



Occurrence and synoptic background of strong and very strong frost in spring and autumn in Central Europe

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Abstract

The objective of the paper was the determination of the circulation conditions of occurrence of strong and very strong frost in Central Europe. A frost day was defined as a day with the minimum temperature lower than 0 °C and maximum temperature higher than 0 °C. Moreover, a division of frost was performed in terms of value of minimum temperature, resulting in the designation of mild frost (up to −2.0 °C), moderate frost (from −2.1 to −4 °C), strong frost (from −4.1 to −6 °C) and very strong frost (< −6 °C). The study was based on data from the years 1966–2015 from the Institute of Meteorology and Water Management—National Research Institute, Deutscher Wetterdienst and National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The analysis of baric conditions employed values of pressure at sea level, height of isobaric surface of 500 hPa and air temperature at a level of 850 hPa, as well as their anomalies. The spatial analysis showed that the number of frost days in spring and autumn increased from the west to the east of Central Europe. A decrease in the number of frost days, however, is observed over the prevailing area. Average conditions favouring the occurrence of strong and very strong frost both in spring and autumn were related to higher than average pressure at sea level over the prevailing area of the Euro-Atlantic sector. Such baric conditions caused advections of cool air masses from the northern sector.

Keywords Spring and autumn frost · Circulation conditions · Climate change · Central Europe

Introduction

Contemporary climate change is unquestionable and evident, among others, in the observed increase in mean global air temperature (IPCC 2013). Global warming is also expressed in the declining number of frost days and in the lengthening of the frost-free seasons (Scheifinger et al. 2003; Jylhä et al. 2008; Potop et al. 2014; Tomczyk et al. 2015; Wypych et al. 2017; Bielec-Bąkowska et al. 2018) and vegetation seasons (Goergen et al. 2013; Tomczyk and Szyga-Pluta 2018). Scheifinger et al. (2003) evidenced that in the second half of the twentieth (1951–1997) century, changes in the date of

occurrence of the last day with spring frost in Central Europe fluctuated at a level of 2 days/10 years. The latest studies show the intensification of the changes, reaching approximately 5 days/10 years in the west of the country in recent years (1951–2010) (Wypych et al. 2017). Temperature increase can have serious consequences for vegetation, because air temperature not only does stimulate the cycle of growth of plants but also constitutes a potential threat to them, e.g. through the risk of occurrence of hot days during the vegetative season or late frost in the early beginning of the vegetative season (Scheifinger et al. 2003; Barlow et al. 2015). Increase in temperature in winter and early spring and, consequently, earlier commencement of the frost-free season and vegetation season are of particular importance for the development of plants. It determines the duration of the dormant period and the length of the period of plants development (Chmielewski et al. 2004). The occurrence of late spring frost in combination with increasingly frequent and mild winters constitutes a challenge even for frost-resistant plant species (Burroughs 2002).

The temperature decrease below 0 °C is one of the most dangerous weather conditions for plants in the vegetative season (Schnelle 1963, after Kalma et al. 1992; Dudek et al.

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2012; Chmielewski et al. 2018). The threat of frost to crops particularly occurs at the stage of their sprouting and blooming and in some species also at the stage of ripening (Kozłowski and Trzeciak 1971). The spring air temperature increase causes the beginning of the ontogenetic development. In the beginning, the water content in buds increases and as a consequence, the first visible changes occur (Chmielewski and Götz 2017). From this stage of development, the resistance of buds to cold continuously decreases (e.g. Dennis and Howell 1974; Proebsting and Mills 1978; Longstroth and Perry 1996; Miranda et al. 2005; Chmielewski et al. 2018). The occurrence of frost before the onset of blooming may cause damage to flower buds, but the damage is even larger in the blooming period, when frost may lead to complete loss of crop yield (Chmielewski et al. 2004; Matzneller et al. 2016). At mid-latitudes, most damage occurs during the spring bloom season, when below-freezing temperatures harm flower buds after the loss of cold hardiness; in a changing climate, this risk will remain, due to increasing variance of temperature (Rigby and Porporato 2008).

According to Proebsting (1982), even a single case of frost can lead to losses in efficiency of up to 90% in the case of production of stone fruits. Moreover, frost causes general weakening of the plant organism, resulting in a decrease in its resistance both to diseases and to an effect of unfavourable environmental conditions (Kreyling et al. 2012); damaged tissues also facilitate penetration by, e.g. parasites (Doroszewski et al. 2013).

In Central Europe, both winter and the transient seasons are characterized by high intra- and inter-annual weather variabilities. It is due to the atmospheric circulation, determining an inflow of air-masses of oceanic, continental, or Arctic origin. Therefore, pressure patterns and circulation conditions are the dominant factors modifying weather regime in local and regional scales. The influence of circulation on thermal conditions in Europe, including the occurrence of extremes, has been an object of several studies. It was evidenced that the vulnerability to frequent and rapid weather changes is a key feature of the European climate, related to dynamic circulation conditions (Buishand and Brandsma 1997; Niedźwiedz 2000; Wibig 2001; Huth et al. 2008; Ustrnul et al. 2010). Such rapid day-to-day changes in air temperature (particularly decreases below freezing point) during spring and autumn are strongly relevant to climate-related branches of human activity, particularly agriculture.

The objective of the paper was to determine the temporal and spatial variabilities of occurrence of spring and autumn frost in Central Europe and, secondly, to work out synoptic and circulation conditions causing strong and very strong frost in the studied area. Synoptic conditions were described throughout the air temperature and pressure patterns on different levels in the troposphere. The anomaly-based method, showing departures of sea level pressure and geopotential

heights, as well as departures of temperature on horizontal and vertical cross sections through the troposphere, was applied. Additionally, analysis of antecedent conditions of the frost occurrence was performed by showing the tracks of temperature anomaly centres predating spring and autumn frost in Central Europe.

Research on the frequency and reasons of the extreme weather, which trigger risk for growing and for natural vegetation, is essential for agriculture and bioclimatology of plants. Due to the threat of strong and very strong frost, particularly in the case of crops, the study results, with the feedback of future circulation models, may help understand weather risk in the transient seasons and therefore they can be useful for a broad group of recipients.

Data and methods

The study was based on values of maximum (T_{\max}) and minimum air temperature (T_{\min}) from 40 stations in Central Europe from the period 1966–2015 (in the case of two stations—Kassel, Elbląg—in the years 1966–2013) (Fig. 1). Data verified in terms of quality and homogeneity were obtained from the resources of the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for the stations in Poland and from Deutscher Wetterdienst for the stations in Germany.

A frost day is defined as a day with minimum temperature lower than 0 °C and maximum temperature higher than 0 °C (Kossowska-Cezak 2003). Moreover, a division of frost was performed in terms of the value of minimum temperature into mild frost (up to -2.0 °C), moderate frost (from -2.1 to -4 °C), strong frost (from -4.1 to -6 °C) and very strong frost (< -6 °C) (Dragańska et al. 2004). Then, the number of days with frost in particular categories in the spring season (April–May) and autumn season (September–October) was calculated. Moreover, sequences of days with strong and very strong frost were designated. Next, the multi-annual course of the number of days with frost was analysed, including the tendency of changes and variability of the frequency of occurrence of frost in particular categories. The assessment of statistical significance of changes employed a non-parametric Mann-Kendall test applied for the analysis of data with a distribution deviating from normal, and their statistical significance was assessed by means of the Sen method at a level of $\alpha = 0.05$.

Then, the baric conditions causing the occurrence of strong and very strong frost in spring and autumn were analysed. Spring/autumn frost often appears as a local phenomenon. For the purpose of eliminating days on which the considered frost occurred locally from the study, the analysis covered only days on which frost occurred at least in 10% of stations. Therefore, only days, when frost occurred in at least four stations, were taken into further synoptic analysis.

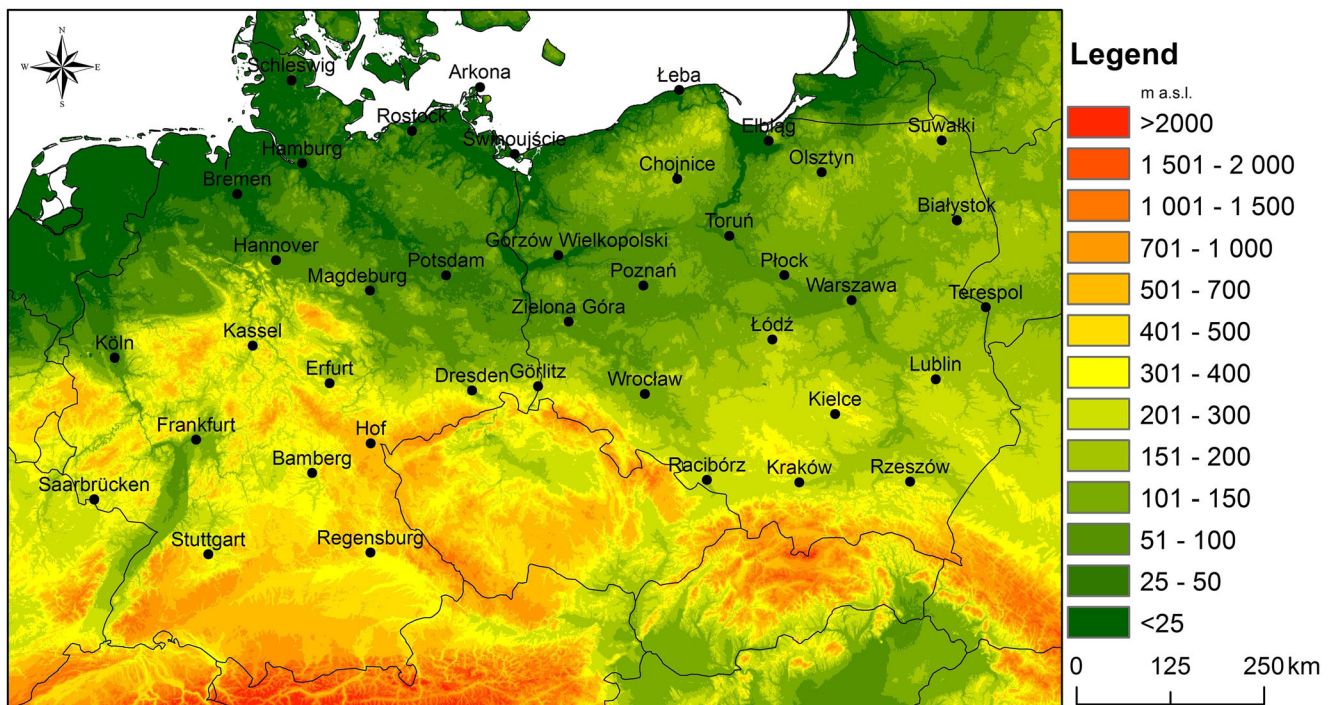


Fig. 1 Location of meteorological stations

Considering that the distance between neighbouring stations exceeds 100 km for most of them, the threshold of at least four stations eliminates local appearance of the analysed phenomenon.

The analysis of baric conditions employed average daily values of atmospheric pressure at sea level and heights of geopotential levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100 and 70 hPa, as well as air temperatures at the specified levels. Data for nodes of the geographic grid $2.5 \times 2.5^\circ$ for the area $25\text{--}75^\circ\text{N}$ and $35^\circ\text{W}\text{--}65^\circ\text{E}$ were obtained from the collection of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996) available in the archives of NOAA ESRL PSD (Earth System Research Laboratory Physical Science Division).

Based on the above data, cross sections through the atmosphere were designated (from the level of 1000 hPa to the level of 70 hPa) with anomalies of geopotential heights and air temperature along three meridians ($10, 15, 20^\circ\text{E}$) and one parallel (52.5°N) separately for strong and very strong frost in spring and autumn. Then, average maps of sea-level pressure (SLP) and 500 hPa geopotential height (z500 hPa) and maps of anomalies of the above parameters and air temperature at 850 hPa geopotential height (T850) for spring and autumn cases were prepared. All anomalies were calculated as a difference between mean sea level pressure value on a particular day, heights of isobaric surfaces and air temperature on such levels and mean value of the aforementioned elements on a given day in the studied multi-annual period. At the next

stage, circulation types were designated through grouping particular days in terms of values of sea level pressure with the application of the minimum variances method known as the Ward method (1963). For the designated types, maps of average SLP, z500 hPa and T850 were prepared, as well as maps of anomalies. Then, for the longest series of days (waves) with strong and very strong frost, maps were prepared with courses of movement of centres of anomalies of T850 on days preceding their occurrence in a given area.

Results

Occurrence of spring frost

The number of frost days in the spring season in Central Europe in the years 1966–2015 increased from the west to the east, from 67 days in Rostock to 571 days in Białystok (Table 1). It was also larger in stations located higher a.s.l. (e.g. Hof, 517 days). The highest number of spring frost days occurred in 1997 (in 10 stations) and 1981 (in 7 stations) (Fig. 2). The maximum number of spring frost days varied from 8 days in Rostock (1970) and 9 days in Kassel (1997, 2008) and Świnoujście (1996) to 26 days in Olsztyn (1980), 24 days in Kielce (1980) and 23 days in Hof (1973).

Over the prevailing area of Central Europe, a decrease in the number of days with frosts in spring was observed. It was statistically significant in 55% of stations. Only in 1 station (Terespol), located in the east of the study area, an increasing

Table 1 Total number of spring and autumn frost days in particular categories in Central Europe (1966–2015)

Country	Station	Spring				Autumn				Total	
		Mild	Moderate	Strong	Very strong	Mild	Moderate	Strong	Very strong	Spring	Autumn
Germany	Arkona	83	13	0	0	5	0	0	0	96	5
	Bamberg	228	119	34	7	140	52	17	7	388	216
	Bremen	175	63	17	7	68	21	8	5	262	102
	Dresden	144	50	10	1	70	17	4	0	205	91
	Erfurt	221	92	29	5	93	44	10	3	347	150
	Frankfurt	142	45	11	1	84	19	3	0	199	106
	Gorlitz	208	50	23	1	108	35	14	0	282	157
	Hamburg	189	66	11	5	79	23	4	3	271	109
	Hannover	170	86	21	5	78	31	7	3	282	119
	Hof	338	129	40	10	148	75	17	4	517	244
	Kassel	135	36	3	3	72	13	0	2	177	87
	Köln	190	70	18	4	79	26	11	0	282	116
	Magdeburg	154	51	19	2	92	22	5	2	226	121
	Potsdam	155	47	8	0	59	21	3	0	210	83
	Regensburg	193	55	13	1	128	39	9	0	262	176
	Rostock	58	9	0	0	14	0	0	0	67	14
	Saarbrücken	149	47	7	0	66	16	0	1	203	83
	Schleswig	189	46	6	0	32	16	1	0	241	49
	Stuttgart	175	55	6	1	91	37	8	1	237	137
Poland	Białystok	331	166	50	24	197	115	40	33	571	385
	Chojnice	292	110	34	6	131	56	10	2	442	199
	Elbląg	219	77	17	1	115	32	4	2	314	153
	Gorzów Wlkp.	170	60	11	0	90	36	8	0	241	134
	Kielce	309	132	45	14	184	93	32	12	500	321
	Kraków	315	79	16	2	248	85	24	4	412	361
	Lublin	219	85	9	4	159	82	20	8	317	269
	Łeba	231	119	30	4	83	24	1	0	384	108
	Łódź	205	92	23	3	133	65	13	6	323	217
	Olsztyn	282	170	36	14	142	83	21	8	502	254
	Płock	202	88	13	1	131	56	10	3	304	200
	Poznań	196	96	28	9	116	42	21	8	329	187
	Racibórz	162	73	9	0	120	29	18	4	244	171
	Rzeszów	236	102	41	5	138	88	29	14	384	269
	Suwałki	331	162	47	15	192	109	40	16	555	357
	Świnoujście	116	33	2	0	38	5	0	0	151	43
	Terespol	247	85	23	2	193	94	38	13	357	338
	Toruń	271	133	50	16	142	69	23	14	470	248
	Warszawa	201	91	19	0	138	78	17	8	311	241
Wrocław	217	88	34	6	120	59	28	9	345	216	
Zielona Góra	148	39	13	0	77	22	4	0	200	103	
Average		205	80	21	4	110	46	13	5	310	173

tendency was determined, although it was not statistically significant.

A lower frequency of spring frost was characteristic of the western coast of the Baltic Sea from Schleswig to Świnoujście

together with stations located in the central part of the study area, as well as the south-western part. Spring frost occurred the most frequently in the north-east of Poland (Białystok, Suwałki and Olsztyn) and in the south-eastern part of

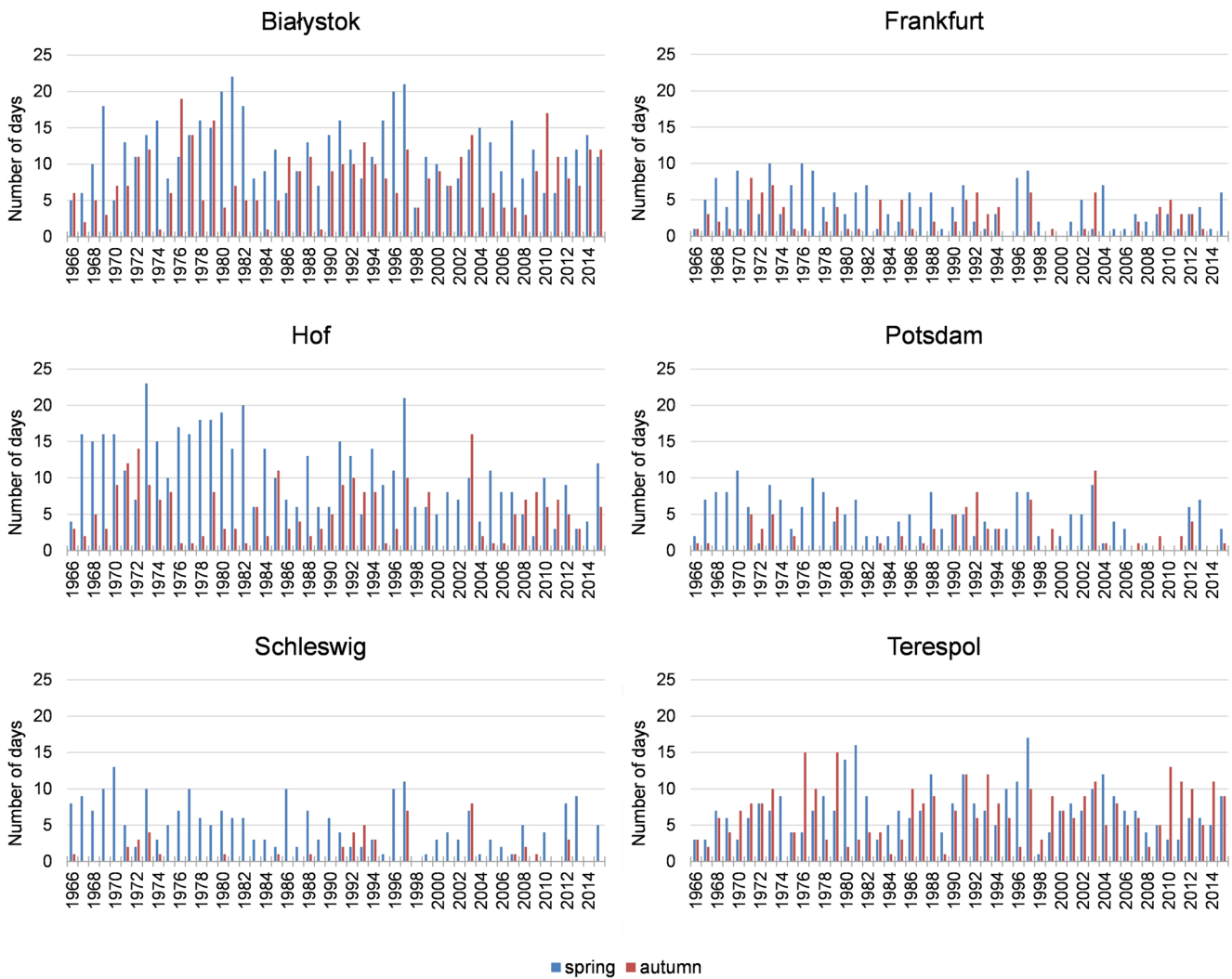


Fig. 2 Annual number of spring and autumn frost days in selected stations (1966–2015)

Germany (Hof, Erfurt and Bamberg). Mild frost was the most frequent in spring—averaging 205 days in the period 1966–2015 in Central Europe (Table 1). Their highest number was recorded in the station located the highest—Hof (338 days)—and the lowest in Rostock (58 days). Moderate frost occurred 80 days on average in the study period. Their number varied from 166 days in Białystok to 13 days in Arkona. Strong frost was the most frequent in Białystok and Toruń (50 days), and in Rostock, it was not recorded at all. The average number of days with strong frost in spring was 21. Very strong frost occurred on average 4 days in the spring period, particularly in the north-eastern part of the analysed area (24 days in Białystok) and in areas located higher (10 days in Hof). They particularly occurred in April. In May, only 2 days were recorded in Toruń. In a vast majority of stations, single days with strong and very strong frost were predominant. In two stations, i.e. in Elbląg and Świnoujście, all days with strong and very strong frost were recorded as single cases. The longest sequence of days with the analysed frost occurred in Rzeszów in 1974 from 14 to 18 April. Four-day sequences were

also recorded in several stations (Bamberg, Bremen, Hof, Kielce, Suwałki). In the study period, during 4 days, the occurrence of strong and very strong frosts in at least half of the analysed stations was recorded. They particularly occurred in the central belt of the study area, extending from west Germany to east Poland. An exception was 8.04.1997, when the analysed frosts occurred mainly (81%) in the territory of Poland.

Impact of the circulation on the occurrence of strong and very strong frost in spring

For the analysis of synoptic background of frost occurrence, the days with frost were selected along the particular criteria namely, occurrence of strong and very strong frost ($< 4\text{ }^{\circ}\text{C}$) in at least 10% of stations within the research area. This allowed to appoint 93 cases of frost occurrence in spring and 64 cases in autumn.

The occurrence of strong and very strong frost in spring was related to lower-than-normal height of geopotential levels in the entire vertical profile taken to the analysis (Fig. 3). The greatest

negative anomalies were recorded in the upper troposphere, at the height of 300–250 hPa, and their extremes were identified along meridian 20° E (< -120 gpm). The centre of the negative anomalies was located over eastern Poland, and it extended to the north-east. Negative anomalies throughout the entire vertical profile, however, covered the area located south of 47° N. In the air column below the centre of negative geopotential anomalies, i.e. below the level of 250 hPa, negative anomalies of air temperature were recorded over the prevailing area of the continent. The greatest anomalies were observed on the lowest geopotential levels (1000–850 hPa), where air temperature was lower by even > 6 °C than on average in the multi-annual period. The centre of the anomalies was located over the south-eastern part of the study area. In the upper troposphere (above the isobaric level of 250 hPa), positive air temperature anomalies occurred, exceeding at most 2 °C. This is a typical vertical pattern of temperature anomalies in the high-pressure system, and it is caused by the convergence of warmer air masses in the upper troposphere, over the subsidence zone in the anticyclonic centre.

During the occurrence of strong and very strong frost in spring, the Euro-Atlantic sector was under the influence of the expanded and slightly shifted towards the north (comparing to the average pressure pattern) high-pressure wedge within which a local high developed over the British Isles (> 1018 hPa) (Fig. 4). Simultaneously, over north Europe and the Mediterranean Sea, shallow low-pressure systems were located. On the analysed days, over a considerable part of western, central and northern Europe, and the ocean, SLP was higher than the multi-annual mean. In the centre of the high-pressure system, anomalies exceeded 4 hPa. Over the study area, SLP was higher than average from approximately 1 hPa in the south to around 4 hPa in the north-west. The isohyps of the isobaric surface of

500 hPa over the major area of Central Europe were bent towards the south, creating a distinct depression. Negative anomalies of z500 hPa ran through the north-east to the south-west and their centre (< -80 gpm) covered among others the eastern part of the analysed area. The described baric situation generated advection of cool air masses from the northern sector. The course of anomalies of T850 suggests advection from the north-eastern sector. Negative anomalies of T850 covered the entire study area, and their centre particularly covered east and south-east Poland (< -6 °C).

Detailed research on circulation conditions led to the designation of two types of circulation favouring the occurrence of strong and very strong frost in spring. Seventy-four percent of the analysed cases were classified in type 1 and the remaining 26% in type 2. In type 1, a high-pressure system persisted over the British Isles (> 1020 hPa in the centre), with simultaneous occurrence of a low over the Mediterranean Sea (< 1009 hPa) (Fig. 4). The area north of 47° N was covered by positive SLP anomalies, exceeding 8 hPa in the centre. Over the southern regions, SLP was lower than average, by more than 4 hPa in the centre, while in Central Europe, SLP anomalies varied from 0 to 5 hPa. In type 2, the key role in shaping weather conditions was played by two baric systems, i.e. high-pressure wedge, shifted southwards of an average position and a low with a centre located east of Iceland (< 995 hPa) (Fig. 4). The high-pressure wedge brought the radiative conditions under the clear sky in the subsidence zone, which contributed to lowering temperature. At the same time, both positive (in the south) and negative (in the north) pressure anomalies resulted in high horizontal pressure gradient causing strong advection of air masses from the north-west. The pressure difference between the described centres of anomalies was more than 20 hPa, and over the study area, SLP

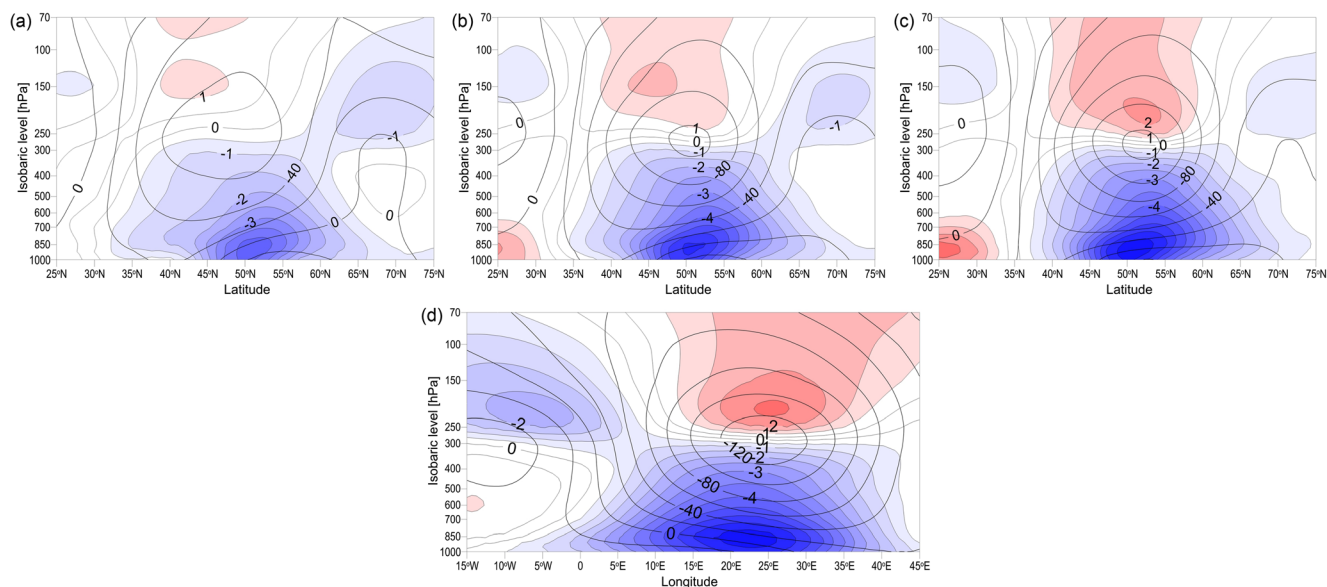


Fig. 3 Vertical cross sections through the troposphere with mean anomalies of heights of isobaric surfaces (black lines) and air temperature (colour scale) along meridians 10, 15, 20° E (a–c) and parallel 52.5° N (d) during the analysed days with strong/very strong frost in spring

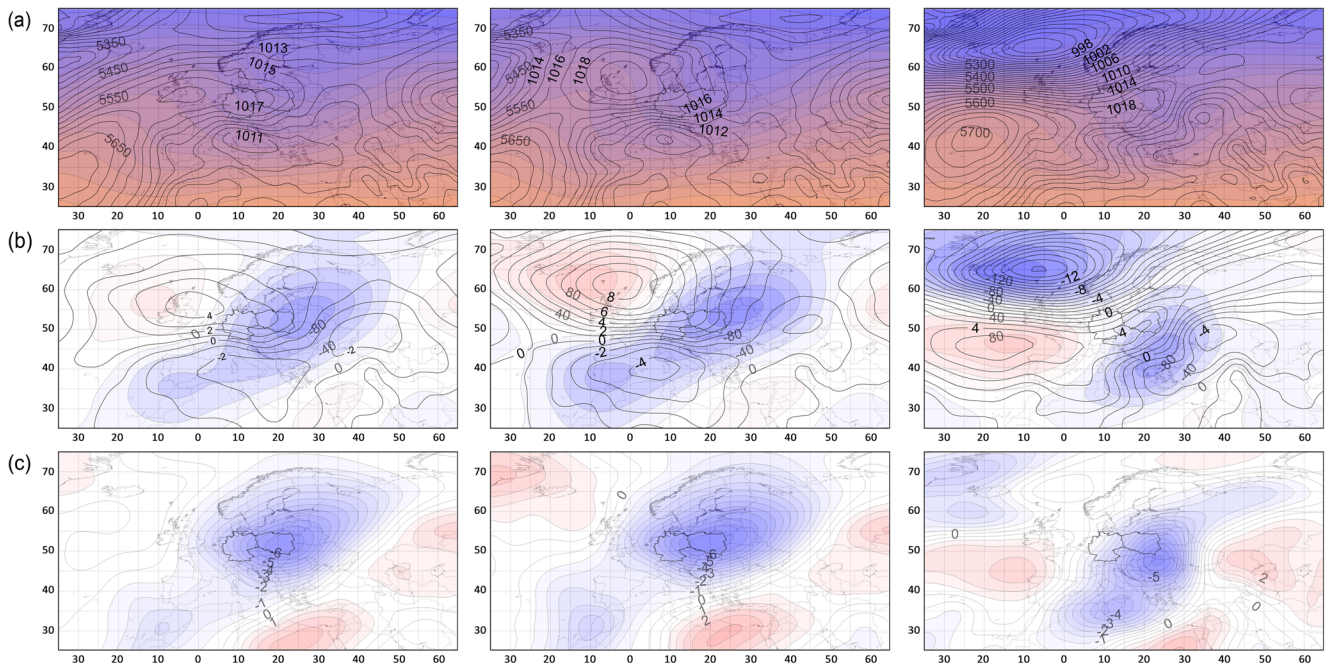


Fig. 4 Mean SLP (black lines) and z500 hPa (colour shades) (a); anomalies of SLP (black lines) and z500 hPa (colour shades) (b); and anomalies of T850 (colour shades) (c) during the all analysed days with strong/very strong frost in spring (left column) and for types 1 (middle column) and 2 (right column)

anomalies varied from 0 to more than 4 hPa. Both in types 1 and 2, isohips of the isobaric surface 500 hPa were bent southwards, although in type 2, the system was shifted somewhat to the east. In type 1, the entire study area remained within the range of negative anomalies of z500 hPa with the centre extending from south-west Poland to west Russia (< -100 gpm). A different situation was determined in type 2, where the western part of the study area was within the range of positive anomalies and the eastern one in the range of negative anomalies with the centre over the Balkan Peninsula (< -80 gpm). The designated types caused advection of cool air masses that in type 1 particularly persisted over Central Europe and in type 2 over Central and south Europe. Both in types 1 and 2, the negative anomalies of T850 were recorded over the entire study area (the greatest over Poland), whereas in type 2 particularly over the south-eastern

part of the study area. Consequently, type 1 made favourable conditions for strong and very strong frost all over Central Europe, while at type 2, strong and very strong frost appeared mainly in stations located in eastern, south eastern and central Poland.

For the longest periods of days with strong and very strong frost, the air temperature (T850) anomalies in the days preceding the frost events were computed and the locations of the centres of T850 negative anomalies were identified. In 3 out of 4 of the selected spring frost cases, the centres of T850 anomalies moved from the north or north-west towards the study area and in one case from the east (Fig. 5). The development of anomalies of T850 lasted from 2 days (in 1986) to 4 days (in 1988 and 2002) before the occurrence of the wave of the frost days in Central Europe. At the beginning, the formed

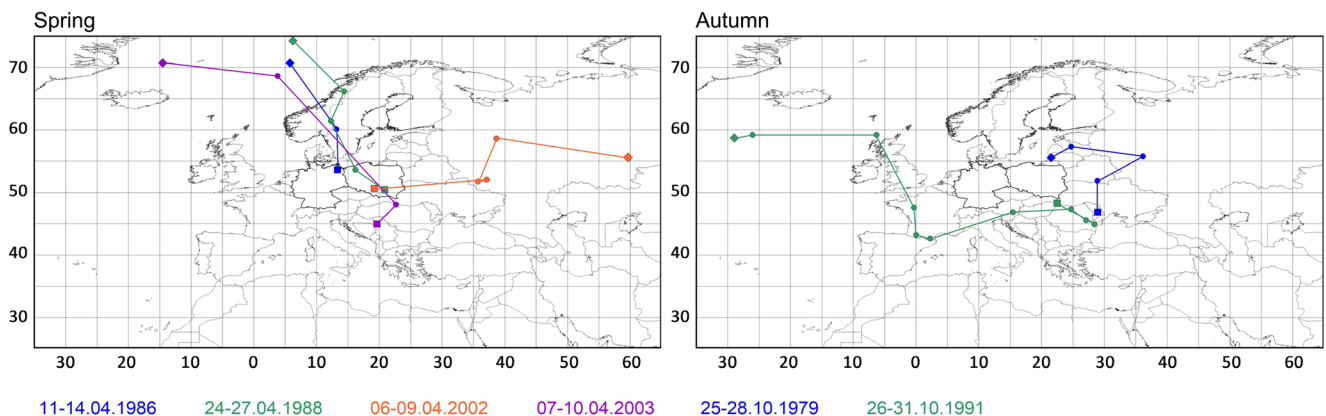


Fig. 5 Selected tracks of T850 anomaly centres on days preceding the occurrence of frost waves (rhombus—development of the centre of anomalies, square—first day of the waves) in spring and autumn

T850 anomalies were weak and they strengthened over the studied area; their highest values were usually recorded on the first day of the spring frost event, when the air temperature at 850 hPa was lower than average from 11 °C (in 2002) to 13 °C (in 1986 and 2003).

Occurrence of autumn frost

The number of frost days in the autumn season (September–October) in Central Europe in the years 1966–2015 also increased from the west to the east, from 5 days in Arkona to 385 days in Białystok (Table 1). The highest number of frost days occurred in 2003 (in 21 stations) and 1979 (in 11 stations). The maximum number of autumn frost days varied from 2 days in Arkona and 3 days in Rostock (2003) to 23 days in Suwałki and 19 days in Białystok and Kraków (1976).

Over the prevailing area of Central Europe, an increase in the number of days with frost in autumn was observed (Fig. 2); however, it was not statistically significant. Only in 8 stations, located in the west of the study area, a decreasing tendency was determined, although it was not statistically significant as well.

Autumn frost occurred the most frequently in the eastern part of Central Europe and the most seldom on the western coast of the Baltic Sea. Mild autumn frost was recorded 110 days on average in the study period. Their number varied from 5 days in Arkona to 197 in Białystok (Table 1). An average of 46 days of moderate frost occurred in autumn. They were the most frequent in Białystok (115 days) and Suwałki (109 days) and did not occur at all on the western coast of the Baltic Sea (Arkona, Rostock). Strong frost particularly occurred in October (13 days on average)—the most frequently in Białystok and Suwałki (40 days). In September, single days of frost from -4.1 to -6 °C were recorded in stations located furthest in the east of the study area. The very strong frost occurred 5 days on average in autumn. They were the most frequent in Białystok (33 days). In a vast majority of stations, single days with strong and very strong frost were predominant. In seven stations, i.e. in Frankfurt, Gorzów Wielkopolski, Kassel, Łeba, Saarbrücken, Schleswig and Zielona Góra, all days with strong and very strong frost were recorded as single cases. The longest sequence of days with the analysed frost occurred in Suwałki in 1976 from 16 to 22 October. Five- and 4-day sequences were also recorded in several stations. In the study period, during 3 days, the occurrence of strong and very strong frosts in at least half of the analysed stations was recorded. They particularly occurred in the central belt of the study area, extending from west Germany to east Poland. An exception was 26 October 1988, when the analysed frosts occurred mainly (95%) in the territory of Poland.

Impact of the circulation on the occurrence of strong and very strong frost in autumn

Similarly as in the case of spring frost, the occurrence of strong and very strong autumn frost was related to a lowering of geopotential levels (Fig. 6). The greatest height anomalies were recorded in the upper troposphere, at the level of 250 hPa. Over the study area, the greatest deviations from the average height of geopotential levels was recorded over the eastern regions which along meridian 20° E amounted to < -100 m. The centre of the entire system of anomalies, however, was located east of the study area, where the maximum anomalies exceeded -160 gpm. The performed cross sections suggest that the greatest anomalies occurred in the south and south-east of the analysed area. Negative anomalies of geopotential heights indicate the presence of cooler air masses, which is as also confirmed by negative anomalies of air temperature, reaching extreme values at the lowest levels (1000–850 hPa); over the study area, they amounted to -6 °C.

The occurrence of strong and very strong autumn frost was related to the presence over Central Europe of a high-pressure system with the centre over west Ukraine (> 1024 hPa) (Fig. 7). On the analysed 64 days with strong and very strong frost in autumn, the major part of the Euro-Atlantic sector was located within the range of positive SLP anomalies with the centre extending from north Poland to the Atlantic Ocean (> 7 hPa). Only over the southern regions, SLP lower than the multi-annual mean was recorded. Isohips of the isobaric surface of 500 hPa over Central and particularly east Europe were evidently bent southwards, suggesting its lower persistence. Negative anomalies of $z500$ hPa ran from the north-east to the south-west, covering almost (except for the north-western region of Germany) entire study area. The centre of anomalies was located over north-east Ukraine and west Russia (< -100 gpm). The described baric conditions caused advection of cool air masses from the north-east, due to clockwise circulation around the anticyclonic centre. The direction of advection is also suggested by the course of isoanomalies of T850. Negative anomalies of air temperature covered the entire study area. They varied from -1 to < -6 °C.

Further research led to the designation of two types of circulation favourable to autumn frost events. In type 1, explaining 64% of cases over Central Europe, a strong high-pressure system persisted with the centre over east Poland and west Belarus and Ukraine (> 1029 hPa) (Fig. 7). Over the majority of the continent, SLP was higher than the multi-annual mean. The maximum anomalies occurred over the southern regions of the Scandinavian Peninsula (> 14 hPa), and over the study area, they varied from 4 to 13 hPa. Under anticyclonic conditions, the clear sky intensified radiation, which contributed to lowering temperature, together with the advection of cold air masses from the north-east, which were

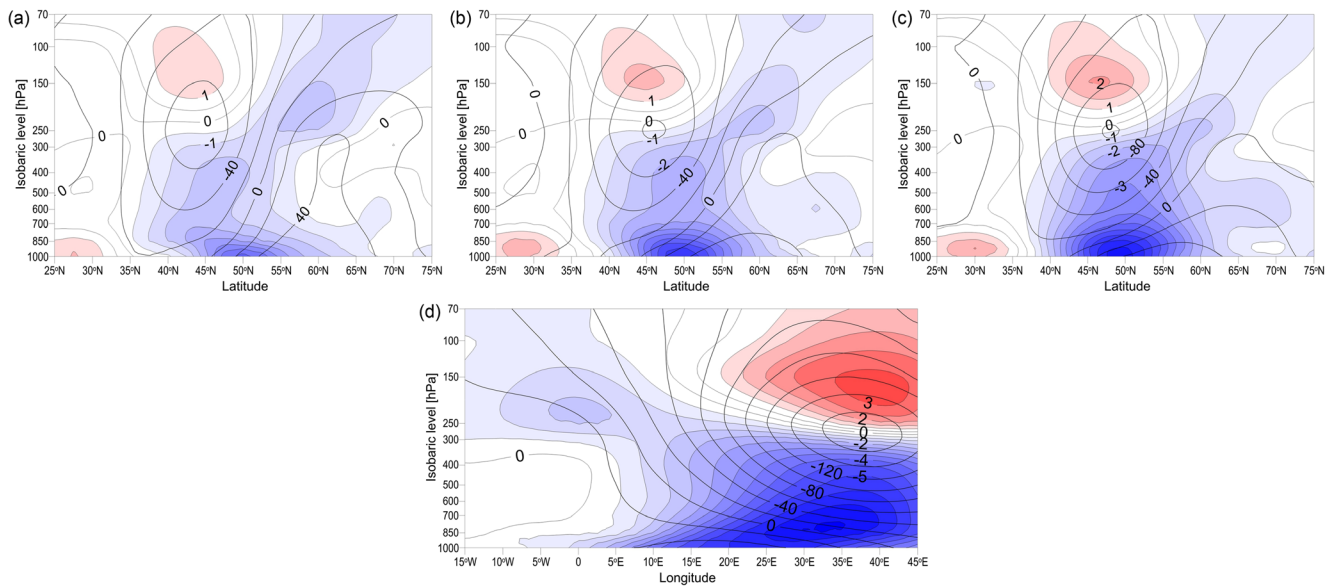


Fig. 6 Vertical cross sections through the troposphere with mean anomalies of heights of isobaric surfaces (black lines) and air temperature (colour scale) along meridians 10, 15, 20° E (a–c) and parallel 52.5° N (d) during the analysed days with strong/very strong frost in autumn

transported to the study area by the clock ward circulation around the anticyclonic centre.

Similarly in type 2, causing 36% of cases (most of them occurring in the southern and south-eastern part of the analysed region), a high persisted over Central Europe, although it was considerably weaker and shifted southwards from the highs from type 1 and it encompassed the southern part of the studied area (Fig. 7). In the analysed cases, the low-

pressure system with the centre over north Scandinavia was of dominant importance (< 1000 hPa). A high horizontal pressure gradient occurred between the aforementioned baric systems, intensifying advection of cool air masses from the northwest. Over the majority of the continent, SLP was lower than the multi-annual mean, and the centre of anomalies was located over north Sweden (< -7 hPa). In both types, isohips of the isobaric surface were bent southwards, although they were

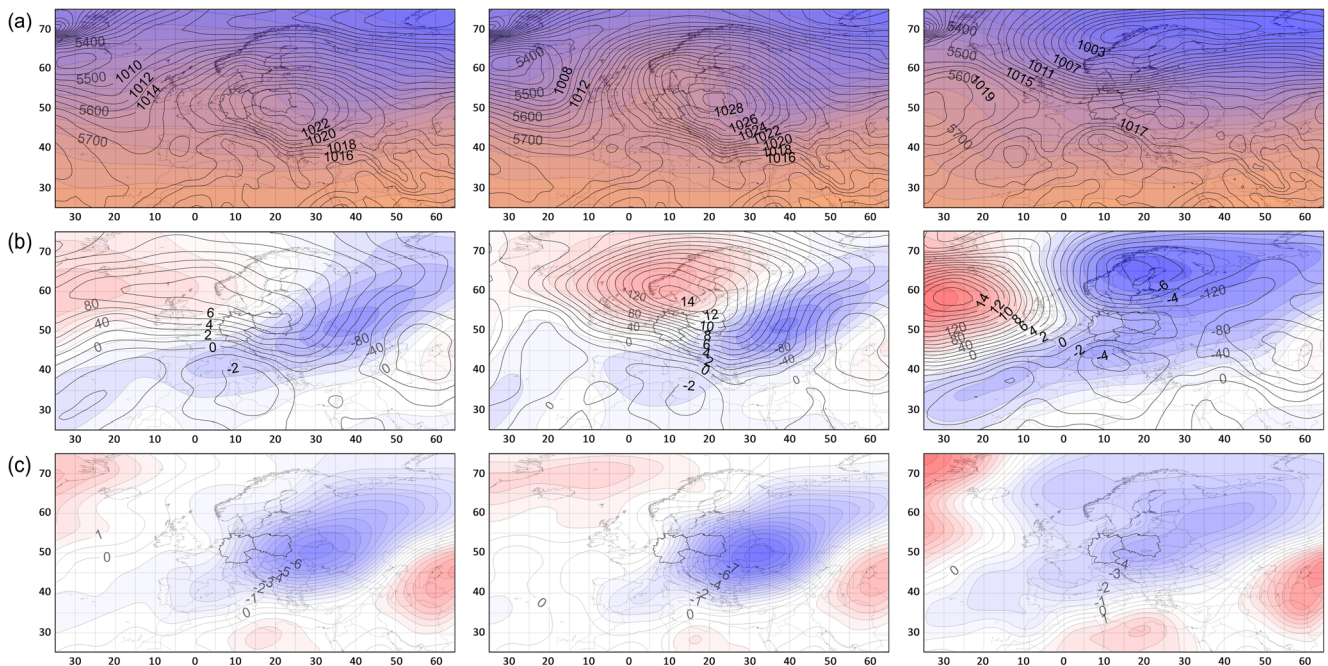


Fig. 7 Mean SLP (black lines) and z500 hPa (colour shades) (a); anomalies of SLP (black lines) and z500 hPa (colour shades) (b); and anomalies of T850 (colour shades) (c) during the all analysed days with

strong/very strong frost in autumn (left column) and for types 1 (middle column) and 2 (right column)

more evident in type 1. In type 1 in the Euro-Atlantic sector, 2 centres of anomalies of z500 hPa were observed, i.e. positive anomalies over the northern and north-western part and negative from east to south Europe. In type 2, almost the entire continent was within the range of negative anomalies of z500 hPa with the centre over north Sweden and Finland (< -140 gpm). Both baric situations caused advection of cool air masses, whereas evidently cooler air flew in type 1. This is suggested by anomalies of T850 with the centre in type 1 remaining over Ukraine and in type 2 over south Poland. In German stations, types 1 and 2 equally contributed to occurrence of strong and very strong frost, while in Poland, more frost days appeared under synoptic conditions of type 1.

In autumn, the longest sequences of days with strong and very strong frost included 6 and 4 days, and for those cases, T850 anomalies in the preceding days were followed (Fig. 5). Anomalies of T850 before the commencement of the wave of the analysed frost days in 1979 began developing in the area of the Gulf of Riga and in 1991 in the area of Greenland. In the first case, they developed 3 days and, in the second case, 10 days before the commencement of the waves in Central Europe. In both cases, the centre of anomalies (< -12 °C) on the first day of the frost wave persisted south-east of the study area.

Discussion and summary

Scenarios of climate changes for Europe show the tendency for a decrease in the threat related to frost as an effect of a considerable decrease of both the number of frost days and prolongation of the period without frost, as well as a decrease in the intensity of frost (Jylhä et al. 2008). The changes, however, do not occur evenly over the area of Europe.

The spatial analysis showed that the number of frost days in spring and autumn in the years 1966–2015 increased from the west to the east of Europe. It is a consequence of an increase in the continentalism of the climate towards the east. It was also higher in stations located at a highest altitude. However, the occurrence of frost days seems to be influenced mainly by local conditions rather than the location of the station above the sea level. The location of the station in the range of the sea impact reduces the number of days with frost. Over the majority of Central Europe, however, a decrease in the number of frost days was observed. Only in 3 stations, located in the east of the study area, an increasing tendency was determined. The analysis showed that spring frost occurred more often in Central Europe than autumn frost. In the western part of the study area, the number of spring frost events was prevalent. The further to the east, the more days of autumn frost occurred. Changes in the terms of frost lead to a change in the duration of the frost-free period. The greatest increase in the duration of the frost-free period is forecasted in areas where the period is currently the shortest (Graczyk and Kundzewicz 2016). A tendency for the

earlier occurrence of the last frost was determined by Scheifinger et al. (2003) and a tendency for delaying the first autumn frost in Central Europe by Tomczyk et al. (2015). According to Bielec-Bąkowska and Piotrowicz (2011), the prolongation of the frost-free period results from an evident increase in air temperature in the 1990s. A decreasing tendency of the number of frost days is confirmed by earlier studies concerning both Europe (Heino et al. 1999; Tomczyk et al. 2015) and North America (Bonsal et al. 2001; Easterling 2002; Kunkel et al. 2004; Meehl et al. 2004) or China (Liu et al. 2008). In Central Europe, spring frost occurred more frequently than autumn frost, although their frequency is spatially variable. In the western part of the study area, spring frost was dominant. In the further east, the more cases of autumn frost were recorded. Spring frost poses a greater threat in the western part of the study area, where the frost-free and vegetation period begins earlier (Tomczyk et al. 2015; Wypych et al. 2017; Bielec-Bąkowska et al. 2018; Tomczyk et al. 2018a) and the difference in the commencement of the periods between the eastern and western regions of Central Europe can be even more than a month. According to Wypych et al. (2017), such a spatial variability in Central Europe results from circulation factors.

Spring days with strong frost particularly occurred in April and in May only sporadically in east Poland. Very strong frost occurred particularly in the north-eastern part of the study area and in areas located at greater heights. They mainly occurred in April. In May, only 2 cases were observed in Toruń. Strong autumn frost occurred particularly in October. In September, single cases of such frost were recorded in stations located the furthest east of the study area. The strongest frost in the study area occurred in autumn approximately 5 times—usually in Białystok (33 days). A tendency for an increase in the number of cases of strong frost in Central Europe in the vegetative period is pointed to by Wypych et al. (2017).

It is assumed that despite warming trends in all seasons in Central Europe, the risk of cold spells in winter and frost days in transient seasons will still remain (Wypych et al. 2017). This is due to the Arctic amplification and the weakening of the jet stream which lead to enhanced transport of polar air masses to lower latitudes (Francis and Vavrus 2012). These circulation processes govern the occurrence of frost days in Central Europe. The average conditions favouring the occurrence of strong and very strong frost both in spring and in autumn were related to increased pressure at sea level, as suggested by positive SLP anomalies occurring over the majority of the Euro-Atlantic sector. In both seasons, detailed analyses permitted the designation of two types of circulation in each, causing the occurrence of the analysed frost. In the case of spring, in type 1, a stable baric situation was observed with a high over the British Isles, and in type 2, Europe was under the influence of two baric systems, with a high horizontal pressure gradient in between, causing intensive advection of cool air masses. In the case of autumn, in type 1, over the eastern regions of the study area, the centre of a strong high system persisted, and in type 2, the influence of the

low from over the Scandinavia was determined over the study area and influence of a weak high over the southern regions. The obtained result are in accordance with earlier research conducted in this part of Europe (Ustrnul et al. 2014; Wypych et al. 2017), showing that the dominant baric system causing the occurrence of frost is an extensive high-pressure system over east Ukraine and Belarus, bringing continental air masses. Similarly, Tomczyk et al. (2015) determined that the occurrence of very strong frost is related to the presence of a high over Central Europe with the centre over Poland, and its presence in May causes inflow of cool air in the period of so-called Ice Saints, i.e. in the first half of May.

The occurrence of strong and very strong frost, both in spring and autumn, was related to the advection of air masses from the northern sector in general. Moreover, an important factor favouring cooling was small or lack of cloudiness, which is typical for the anticyclonic conditions. This is confirmed by the negative air temperature anomalies in the middle and lower troposphere. The greatest temperature anomalies occurred on the lowest isobaric levels, where air temperature over Central Europe was lower-than-average by even 6 °C, and the centres of these anomalies were located south-east and east of the study area.

The study showed the occurrence of the greatest anomalies of geopotential heights in the upper troposphere at levels of 300–250 hPa. Over the study area, the highest values of anomalies were recorded over the eastern regions, where isobaric levels persisted even more than 170 gpm lower than on average. It was also evidenced that the occurrence of strong and very strong frost in autumn was related to higher anomalies than in spring. A similar course of anomalies of geopotential heights was pointed to by Qian et al. (2015) analysing episodes of low air temperature in spring and autumn in the Yangtze River valley. The authors evidenced that disturbances in the upper troposphere co-occurred with strong air temperature anomalies at a level of 850 hPa. The occurrence of the greatest anomalies of heights of isobaric levels in the upper troposphere was also evidenced during other extreme weather phenomena, such as heat waves (Qian et al. 2016; Chen et al. 2017; Tomczyk et al. 2017; Tomczyk et al. 2018b; Geirinhas et al. 2019), cold waves (Qian et al. 2016; Tomczyk et al. 2018b; Tomczyk et al. 2019) and hot nights (Tomczyk 2018). Many studies evidenced (Qian et al. 2016; Chen et al. 2017) that the occurrence of extreme weather conditions is preceded by the development of disturbances in the upper troposphere, which can be helpful in forecasting such phenomena. As evidenced by Qian et al. (2015) in the case of low temperature episodes in spring and autumn in China, the disturbances developed respectively 6.9 and 10.2 days before the occurrence of the phenomenon.

Understanding the complex pressure and circulation conditions causing spring and autumn frost events may help understand weather risk in agriculture. Furthermore, with the feedback of future circulation models, it has the potential to become

essential for investigating future frost day occurrence in the transient seasons.

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