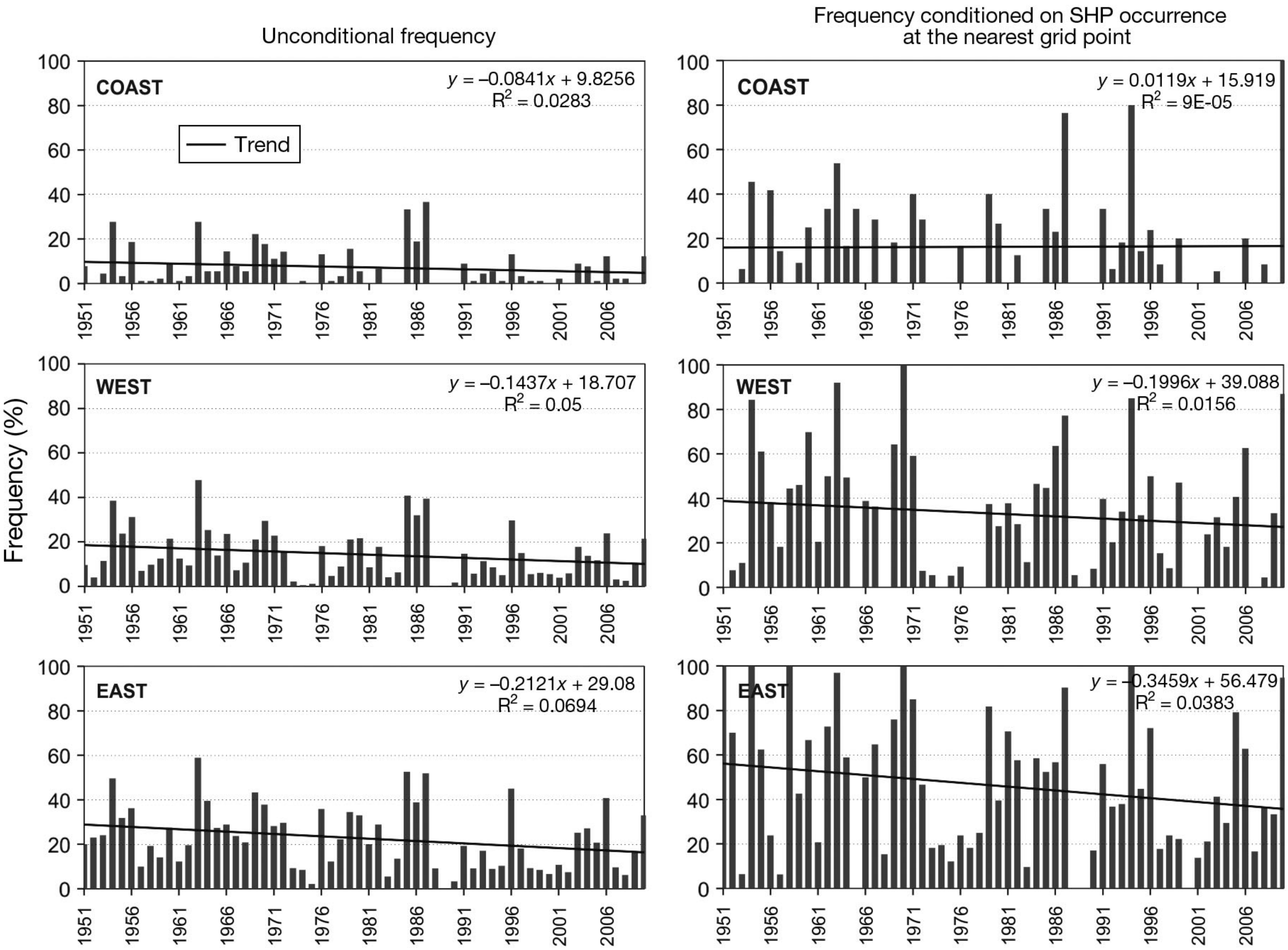

Fig. 9. Unconditional and conditional (strong high pressure [SHP] at the nearest grid point) frequency of days with frosty weather types (T7) in 3 Polish regions (January to March, 1951 to 2010)

The identified warming trend is in keeping with the results of several other studies and with the observed increase in westerly winter flows over the study area (Moberg & Jones 2005, Hoy et al. 2013, etc.). Declining numbers of frosty days in Poland have also been reported by Łupikasza et al. (2014). More significant warming in the second half of the cold season as compared to its onset has also been reported in other European countries: the warming trend is most significant from January to April in Estonia (Jaagus 2006), and from December to March in Hungary (Domonkos & Tar 2003). Irannezhad et al. (2016) reported that the trend of the spring snow ablation date contributes to the shortening of the snowy season in southern Finland to a greater degree than that of the onset date in autumn.

Winter and early spring warming in Europe during the last decades of the twentieth century has been more intensive than in other parts of the year. van den Besselaar et al. (2010) argue that although both circulation changes (i.e. increasing intensity of westerly flows) and radiation changes (increasing greenhouse effect) significantly contribute to and explain the observed warming, a gap still remains between the observed and expected trends. In particular, the intensity of the observed warming in winter and early spring is greater than the observed circulation changes and direct greenhouse effect would suggest. A hypothesis put forward by van den Besselaar et al. (2010) suggests that the gap in our understanding can be filled by considering the long-term decline in the extent of snow cover in Europe. Indeed, a decreasing trend in the number of snowy days has been reported both for Poland (Falarz 2004) and for the wider European region (Henderson & Leathers 2010), although the trends for Poland are only slight and not statistically significant. Snow depletion is likely to be an explanatory factor for the asymmetry between the temperature trends around the onset of the cold season on the one hand, and those characteristic of the end of the cold season on the other hand, as the snow radiation effect is more pronounced in early spring than in late autumn (Frei & Robinson 1999). Note, however, that without an in-depth analysis of this connection, snow depletion could either be an explanatory factor or a consequence of the intensive early spring warming, or both.

In this study, special attention was paid to long-term changes in strong high atmospheric pressure events (sea level pressure above 1030 hPa, SHP) and the weather types which accompanied them. The analysis was based on observed climatic data from 8 weather stations and gridded observational atmospheric pressure data covering the period from 1951 to 2010. The results confirm that winter warming is a notable change in the observed climate of Poland. This change manifests itself in the frequency changes of warm, cool and frosty thermal weather types, and is particularly prominent in the second half of the cold season (January to March). The frequency of the analysed SHP events shows clear seasonality, i.e. such events are much more frequent in winter than in summer. This seasonal difference is a consequence of dynamic differences in atmospheric processes triggered by differences in surface radiation processes between winter and summer. Cold and snowy continental surfaces favour the development of SHP; therefore, it is a somewhat surprising result that the frequency of winter SHP does not decline along with increasing temperature. In fact, our study has revealed evidence of a slight upward trend in the frequency of SHP events both for winters and summers, but especially from October to December. This may result from the fact that most SHP events are linked to the occurrence of the Siberian High, which in the cold half-year also extends over Eastern Europe. Some studies indicate that the pressure values in this system were decreasing until the 1990s, only to start increasing again in the last 2 decades (Jeong et al. 2011). This may in turn be a consequence of the autumn growth of the snow cover over Eurasia, which has been observed during this period (since the 1990s) (Allen & Zender 2011, Cohen & Jones 2011).

During the SHP events, a shift towards warmer weather types also appears, although few such trends were found to be statistically significant. Together with the shift towards warmer thermal types, an increase in the frequency of sunny weather with winter SHP events was found and the latter change was statistically significant for the January to March period in the western half of the country.

Considered jointly, the results indicate that it is difficult to separate the origin of the observed climate change from the circulation component and the local radiation component, as the characteristics of circulation patterns and those of the accompanying weather change along with ongoing climate change.

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