BADANIA FIZJOGRAFICZNE
R. III – SERIA A – GEOGRAFIA FIZYCZNA (A63) str. 255–279

DOI 10.2478/v10116-012-0013-4

DEPENDENCE OF SEVERE STORM OCCURRENCE ON CIRCULATION TYPES IN POLAND

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Abstract: The paper investigates the relationships between the occurrence of thunderstorms with heavy precipitation (> 30 mm) and atmospheric circulation types. The study covers the period 1951–1998 and is based on a matching span of records of thunderstorm occurrence and daily precipitation totals at 47 weather stations in Poland. A catalogue of circulation types by Osuchowska-Klein, data on frequency of fronts over south-eastern Poland by Niedźwiedź and weather maps were used. In Poland, days with a thunderstorm and more than 30 mm of precipitation are extremely rare and occur mainly in summer. Their recurrence period amounts to about two to four years, with the exception of mountain areas (southern Poland) where they occur nearly every year. The heaviest precipitation on a day with thunderstorm, 166.1 mm, was recorded at a high-mountain station on Mt. Kasprowy Wierch. Apart from this station the highest precipitation was 141.0 mm and only eight stations had at least one record of more than 100 mm. Four regions characterised by different circulation types most favourable for the occurrence of thunderstorms with heavy precipitation were identified. In all of them southerly advection was most favourable for the occurrence of the phenomena studied (Sc, SEc, Sa/c), but that effect was especially prominent in the south-western region. Most of the days with thunderstorm and heavy precipitation coincided with the passing of an atmospheric front over Poland (53.8–81.9% days depending on the station). Days with air-mass thunderstorm and heavy precipitation were rare and mostly occurred in areas of variable topography.

Keywords: thunderstorm, heavy precipitation, atmospheric circulation, Poland

INTRODUCTION

Thunderstorms and the phenomena they produce – lightning, tornadoes, hail, high winds, and heavy precipitation – have received great attention because of the significant damage they produce (Changnon 2001a). In Poland, thunderstorms are rated among the most extreme meteorological phenomena. The most severe of these can lead to serious damage on a local and larger scale. Severe thunderstorm-related precipitation very often tends to trigger local flooding, landslides and damage to infrastructure, such as roads and bridges. For example a severe thunderstorm which was accompanied by a gale and precipitation of 32.7 mm (daily amount) caused serious traffic impediments (impassable roads due to fallen trees) in the vicinity of Poznań on 20th Sep 2000. In the vicinity of

Łódź heavy thunderstorm rain (36.5 mm daily amount) brought on a flooding of roads, schools and basements and caused traffic impediments on 2nd Jul 2001. On 27th Jul 2003, in Szczecin, many houses, basements, shops, gastronomic outlets (restaurants, pubs, cafes) and roads were flooded due to thunderstorm precipitation of above 20 mm (daily amount: 28.4 mm). The Fire Service answered more than 100 calls for help. A falling tree crushed a car parked nearby (press reports). Thunderstorms with heavy precipitation may also accompany synoptic flood situations over large areas, such as was the case during the 1997 floods in Poland.

The climatological perspective has been relatively rarely used in approaching the topic of thunderstorms and heavy precipitation because sufficiently long and detailed meteorological records of these phenomena are virtually unavailable in many parts of the world. The earliest studies of thunderstorm precipitation are mostly limited to the territory of the USA. They focus on investigating thunderstorm precipitation totals (Changnon 1957; Osborn and Hickcock 1968; Easterling and Robinson 1988), comparing thunderstorm frequency with daily precipitation in various ranges of totals (Wallace 1975), or identifying regions of thunderstorm precipitation distribution (Easterling 1989). More recent studies analysed thunderstorm precipitation totals, their share in overall precipitation and the spatial distribution of totals (Changnon 2001b). Dai (2001a and b) offers a detailed study of the daily, seasonal and spatial variability of precipitation types, including thunderstorms, on a global scale.

Polish climatological literature on the subject, mostly dealing with hailstorm occurrence, its annual as well as daily course and its paths, dates to before 1970 (Schmuck 1949; Smosarski 1952; Zinkiewicz and Michna 1955; Koźmiński 1965, 1968; Koźmiński and Rytel 1963). The latest research mostly looks at the amount of precipitation on days with a thunderstorm and at its long-term variability (Bielec-Bakowska and Lupikasza 2009). The study concludes that in Poland most days with a thunderstorm are accompanied by precipitation, which in 7–8% of cases is greater than 20 mm. The long-term course of the number of days with thunderstorm and precipitation is spatially incoherent and even varies from station to station. During the period 1951–2000, the frequency of days with a thunderstorm and with more than 20 mm of precipitation did not follow any statistically significant trend (Bielec-Bakowska and Lupikasza 2009). The only research into the origin of thunderstorm precipitation covered the city of Krakow, in southern Poland (Bielec 1997; Twardosz 2010). There, thunderstorm precipitation is recorded on approximately 20 days per year and constitutes about 30% of the annual precipitation total (Twardosz 2010). While the thunderstorm precipitation frequency was distributed more or less evenly between cyclonic and anticyclonic situations, the heaviest thunderstorm precipitation was recorded twice as frequently in anti-cyclonic situations (Bielec 1997). Thunderstorm precipitation is normally associated with atmospheric fronts and this category accounts for around 58% of days with thunderstorm precipitation, while the remaining 42% of days represent air mass-precipitation. These latter are the most frequent in marine polar air masses (Twardosz 2010).

The objective of this study was to identify the relationship between the occurrence of thunderstorms with heavy precipitation and atmospheric circulation in Poland during the period 1951–1998. The types of circulation most favouring the occurrence of thunderstorms with heavy precipitation were identified. Knowledge of the probability of severe thunderstorm occurrence in various circulation types has a prognostic, which means it has practical importance. Moreover, it allows indirect assessment of tendencies in the frequency of this rare event, based on the knowledge of changes in the frequency of particular synoptic types. Particular attention was paid to thunderstorms in the cool half of the year, which are rare in Poland, and thunderstorms with the heaviest precipitation. Additionally classification of all thunderstorms with heavy precipitation was carried out, assigning individual cases to the air mass and frontal classes.

DATA AND METHODOLOGY

The establishment of the course of an event so local as a thunderstorm carries a degree of subjectivity on the part of the observer (Bielec and Kolendowicz 2001). Certain errors and inaccuracies may occur in the details of thunderstorms recorded despite the great skills of observers normally employed by weather stations.

These errors may particularly concern thunderstorm duration, the direction of its movement (track direction) and number of thunderstorms recorded during a day (according to the Institute of Meteorology and Water Management's guidelines for meteorological stations (1988) thunder indicates both the beginning and the end of a thunderstorm; if there is a time interval longer than 15 minutes between two claps of thunder, they are considered separate thunderstorms). For this reason, most studies devoted to thunderstorm occurrence do not analyse their numbers as such, but rather the numbers of days with a thunderstorm. Also direct assessment of thunderstorm intensity performed during the observation of a thunderstorm carries a subjective element that influences the comparability of the data. One solution to this is to use precipitation totals, and even better intensities, as indirect measures of thunderstorm severity. To determine precipitation intensity, however, highly detailed data is necessary, such as the time of the beginning and the end of the precipitation episode and the precipitation total. Since sufficiently long records of such data are unavailable from most weather stations, many studies discuss thunderstorm precipitation using ubiquitous data on the precipitation totals on days with a thunderstorm (e.g. Wallace 1975; Bielec--Bakowska and Lupikasza 2009).

This study follows a similar approach. The authors realise that often, and especially in frontal thunderstorms, a portion of the daily precipitation was not necessarily linked to a specific thunderstorm event, but nonetheless this approach helps assess the order of magnitude of thunderstorm precipitation and, as a consequence, estimate its intensity.

The study involved meteorological records of thunderstorm occurrence and daily precipitation totals from 47 weather stations in Poland (Fig. 1). The data spans the period 1951–1998, except for the Rzeszów station where records begin in 1952. The entire set was tested and proven homogeneous (Bielec-Bakowska and Lupikasza 2009). A day with a thunderstorm was defined as a calendar

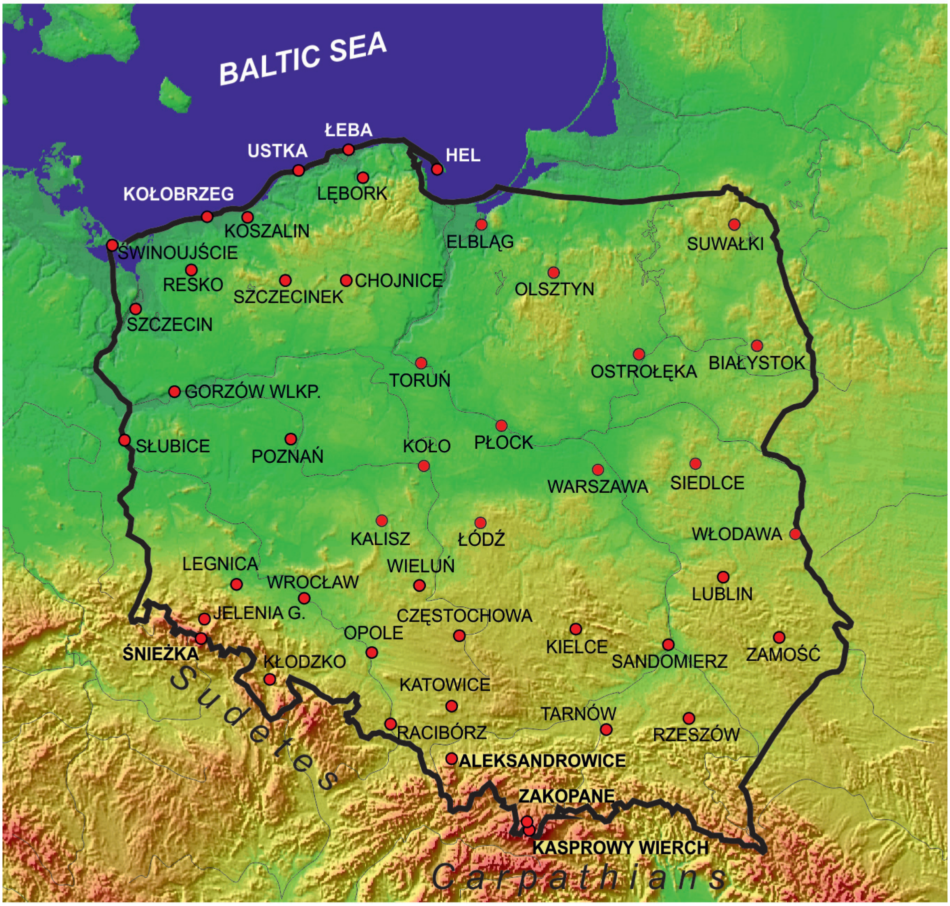


Fig. 1. Location of meteorological stations with relief

Ryc. 1. Stacje meteorologiczne uwzględnione w opracowaniu

24-hour period starting at 00:01 and ending at 24:00 UTC and which included at least one observation of a thunderstorm. Thunderstorms were not broken down into near and remote, and events that straddled midnight were included in both days. Precipitation was measured between 06:01 and 06:00 UTC, which is inconsistent with the definition of a day with a thunderstorm, but this should not have a significant impact on the final result of the study for reasons detailed in an earlier paper (Bielec-Bakowska and Lupikasza 2009).

For the purpose of this study the most severe thunderstorms were defined as those with more than 30 mm precipitation. In Poland, such events are classified as very heavy (Olechowicz-Bobrowska 1970; Paszyński and Niedźwiedź 1999). Precipitation of 30 mm equals monthly totals in winter and about half the monthly totals in summer.

The catalogue of atmospheric circulation types by Osuchowska-Klein (1978, 1991, 1998) was used to analyse the relationships between the occurrence of severe thunderstorms and atmospheric circulation. In this study the original classification symbols were modified to make them, in the authors' humble opinion, more reader-friendly (Tab. 1).

A catalogue of circulation types by Niedźwiedź (2009) containing data on the occurrence of fronts over the territory of south-eastern Poland was used to determine the type of severe thunderstorms (air mass or frontal). This was performed by linking each day with a thunderstorm and with more than 30 mm of precipitation with information about any frontal activity, or the lack of it. The analysis was only done for south-eastern Poland due to the lack of proper data (fronts occurrence with daily resolution) for other parts of the country. An assumption was made that if an atmospheric front passed over the area on a day with a severe thunderstorm then this thunderstorm was classified as a frontal type. Naturally, each of those thunderstorms could have occurred in a uniform air mass preceding or trailing the front, but owing to the fast pace of frontal movement over Poland, ranging from single hours to a full day, it was assumed that any error in type attribution would not impact the final results significantly (Kolendowicz 2005). Weather maps were also used to analyse specific examples of severe thunderstorms.

In Poland, during the cool half of the year thunderstorms with heavy precipitation are infrequent, and because of this the first section of the study only looks at thunderstorms from May to September. This reduced the overall number of days with a thunderstorm to only 19 of the stations and in most cases by no more than one or two days. The frequency and conditional probability of the occurrence of days with a thunderstorm and heavy precipitation in each type of circulation were determined. This produced a breakdown of stations into groups with similar relationships between the phenomena studied and atmospheric circulation. The groups were identified using cluster analysis with the k-mean method (Cluster analysis 1997) and, additionally, a correlation method. The best

Table 1. Classification of circulation types by Osuchowska-Klein (1978, 1991, 1998)
Tabela 1. Klasyfikacja typów cyrkulacji według Osuchowskiej-Klein (1978, 1991, 1998)

Symbols of circulation types introduced by Osuchowska-Klein Symbole typów cyrkulacji wg Osuchowskiej-Klein	Description of circulation types after Osuchowska Klein (1978,1991, 1998) Opis typów cyrkulacji za: Osuchowska-Klein (1978,1991, 1998)	Modified symbols* Symbole przyjęte w opracowaniu*
A	West cyclonic circulation	Wc
CB	North-west cyclonic circulation	NWc
D	South-west cyclonic circulation	SWc
B	South cyclonic circulation	Sc
F	South-east cyclonic circulation	SEc
C_2D	West anticyclonic circulation	Wa
D_2C	South-west and south anticyclonic circulation	SW/Sa
G	Central anticyclonic circulation	Ca
E_2C	North-west anticyclonic circulation	NWa
E_0	North-east and east cyclonic circulation	NE/Ec
E	North-east anticyclonic circulation	NEa
E_1	South-east and east anticyclonic circulation	SE/Ea
BE	Southern circulation transitional between cyclonic and anticyclonic	Sa/c
X	Unclassified circulation	x

*New symbols were created using direction of air mass advection (capital letters) and kind of baric centre (small letters: a – anticyclonic type, c – cyclonic type) according to Osuchowska-Klein's definitions of the circulation types.

*Symbole przyjęte w opracowaniu uwzględniają kierunek adwekcji masy powietrza (wielkie litery) i rodzaj ośrodka barycznego (małe litery: a – typ antycyklonalny, c – typ cyklonalny) wg definicji typów cyrkulacji Osuchowsiej-Klein

clustering was achieved when the maximum distance method was applied to identifying the initial cluster centres. The clustered regions were then slightly modified following the correlation analysis using Spearman's non-parametric method.

Cold period thunderstorms (Oct-Apr), with particular attention paid to the months when they occur most rarely (Nov-Mar) were discussed in the next section. A description of synoptic situations during selected thunderstorm and heavy precipitation cases completes the study.

DAYS WITH HEAVY THUNDERSTORMS

In Poland severe thunderstorms are rare and their season of peak activity lasts from April to September when 96% of all thunderstorms occur. The average number of days with a thunderstorm per year ranges between 15 in the northwest and 33 in the southeast of the country. The actual numbers vary widely from year to year depending on weather conditions, but this variability is clearly lower in the south than in the north (Bielec-Bakowska 2002). On a clear majority of days with a thunderstorm there is also precipitation (85% of days on average), including precipitation heavier than 20 mm in 7–8% of cases and heavier than 30 mm in 3% of cases (Bielec-Bakowska and Lupikasza 2009).

A day with both a thunderstorm and heavy precipitation (of more than 30 mm) is such a rare occurrence that it is not recorded every year in most of the country (Fig. 2a). Only in the mountains (the Sudetes and the Carpathians) are such days slightly more frequent, peaking at the weather station on Mt. Kasprowy Wierch (2.1 days per year on average). This means that the recurrence periods for these phenomena vary from ca. one year in southern mountainous regions to more than four years on the Baltic coast (Fig. 2b). Days with a thunderstorm and heavy precipitation are concentrated primarily in the warmest months (May-Sep) and are extremely rare between October and April. Indeed,

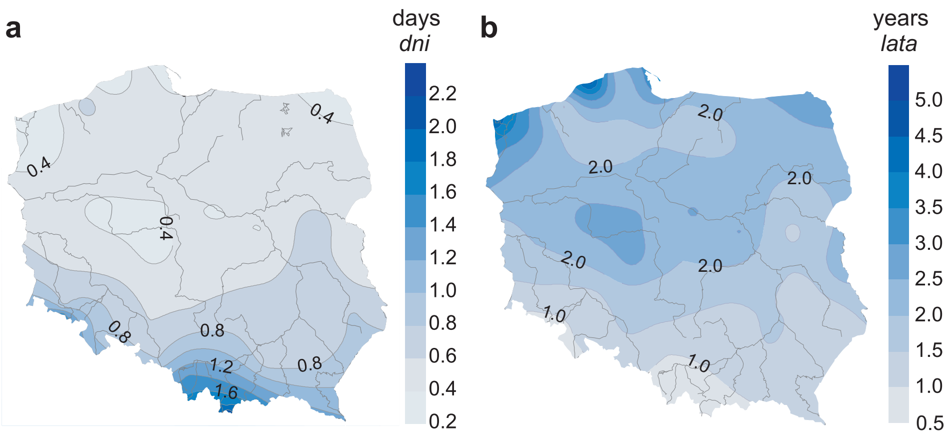


Fig. 2. Selected characteristics of days with thunderstorm and heavy precipitation (> 30 mm) in the period 1951–1998: a) average number of days with thunderstorm and heavy precipitation (> 30 mm), b) recurrence period (e.g. 2.0 – a day with thunderstorm and precipitation > 30 mm occurred once every two years on average)

Ryc. 2. Wybrane charakterystyki dni z burzą i wysokim opadem (> 30 mm) w okresie (1951–1998): a) średnia liczba dni z burza i wysokim opadem (30 mm), b) okres powtarzalności (np. 2,0 – dzień z burzą i opadem > 30 mm występuje średnio raz na dwa lata) during the whole of the study period there were only 35 such days observed during these months (Oct-Apr), these mostly either in the coastal north or in the mountainous south.

The actual precipitation total recorded on days with a severe thunderstorm varied geographically. During the study period, every one of the stations recorded at least one example of more than 50 mm of precipitation, 22 stations (47%) had more than 80 mm, 13 (28%) more than 90 mm and 8 stations (17%) measured precipitation of more than 100 mm. The highest daily value of precipitation on a day with a thunderstorm (166.1 mm) was recorded on 8 July 1997 at Mt. Kasprowy Wierch (Fig. 3) and this station also had four other cases where there was more than 100 mm of precipitation. The highest total recorded at any of the other stations was in Łeba where 141.1 mm fell on 24 July 1988.

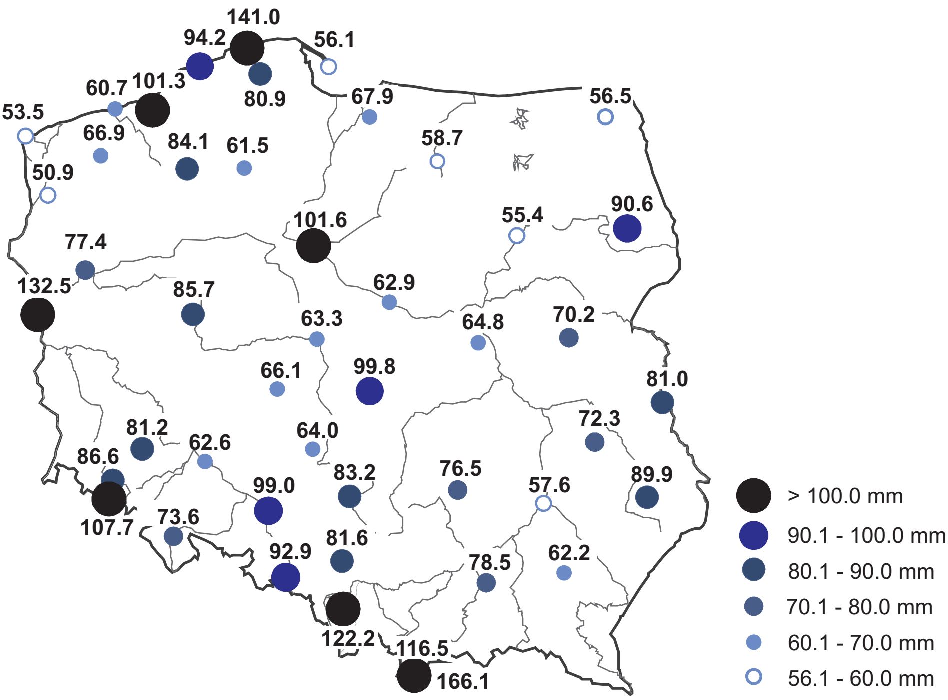


Fig. 3. Maximum precipitation [mm] on days with a thunderstorm in the period 1951–1998
Ryc. 3. Maksymalny opad [mm] w dniach z burzą w latach 1951–1998

SYNOPTIC SITUATIONS FAVOURING A THUNDERSTORM WITH HEAVY PRECIPITATION

The research published so far has shown that the influence of macro-scale atmospheric circulation on the occurrence of thunderstorms in Poland is less than might have been expected (Bielec-Bakowska 2003). Air advection from the south linked to a cyclonic system has been found to favour this phenomenon the most. In the south of the country thunderstorms also tend to be linked to air masses from the east regardless of the pressure system. At the other end of the spectrum, high-pressure systems prevailing over Poland make thunderstorms the least likely (Bielec-Bakowska 2002, 2003). It was also shown that the occurrence of thunderstorms in Poland was considerably influenced less by the exact type of weather conditions than by the temperature and pressure of water vapour in the air mass where they occur (Stopa 1964; Kolendowicz 2005).

Using the methods described in Section 2 (Data and Methodology) four types of relationships between the occurrence of severe thunderstorms and atmospheric circulation (type I – TI, type II – TII, type III – TIII and type IV – TIV) were identified in Poland, as depicted in Figure 4. At the majority of stations, days with a thunderstorm and heavy precipitation mostly occurred in air masses arriving from the northeast or east, linked to either cyclonic and anticyclonic systems (NE/Ec and NEa) or from the northwest linked to cyclonic systems (NWc). In types TII and TIV ca. 45% of all days with a thunderstorm and heavy precipitation were linked to NE/Ec and NWc situations. The NE/Ec situation was observed on 39.1% of all such days in Białystok. In the TI type, especially in the south of the country, there were relatively large numbers of cases during an NEa situation (33% Opole, 25% Słubice, 24% Tarnów, 22% Kalisz and 23% Mt. Śnieżka) and during southerly advection (40% days on average). The TIII type are characterised by a high degree of spatial dispersion and a high frequency of days with a thunderstorm and heavy precipitation during air advection from the southeast. This is particularly true for weather stations located in the west (Świnoujście: 18% in SEc and SE/Ea, Resko: 23% in SEc, Chojnice: 17% SEc and Poznań: 17% in SE/Ea).

There is a degree of seasonal variation in the frequency of occurrence of circulation types. To find out whether the concentration of days with a thunderstorm in certain weather conditions was only a function of the latter's frequency or whether these situations genuinely favoured thunderstorms and heavy precipitation, conditional probabilities of the occurrence of these days during certain circulation types were calculated. The probability values obtained were very low, but this was due to the extremely low frequency of the phenomena studied. The k-means method was again applied to cluster analysis, producing four regions with different circulation types that most favoured the occurrence of days with a severe thunderstorm (Fig. 5). Region one (RI) included 36 weather stations in

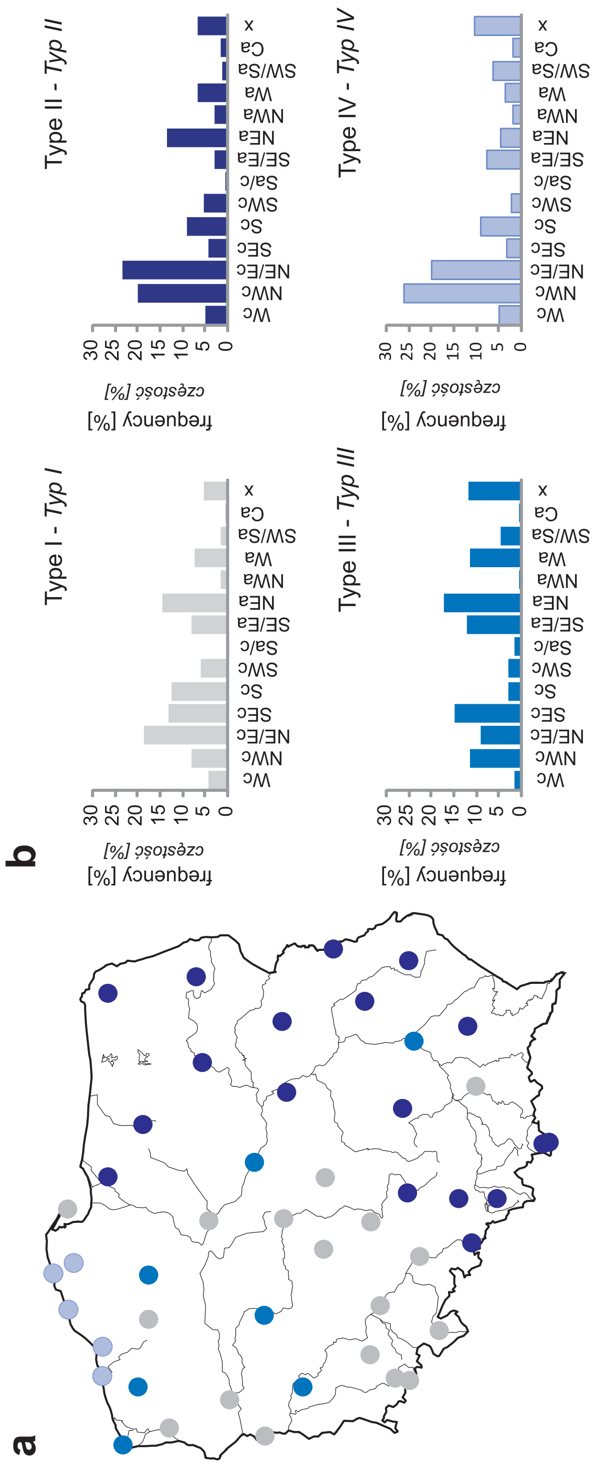


Fig. 4. Relations between frequency of days with severe* thunderstorm (from May to Sep) and atmospheric circulation in the period 1951–1998: a) spatial distribution of relation types, b) frequency of days with severe* thunderstorm in circulation types by relation types
(*severity of thunderstorm defined based on precipitation amount of > 30 mm)

Ryc. 4. Związki pomiędzy częstością występowania dni z silnymi burzami* (od maja do września) i typami cyrkulacji atmosfery w okresie 1951–1998: a) przestrzenny zasięg wydzielonych typów zależności, b) częstość dni z silnymi burzami* w poszczególnych typach cyrkulacji w wydzielonych regionach
(*dni z burzą i opadem > 30 mm)

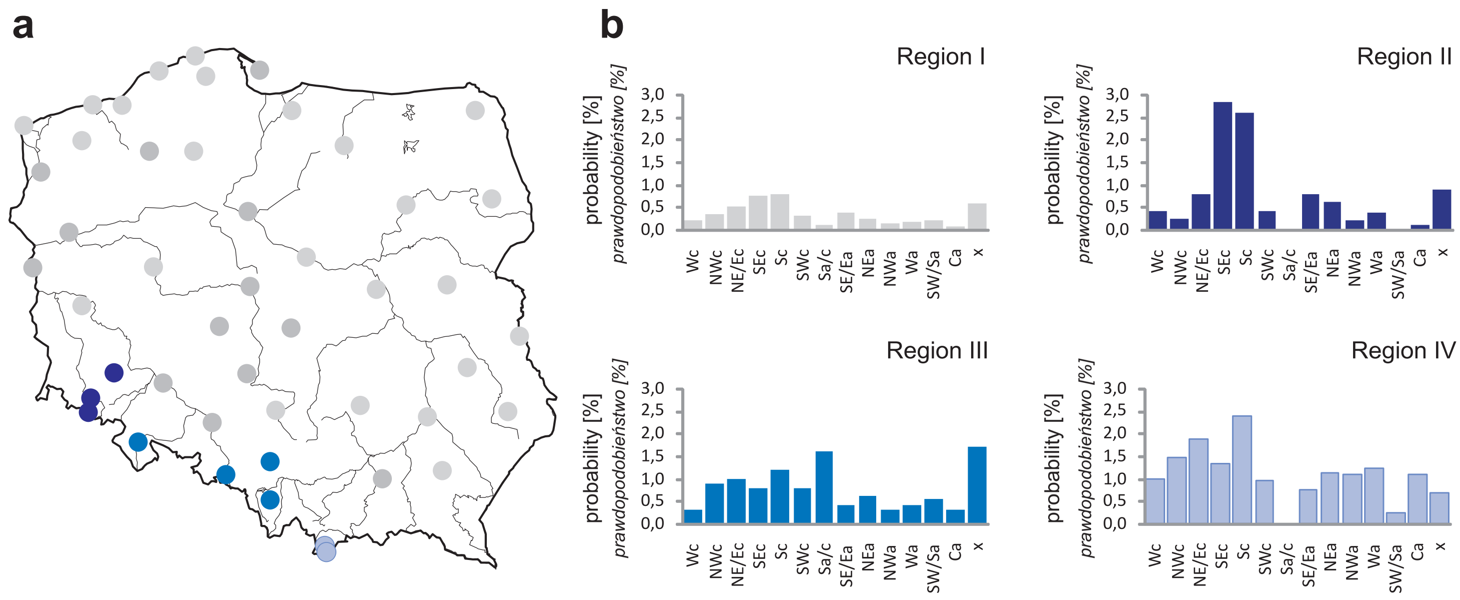


Fig. 5. Conditional probability of severe* thunderstorm occurrence (from May to Sep) on condition of an atmospheric circulation type in the period 1951–1998: a) regions of similar probability of severe* thunderstorm occurrence in circulation types, b) probability of severe thunderstorm occurrence in circulation types by regions

(*severity of thunderstorm defined based on precipitation amount of > 30 mm)

Ryc. 5. Prawdopodobieństwo warunkowe wystąpienia silnych burz* (od maja do września) w zależności od typu cyrkulacji atmosfery w okresie 1951–1998: a) przestrzenny zasięg wydzielonych regionów, b) częstość dni z silnymi burzami* w poszczególnych typach cyrkulacji w wydzielonych regionach

(*dni z burzą i opadem > 30 mm)

the vast area of lowland Poland. The other three regions covered the south of the country where the weather is largely modified by the local relief. Each of these regions contained a relatively low number of stations, i.e. between two and four. The RII region has three stations located in the Sudetes Mountains and in their approaches (Mt. Śnieżka, Jelenia Góra and Legnica). The RIII region has four stations at much lower altitudes (Kłodzko in a large mid-mountain basin in the Sudetes Mts., Racibórz, Bielsko-Biała and Katowice where the climate is influenced by nearby mountains and by air advection through the Morava Gate). The final region R4 is represented by two Carpathian stations (Zakopane in the Podhale Basin and Mt. Kasprowy Wierch in high mountains).

While days with a severe thunderstorm occur very frequently during the circulation types NE/Ec, NWc and NEa, the greatest probability of their occurrence is associated with air advection from the south. At the RI region stations this specifically means southerly and south-easterly advection linked with a cyclonic system (Sc and SEc). The type most favourable to the occurrence of days with a severe thunderstorm in its western part is SEc with the highest conditional probability value of 1.9% at Chojnice. In the eastern part this is the Sc type, which has a probability of severe thunderstorm higher than 1% (from 0.7 to 1.8%). The RII region follows a similar pattern, but with much higher probability values (1.9–3.8%). In the RIII region it is the southerly air advection transitional between cyclonic and anti-cyclonic (Sa/c) that favours severe thunderstorms most. The probability values exceed 1% and, at Racibórz, they reach as high as 2.6%. Also in RIV southerly advection has the greatest contribution to the occurrence of the phenomenon: at Zakopane (Sc: 1.5%, SEc: 1.9%) and at nearby Mt. Kasprowy Wierch (Sc: 3.3%, SEc: 0.8%). Interestingly, the NWc and NE/Ec types also favour thunderstorms and heavy precipitation at these stations, which is likely to be linked to the orographic effect on slopes exposed to these sectors of advection.

The four types of severe thunderstorm frequency (TI-TIV) characterised above and the four regions of various probabilities of severe thunderstorm in particular circulation types (RI-RIV) barely correspond to the thunderstorm regions distinguished by Kolendowicz (2005) or Bielec-Bakowska (2002). However, some similarities can be noticed concerning the thunderstorm frequency types. For example, frequency type IV (TIV) corresponds to a coastal region in both classifications: Region 1 by Kolendowicz (2005) and the Seacoast Region by Bielec-Bakowska (2002). The spatial range of frequency type II (TII) is congruent with both Region 4 by Kolendowicz (2005) and the North-eastern and South-eastern Region by Bielec-Bakowska (2002).

The relationship between severe thunderstorm occurrence and atmospheric circulation discussed above confirms the findings of research on thunderstorms in general. Indeed, circulation types with air advection from the southern sector not only favour thunderstorms with heavy precipitation, but also thunderstorms in general, and hail (Bielec-Bakowska 2002; Chromá et al. 2005). This is particularly true when:

– A low-pressure area with a system of atmospheric fronts is passing over Poland from the west, while a high-pressure system is dominating over Central or Eastern Europe. This causes an influx of warm and humid tropical air and thunderstorms developing at the face of the oncoming cold front are more violent than during other synoptic situations. In south-eastern Poland the probability of thunderstorm occurrence in this circulation type from May to August reaches almost 50% (Kolendowicz 2005).
– A local low-pressure system with atmospheric fronts is passing across Western and Central Europe. It is accompanied by an influx of warm and humid air from the south and by thunderstorms on the cold or occluded front. There is between 15–40% chance that a thunderstorm will occur during this type of circulation in the south of Poland (from May to August) (Kolendowicz 2005).
– Thunderstorms form in a homogenous air mass after the passage of a warm front from the south, south-east or east. Such a front separates colder maritime polar air masses from the inflowing warmer continental polar or tropical air masses. The probability of a severe thunderstorm occurrence in such conditions reaches from 16% to 39% in the period from May to August (Kolendowicz 2005).

In southern Poland, the influence of southerly advection is reinforced by the land relief, dominated by the longitudinal chains of the Sudetes and the Carpathian Mountains and the Morava Gate that separates them.

Previous research into the occurrence of thunderstorms has shown that, both in Poland and in other regions of the globe, most thunderstorms are linked to intense cyclonic activity and the atmospheric fronts that accompany it (Changnon 1988a and b; Easterling 1990; Brazdil et al. 1998; Kolendowicz 2005). In Poland between 60 and 80% of all days with a thunderstorm occurred at a time when an atmospheric front was passing over the country. This percentage varies from 100% in winter, to 50–75% in summer, depending on the season of the year, the region and the actual period (Michałowski 1962; Wróbel 1985; Bielec-Bakowska 2002). Normally frontal thunderstorms accompany cold fronts (54% of frontal thunderstorms) and 26% are linked to occluded fronts and the remaining 20% with warm types of front (Parczewski 1965).

Days with a thunderstorm and precipitation higher than 30 mm are very rare, and therefore their share in the number of days with or without a front is meagre. Nonetheless, a comparison of the frequency of atmospheric fronts with the frequency of thunderstorms with heavy precipitation gives an important, relevant characteristic. Such an analysis was only carried out for south-eastern Poland (eight stations) since the data on the frequency of days with and without fronts were available only from this region. It was found that severe air mass thunderstorms are recorded on 0.2–0.6% of days without fronts, while severe frontal thunderstorms account for 0.6–2.4% of all days with a front (from May to September). On the other hand, from 53.8% (Zamość) to 81.9% (Aleksandrowice) of days with thunderstorm and heavy precipitation coincide with atmospheric fronts. Severe frontal thunderstorms are most frequent in central part of the analysed area (Aleksandrowice, Tarnów and Rzeszów: 78.8–81.9%) while air-mass thunderstorms are more often observed in the rest of the south-eastern Poland area (from 29.2% in Katowice to 46.2% in Zamość) characterized by more diversified topography (Tab. 2). Among frontal thunderstorms, those associated with a cold front were dominant (from 18.2% to 54.3% of days with severe thunderstorm, figures for Sandomierz and Rzeszów respectively). There was also quite a high share of thunderstorms with heavy precipitation which occurred on days with various fronts (two or more fronts of different type) passing over the territory of south-eastern Poland (from 12.8% in Zamość to 29.2% in

Table 2. Frequency [%] of the occurrence of days with thunderstorm and heavy precipitation coinciding with atmospheric fronts over southeastern Poland (1951–1998)

Tabela 2. Częstość [%] występowania dni z burzą i wysokim opadem w zależności od rodzaju frontów atmosferycznych w południowo-wschodniej Polsce (1951–1998)

Station Stacja	Day – Dzień			Kind of front – Rodzaj frontu					
	Without fronts Bez frontu	With fronts Z frontem	Sum Suma	Warm Ciepły	Cold Chłodny	Occluded Zokludowany	Stationary Stacjonarny	Various Różne	Sum Suma
Częstochowa	36.7	63.3	100	3.3	23.3	10.0	0.0	26.7	63.3
Katowice	29.2	70.8	100	4.2	35.4	4.2	0.0	27.1	70.8
Kielce	22.9	77.1	100	14.3	37.1	5.7	2.9	17.1	77.1
Tarnów	21.2	78.8	100	9.1	42.4	9.1	3.0	15.2	78.8
Rzeszów	20.0	80.0	100	5.7	54.3	2.9	2.9	14.3	80.0
Sandomierz	42.4	57.6	100	15.2	18.2	0.0	3.0	21.2	57.6
Zamość	46.2	53.8	100	7.7	25.6	5.1	2.6	12.8	53.8
Aleksandrowice	18.1	81.9	100	9.7	36.1	4.2	2.8	29.2	81.9
Zakopane	30.0	70.0	100	4.4	36.7	5.6	7.8	15.6	70.0
Kasprowy Wierch	25.5	74.5	100	7.1	38.8	6.1	3.1	19.4	74.5
south-east Poland*	31.6	68.4	100	7.7	33.0	5.2	3.3	19.2	68.4

*Days with thunderstorm and heavy precipitation recorded at least at one meteorological station in south-east Poland were analysed

* Rozpatrywano dni z burzą i silnym opadem zanotowane przynajmniej na jednej stacji meteorologicznej w południowo-wschodniej Polsce

Aleksandrowice). Such thunderstorms were rarest on days with stationary fronts (ca. 3% of all cases).

DAYS WITH A THUNDERSTORM AND HEAVY PRECIPITATION DURING THE COLD SEASON (OCTOBER – APRIL)

In the study of thunderstorms and accompanying phenomena, their occurrence in the cold season constitutes an interesting aspect. This study looks at two periods with a low number of days with thunderstorm and precipitation higher than 30 mm, i.e. between October and April and its sub-period between November and March, when the frequency of such thunderstorms is extremely low. During the study period, the longer of the seasons (Oct-Apr) had 35 days with a severe thunderstorm (2.4% of all such days), while its sub-season had only six days (0.4%). The occurrences were mostly recorded at the coast and in the south of the country (Fig. 6) and were typically accompanied by northerly

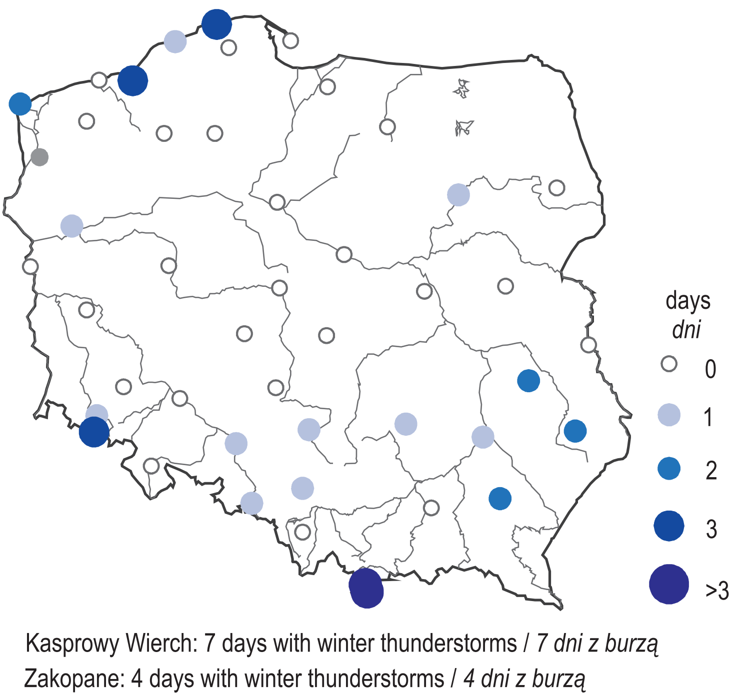


Fig. 6. Number of days with severe thunderstorms (with precipitation > 30 mm) occurring from October to April in the period 1951–1998

Ryc. 6. Liczba dni z silnymi burzami (z opadem > 30 mm) występująca od października do kwietnia w latach 1951–1998

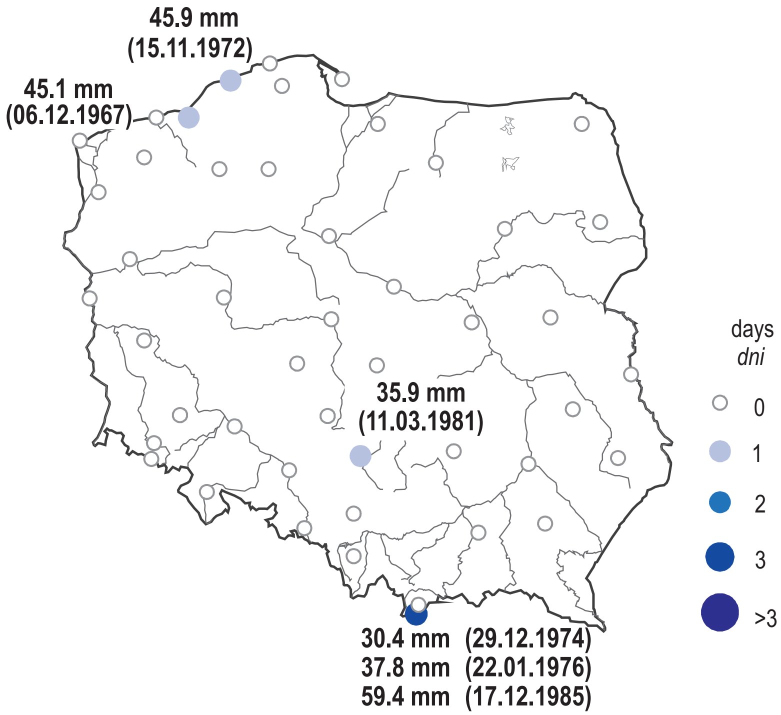


Fig. 7. Number of days with severe thunderstorms (with precipitation >30 mm) occurring from November to March in the period 1951–1998

Ryc. 7. Liczba dni z silnymi burzami (z opadem > 30 mm) występująca od listopada do marca w latach 1951–1998

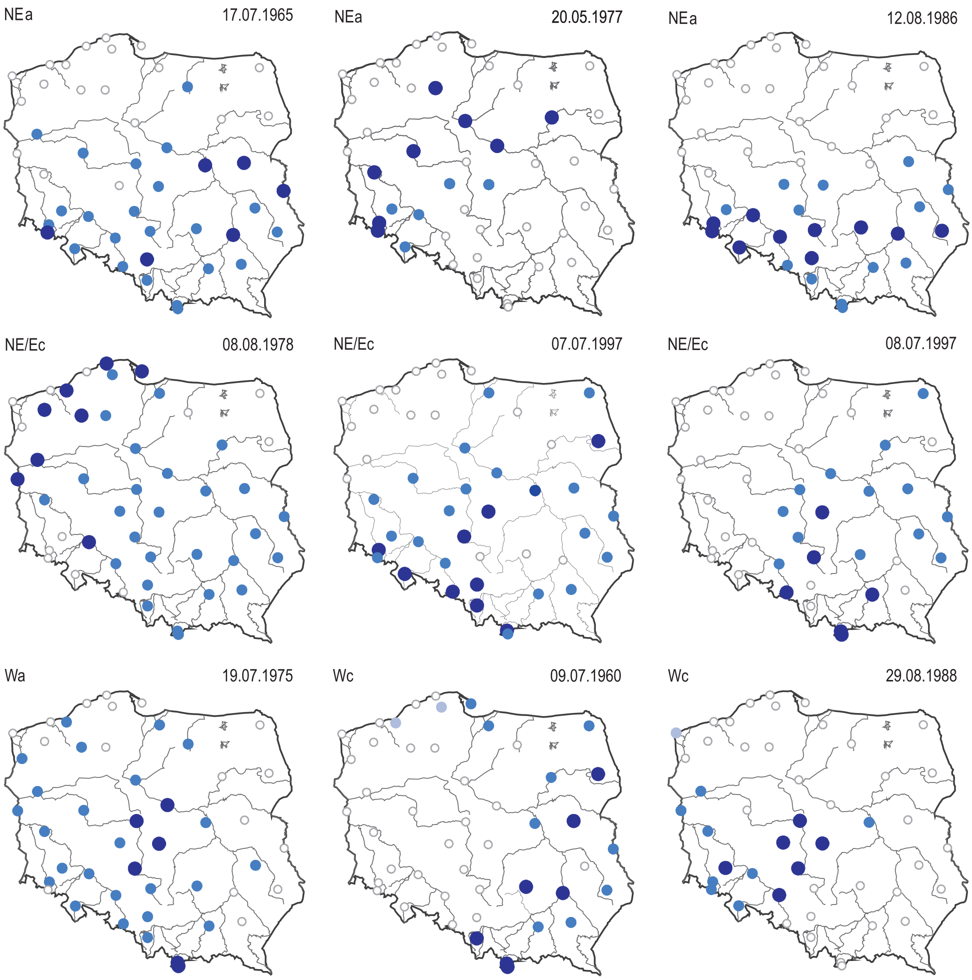
or south-westerly advection (NWc and SWc – 34.3% of all cases), or by north-easterly advection (NE/Ec and NEa – 25.7%). Most stations only recorded a single such occurrence during the whole period. The exceptions of three or more days included: Koszalin and Świnoujście (3 days) on the coast and Mt. Śnieżka (3 days), Zakopane (4 days) and Mt. Kasprowy Wierch (7 days) in the mountains. During the coldest season (November – March), only four stations recorded any severe thunderstorms: Koszalin and Ustka on the Baltic coast, Częstochowa on a southern upland and Mt. Kasprowy Wierch in the Tatras (Fig. 7). There were three severe thunderstorm events (with precipitation > 30mm) observed on Mt. Kasprowy Wierch, including two in December and one in January. On those days, the overall precipitation total only just exceeded 30 mm with the exception of 17 December 1985 when 59.4 mm fell on Mt. Kasprowy Wierch. The thunderstorms mostly accompanied air advection from the northwest or northeast. On the coast and, on one occasion, at Mt. Kasprowy Wierch it was the NWc type, twice at Mt. Kasprowy Wierch it was NE/Ec and only in Częstochowa was it a southerly SWc. All of those days were accompanied by atmospheric fronts.

EXCEPTIONAL CASES OF DAYS WITH A THUNDERSTORM AND HEAVY PRECIPITATION

This section is devoted to an analysis of the special cases, when days with a thunderstorm and more than 30 mm of precipitation occurred. These special cases involve days with severe thunderstorms over a large area (recorded by at least six stations) and the two cases with the highest precipitation. Days with severe thunderstorm observed by at least six stations were rarest, whereas days with thunderstorm and heavy precipitation recorded at a lower number of stations accounted for 98,1% of all examined days and most of them were noted at the same time at only 1–2 stations (85,3%). During the study period, there were 17 such days where severe thunderstorms were observed by 6 to 13 weather stations (Fig. 8). The largest number was recorded in July (9), followed by August (4), May and June (2 each). On most of those days, other stations also recorded thunderstorms, albeit less heavy ones (with precipitation < 30 mm). Just as with days with a thunderstorm and heavy precipitation observed during the cool part of the year, so there were atmospheric fronts passing over Poland on these 17 days. On eight of the days there were southerly advection types of situation (SE/Ea, Sc, SW/Sa, SEc; Fig. 8), on six days the advection was north-easterly (NEa and NE/Ec – Fig. 8) and on three occasions air masses were coming from the west (Wa and Wc – Fig. 8). Normally, stations that recorded thunderstorms accompanied by heavy precipitation were rather tightly grouped in a region or along the path of the front (e.g. on 23 July 1953 with the SEa/Ea circulation type) (Fig. 8). Sometimes, however, they were spread over large distances from one another among many other stations that also recorded thunderstorms on that day (e.g. 30 June 1997 – Sc) (Fig. 8).

The most interesting example occurred on 8 July 1996. An SEc circulation type prevailed on that day, and precipitation fell on a large portion of Polish territory and was particularly intense in the south-western part of the country. Thunderstorms were recorded at 32 of the 47 weather stations surveyed in this study, including 13 that measured more than 30 mm of precipitation (Fig. 9a). A shallow low-pressure system was prevailing over the Alps and Poland found itself within reach of low pressure influence and a related warm front. The system travelled towards the northeast. As the centre of the system arrived over Lower Silesia (south-western Poland) there were two air masses moving into Poland: humid air from the north at ground level and southern air in the middle of the troposphere (Ustrnul and Czekierda 2009). Combined with the orographic influence of the Sudetes and the Carpathians this situation produced intensive precipitation over vast areas.

A similar origin was behind the heaviest precipitation recorded during a thunderstorm: 166.1mm at Mt. Kasprowy Wierch. On that day (8 July 1997), 19 stations recorded thunderstorms, including six that also recorded more than



stations with no both thunderstorm and precipitation
brak burz i opadów

stations with thunderstorm and with no precipitation
burza i brak opadu

stations with thunderstorm and precipitation =< 30,0 mm
burza i opad =< 30 mm

stations with thunderstorm and precipitation > 30.0 mm
burza i opad > 30 mm

Wc, NE, Wa,... - circulation type / *typ cyrkulacji*

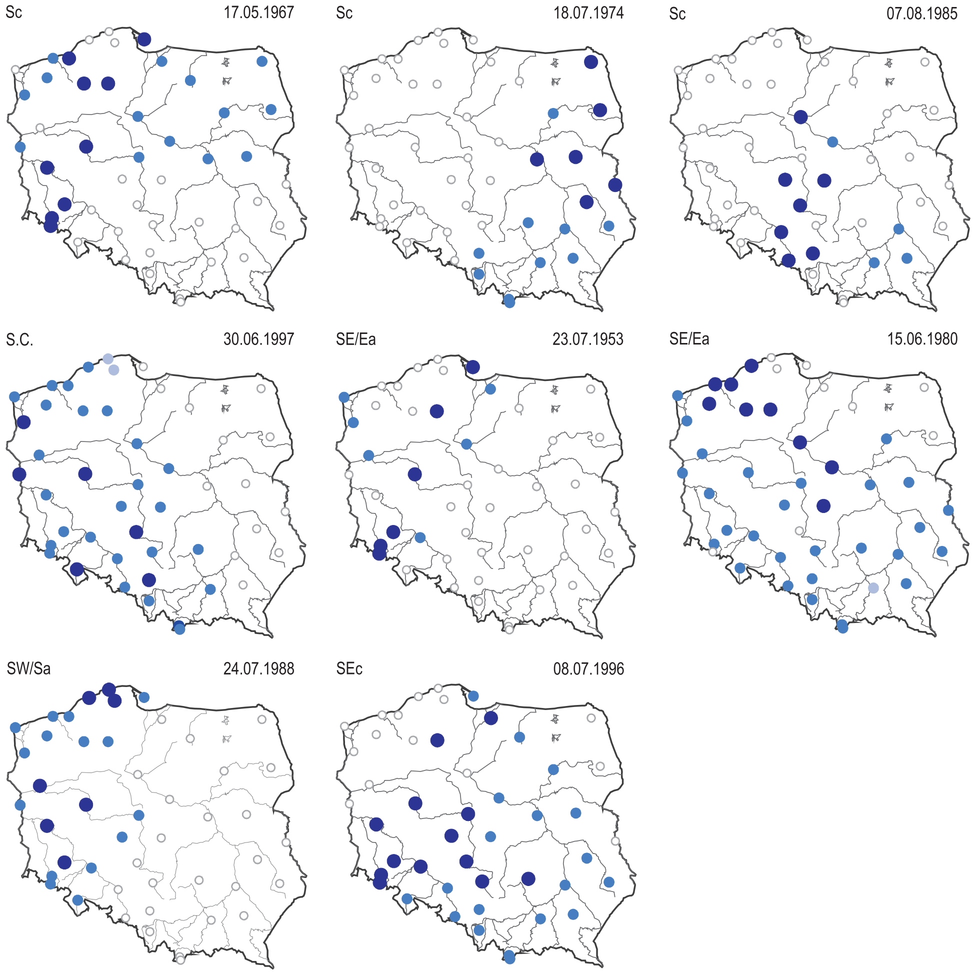
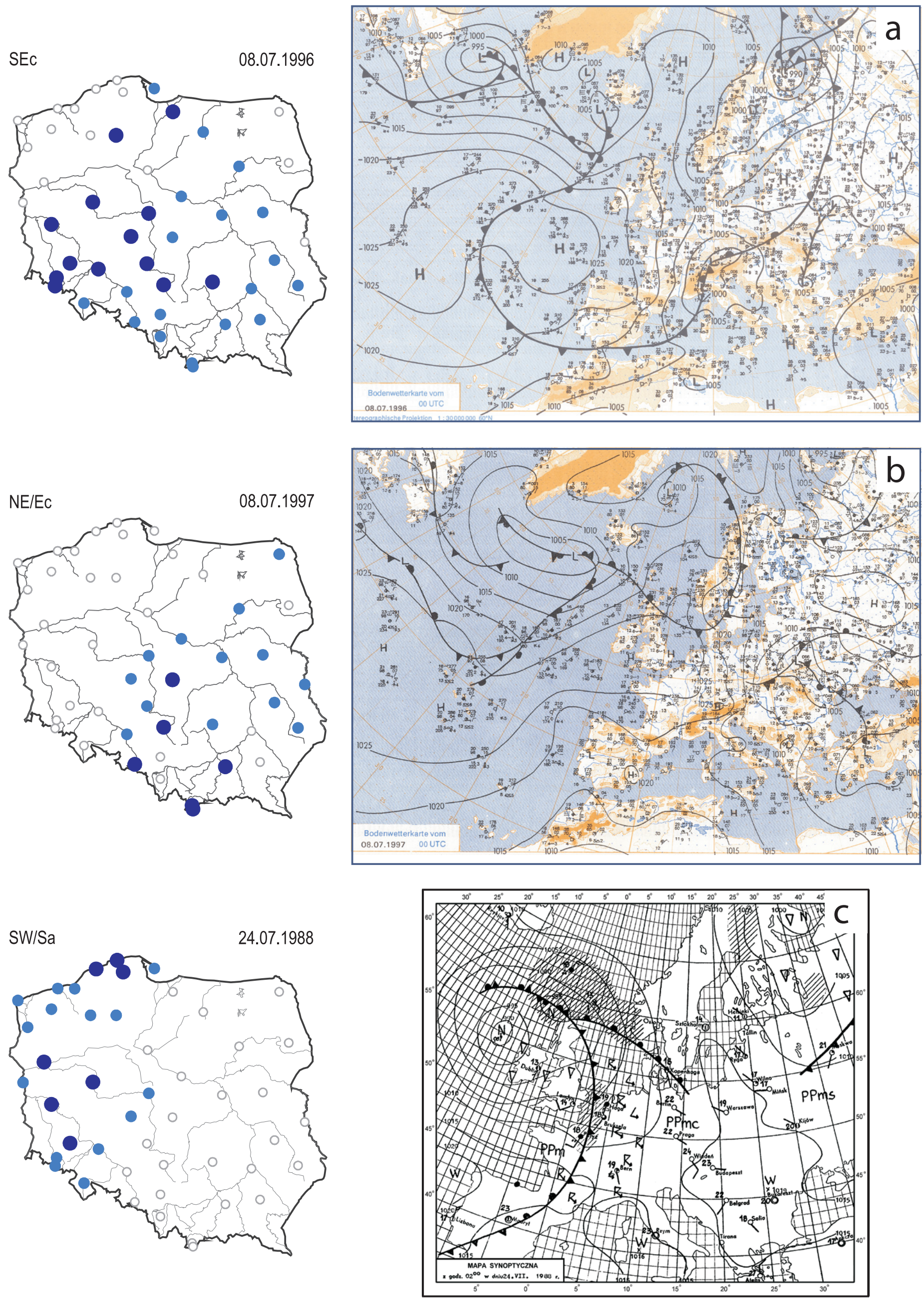


Fig. 8. Exceptional cases* of days with severe thunderstorm (with precipitation > 30 mm) in the period 1951–1998

*A case was recognized as exceptional when a severe thunderstorm was noted by at least six stations on particular day

Ryc. 8. Wyjątkowe przypadki* dni z silnymi burzami (z opadem >30 mm) w latach 1951–1998

*Dni z burzą i opadem >30 mm odnotowane tego samego dnia na co najmniej sześciu stacjach



stations with no both thunderstorm and precipitation
brak burz i opadów

stations with thunderstorm and with no precipitation
burza i brak opadu

stations with thunderstorm and precipitation =< 30,0 mm
burza i opad =< 30 mm

stations with thunderstorm and precipitation > 30.0 mm
burza i opad > 30 mm

30 mm of precipitation. A shallow cyclone, which developed over the western Alps and Germany a few days earlier (on 3 July), was approaching slowly from he southwest, impeded by a high-pressure area stagnating in the east. In a similar manner to the previous example, intensive precipitation and electrical discharges accompanied the situation. On 8 July, the system began to gradually fill in and moved eastwards, engulfing the Tatra Mountains (Fig. 9b). Daytime convection reinforced by the orographic effect led to the development of active thunderstorm cells and heavy precipitation (Adamczyk and Olszowicz 1999).

The last of the special cases occurred on 24 July 1988, when thunderstorms and precipitation were recorded at 22 stations including seven stations (on the coast and in south-western Poland) that measured more than 30 mm of precipitation. The highest total was recorded in Łeba and at 141.0 mm was the second heaviest thunderstorm precipitation recorded in Poland during the study period. For a few preceding days, Poland was under the influence of a vast high-pressure system that had developed in warm marine polar and continental polar air masses. On 24 July, a cold front linked to a strong low pressure area with its centre north of Great Britain entered into Poland from the northwest (Fig. 9c). The front separated hot tropical air moving from the south from the cool and humid marine polar air that accompanied the front. The difference in humidity and temperature was huge (approx. 10°C at 850 hPa) and it triggered violent thunderstorms and very heavy precipitation over much of the country.

CONCLUSIONS

The paper aimed at identifying the atmospheric circulation types that most favoured thunderstorms with heavy precipitation in Poland during the period 1951–1998. Thunderstorms accompanied by heavy precipitation were also broken down into air-mass and frontal types and certain specific cases received detailed discussion.

Fig. 9. Selected exceptional cases of days with severe storms (with precipitation > 30 mm) and accompanying synoptic situations: a) 08.07.1996, b) 08.07.1997, c) 24.07.1988

source of synoptic maps for a) and b) European Meteorological Bulletin, Deutschen Wetterdienstes; for c) Codzienny Biuletyn Meteorologiczny, Institute of Meteorology and Water Management

Ryc. 9. Sytuacje synoptyczne w wybranych dniach z wyjątkowymi przypadkami silnych burz (z opadem > 30mm): a) 08.07.1996, b) 08.07.1997, c) 24.07.1988

źródła map synoptycznych: a) i b) European Meteorological Bulletin, Deutschen Wetterdienstes; c) Codzienny Biuletyn Meteorologiczny, Instytut Meteorologii i Gospodarki Wodnej

In Poland, days with a thunderstorm and more than 30 mm of precipitation occur rarely (less than once per year) except in mountainous areas. The maximum precipitation total recorded varied from station to station, but nearly half of all stations recorded cases of more than 80 mm of precipitation per day, eight stations had peak totals higher than 100 mm and the absolute maximum of 166.1 mm was recorded at Mt. Kasprowy Wierch.

On a clear majority of the days analysed there was a north-easterly or north-westerly air advection (circulation types NE/Ec, NEa, NWc) and at certain stations there was a strong input of southerly advection (primarily SE/Ea and SEc). Despite this dominant position of the north-easterly and north-westerly advection (respectively 45% and 35%; Kolendowicz 2005), however, the study has found that the circulation types most likely to accompany the phenomena studied were those involving southerly air advection (they occur on just 3% of the days of the year).

A detailed analysis of the special cases of thunderstorms with more than 30 mm of precipitation showed that the most severe thunderstorms were often recorded over a large portion of the country and accompanied peculiar weather conditions. In the three cases studied in detail, very cool and humid air from the northern sector trailed fronts into Poland, while very warm air from the south stagnated before a front (sometimes for several days). The high contrast in temperature and humidity led to the development of very potent convection phenomena and to the occurrence of thunderstorms and very heavy precipitation. Similar phenomena involving the important role of air advection from the south can also be found in other regions at moderate latitudes. Examples include thunderstorm occurrence in the Czech Republic and in certain regions of the United States (Changnon 1985; Brazdil et al. 1998).

In Poland, the relative high frequency of occurrence of severe thunderstorms (with more than 30 mm of precipitation) is noted in areas where the climate conditions are strongly modified by local effects, such as the land/sea contrast (in north-western Poland) or land relief (southern Poland). It seems that these local factors may also have a certain influence on both the origin and occurrence of severe thunderstorms. Air-mass thunderstorms are rare in Poland, but they tend to be more frequent in areas where high local differences in elevation may be conducive to convection (such as in Aleksandrowice, Tarnów and Rzeszów).

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WYSTĘPOWANIE SILNYCH BURZ W POLSCE W ŚWIETLE CYRKULACJI ATMOSFERY

Streszczenie

W artykule określono związki pomiędzy występowaniem dni z burzą i wysokim opadem (> 30 mm) a typami cyrkulacji atmosfery. Podstawę opracowania stanowiły: obserwacje meteorologiczne dotyczące występowania burz oraz dobowe sumy opadów atmosferycznych z 47 stacji synoptycznych w Polsce z lat 1951–1998, jak również typy cyrkulacji B. Osuchowkiej-Klein, dane dotyczące rodzajów frontów atmosferycznych przemieszczających się nad południowo-wschodnią Polską, wyznaczone przez T. Niedźwiedzia oraz mapy synoptyczne. Określono typy cyrkulacji najbardziej sprzyjające występowaniu dni burzowych z wysokim opadem oraz dokonano genetycznego podziału rozpatrywanych silnych zjawisk burzowych (z opadem > 30 mm) na frontalne i wewnątrzmasowe. W Polsce dni z burzą i opadem > 30 mm występują niezwykle rzadko, głównie w miesiącach letnich. Okres ich powtarzalności wynosi około 2–4 lata i jedynie w górskich regionach na południu kraju zjawiska te odnotowywane są prawie każdego roku. Najwyższy opad w dniu z burzą osiągnął 166,1mm i został zanotowany na wysokogórskiej stacji Kasprowy Wierch. Na pozostałych stacjach najwyższe opady w dniach z burzą dochodziły najwyżej do 141,0 mm i tylko na 8 z nich chociaż raz przekroczyły 100 mm. Na obszarze Polski wyróżniono 4 regiony różniące się typami cyrkulacji najbardziej sprzyjającymi występowaniu dni z silnymi burzami. Na wszystkich pojawianiu się badanych zjawisk najbardziej sprzyjała adwekcja powietrza z sektora południowego (Sc, SEc, Sa/c), szczególnie na stacjach położonych na południowo-zachodnim krańcu Polski. Podczas większości dni burzowych z wysokim opadem nad Polską przemieszczał się front atmosferyczny (53,8–81,9% w zależności od stacji), natomiast burze wewnątrzmasowe najczęściej notuje się w regionach o silnie zróżnicowanej rzeźbie terenu.