



Original article

Winter thunderstorms in Poland (1951–2020)

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ABSTRACT

One of the climate changes observed in mid-latitudes is the increase in the frequency of winter thunderstorms. These changes are also observed in Poland. For this reason, this study presents changes in the occurrence of thunderstorms in the cold half of the year and in winter in Poland from 1951 to 2020. The synoptic and thermodynamic conditions in the atmosphere, accompanied by particularly strong thunderstorms at this time of year, were also analysed based on selected cases of winter thunderstorms. The research was carried out on the basis of data from 46 synoptic stations, and the basic indicator was a day with a thunderstorm. Additionally, three cases of dangerous winter thunderstorms that occurred in Poland in the 21st century were analysed. For this purpose, synoptic maps, data from ERA5 reanalyses, aerological data and reports from the European Severe Weather Database were analysed. On this basis, it was found that there was a clear spatial differentiation of thunderstorms occurring in the cold half of the year, which in some regions of the country accounted for even more than 8% of all cases in the year. Although these thunderstorms are extremely rare, there are signs of an increase in their frequency during the study period. The strongest influence on the occurrence of these phenomena in the cold season is air circulation and local conditions. Most of the thunderstorms considered were associated with atmospheric fronts. The strongest of them occurred during the passage of dynamic cold fronts, which are characterized by low potential energy and high wind shear values.

KEY WORDS: winter, thunderstorm, atmospheric circulation, Poland, Central Europe

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1. Introduction

Significant attention is drawn to extreme weather phenomena and their relationship to observed climate change. The frequency of such phenomena and damage they cause to the environment and the economy are on the rise in many regions of the World (IPCC, 2021). Changes in the areas of occurrence of these phenomena, their frequency, annual course and their intensity are important. Because of their frequently violent nature, thunderstorms, predominant in the warm season and the accompanying precipitation (including hail), gusty wind or tornadoes, are also usually classified as

extreme meteorological phenomena. Nevertheless, considering the definition stating that extreme phenomena include those that rarely occur at a given place and in a given season (with a frequency lower/higher or equal to 10/90 percentile of all cases analysed (IPCC, 2021)), and the typically small impact of thunderstorms on the environment (AVOTNIECE ET AL., 2017), classifying them among extreme phenomena would be a mistake in many European regions. The exception is formed by the strongest thunderstorms that cause significant damage, often meeting the criteria for natural disasters (PRUCHNICKI, 1999; WISNER ET AL., 2004), and thunderstorms taking place in the cool season,

in particular winter thunderstorms, that usually constitute 1–2% of all cases occurring in a year (MUNZAR & FRANC, 2003; SCHULTZ & VAVREK, 2009). Even though winter thunderstorms are extremely rare and are often restricted to small areas, or even to one station on a given day (MARKET ET AL., 2002), their occurrence may also cause difficult meteorological conditions. This principally refers to strong gusts of wind which are accompanied by heavy snowfall or freezing rain, or even hail, as well as strong lightning discharges. In extreme cases they may include tornadoes (FÖRCHTGOTT, 1969; SCHULTZ & VAVREK, 2009). They cause significant difficulties for transport, principally air and road (SULAN, 2002), blackouts, sudden increases in the thickness of snow cover, as well as flooding and fires (MUNZAR & FRANC, 2003; SCHULTZ & VAVREK, 2009; LETCHER & STEIGER, 2010; PIOTROWICZ ET AL., 2020). However, literature comparing the probability of thunderstorms occurring in the cool season, and the difficulties they cause is rather scarce. These are usually case studies or studies of thundersnow events (FÖRCHTGOTT, 1969; CROWE ET AL., 2006; KONARSKI ET AL., 2008; SCHULTZ & VAVREK, 2009). Even less common are studies involving longer series of observations and a more thorough analysis of thunderstorms in the cool season (MUNZAR & FRANC, 2003; MARKET ET AL., 2002; BIELEC-BĄKOWSKA ET AL., 2021).

This study aims to determine the long-term variability of changes in the occurrence of thunderstorms in the cold half of the year as one of the indicators of climate change. This research examines the spatial and temporal variability of the occurrence of cool-season (October through March) thunderstorms in Poland, an area representative of Central Europe, for the period 1951–2020. Special attention has been given to the occurrence of extremely rare winter thunderstorms (December to February), which may point to changes in the atmospheric dynamics in the study region taking place in recent decades. Furthermore, synoptic conditions favouring the occurrence of such phenomena have been presented using selected examples.

2. Materials and research methods

The study uses meteorological observations from 46 synoptic stations (Fig. 1) within the network of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) for the

period 1951–2020 (<https://danepubliczne.imgw.pl>). Two of these: Śnieżka and Kasprowy Wierch, are located high in the mountains.



Fig. 1. Synoptic stations included in the study

The basis for the study was a day with a thunderstorm, which means that the thunderstorm phenomenon was recorded by the observer at the station, without differentiating between close and distant thunderstorms. Unfortunately, there is also some data missing. These refer to observations in the period 1951–1954 at the stations in Koszalin, Terespol, Włodawa, Nowy Sącz, and Lesko (between 2 and 4 years), and from 2014 at the stations in: Ustka, Kętrzyn, Olsztyn, Słubice, Koło, Płock, Legnica, Leszno, Wieluń, Tarnów, Rzeszów, Sandomierz, and Nowy Sącz (between 1 and 6 years). Values characterizing the occurrence of thunderstorms in the stations listed have been calculated for shorter study periods. In the case of the analysis performed for the cool season (October–March) and for the meteorological winter (December–February), the number of thunderstorms was determined for a season covering two calendar years (e.g. from October 1951 to March 1952).

Furthermore, the following were used in the analysis:

- synoptic maps obtained from The Royal Netherlands Meteorological Institute (KNMI) databases (<https://www.knmi.nl/nederland-nu/klimatologie/daggegevens/weerkaarten>),
- aerologic data from the University of Wyoming database (<http://weather.uwyo.edu/upperair>) and data from the ERA5 reanalysis, which were

processed and made available via the Rawinsonde service ([thunderR](http://rawinsonde.com/thunder_app): http://rawinsonde.com/thunder_app, http://rawinsonde.com/ERA5_Europe; TASZAREK ET AL., 2023),

- data from the European Severe Weather Database (ESWD; <https://eswd.eu>).

In the part of the study devoted to the synoptic analysis of selected cases of winter thunderstorms, the following days were selected: 18 January 2007, 17 January 2022 and 17 February 2022. These cases were selected so that the storms occurring on each analysed day covered a significant part of the country and generated intense weather phenomena, causing significant material damage in most cases.

When analysing long-term trends in thunderstorms occurrence, Pearson correlation coefficients were applied, while the significance of the changes were verified using the Mann-Kendall test (MANN, 1945; KENDALL, 1975).

3. Spatial and long-term variability of thunderstorm incidence in Poland

In the period 1951–2020, there were on average 125.4 days with a thunderstorm per year (days where at least one station recorded a thunderstorm) in Poland, of which 13.1 days were in the period from October to March, including 3.4 days with thunderstorms during the calendar winter (December–

February). Over the same period, at individual stations, the average annual number of days with a thunderstorm in Poland was 24.2 days and ranged from 15.1 days in Świnoujście and 15.6 days in Ustka on the Baltic coast (Fig. 2) to over 30 days in south-eastern Poland (33.7 days in Lesko, 32.2 on Kasprowy Wierch mountain, and 30.8 days in Zakopane). In the years with weather unfavourable to thunderstorms, there were rarely fewer than 10 days with thunderstorms at individual station. In the periods with the most thunderstorms, the greatest annual number of days with a thunderstorm usually exceeded 30 (at 45 stations), while at 18 stations this was even 40 days, and ranged from 26 at Świnoujście (1964) to 54 at Kasprowy Wierch (1963), 52 at Nowy Sącz, and 50 at Katowice (2014).

In the period under consideration most thunderstorms in Poland occur in the warm season, particularly from May to August (over 20 days on average) with the annual peak usually falling in July (24.0 days; Fig. 3). The months with the fewest thunderstorms were: December (1.0 day), January (1.1 days), and February (1.2 days), with a large increase/decrease in thunderstorm activity in spring and autumn, respectively. In the long-term period investigated, no significant changes to the annual course of days with thunderstorms were observed, although from the 1980s, there were slightly more days with a thunderstorm in spring.

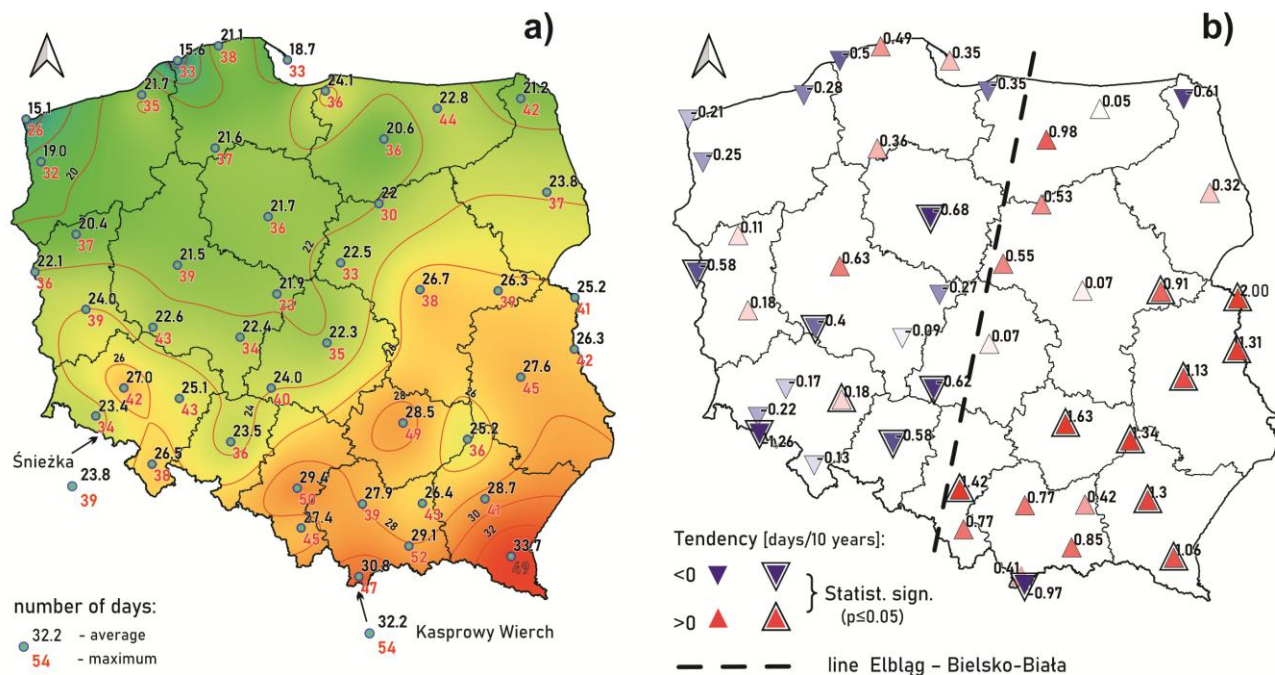


Fig. 2. Average and maximum annual number of days with a thunderstorms (a) and trends in its changes [days/10 years] (b) in Poland during the years 1951–2020

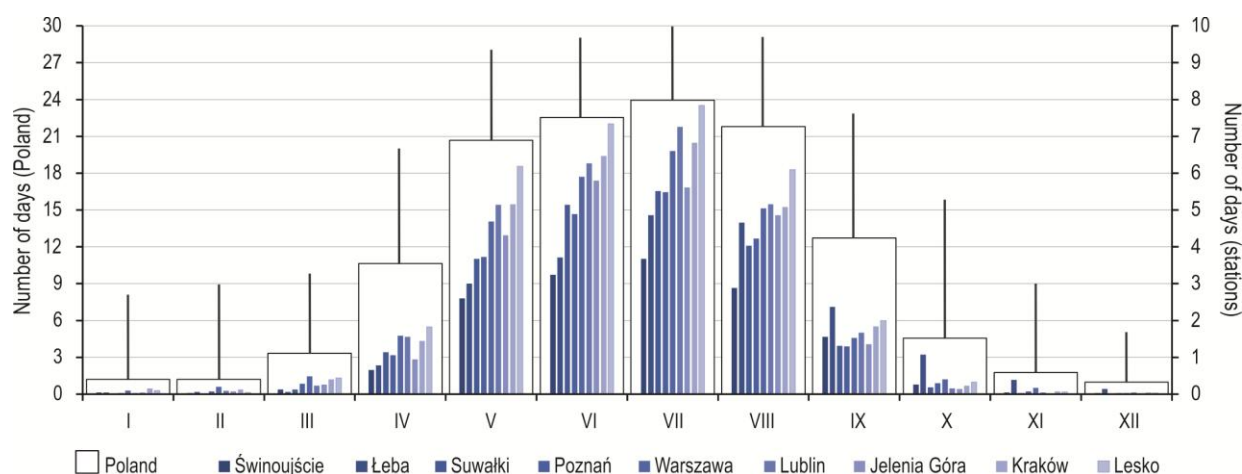


Fig. 3. Average monthly number of days with a thunderstorm in Poland and at selected stations during the period 1951-2020

Thunderstorms occurring in the cool season are much rarer, constituting from 0.7% to 8.4% of all thunderstorms at a given station; the value of at least 3% refers to 21 stations. Most of these days are recorded in the north of Poland (Koszalin – 6.5%, Ustka – 7.5%, Łeba – 8.4%), as well as in Katowice (5.5%) and Warsaw (5.2%). Winter thunderstorms constitute just 0.1% (Suwałki) to 2.0% (Katowice) of all thunderstorm days, and only at 11 stations was this share greater than 1%.

General annual patterns of thunderstorm occurrence at particular stations are maintained but, at stations located in the north and west of Poland, their number is lower with more thunderstorms occurring in the cool season (from October to March), particularly in autumn (Fig. 3). This is related to the impact of the Baltic Sea and its cooling effect in spring and summer, as well as its warming effect in autumn and winter.

When analysing long-term changes, no visible trends were found regarding any changes in the number of days when a thunderstorm was recorded at at least one station. Most of these days were observed in 2014 (152 days), and the fewest were in 1976 (101 days; Fig. 4). It is also worth noting that the period with a significantly increased number of thunderstorm days was in the 1990s and early 21st century (their average number exceeded 132 days). In the cool season and in winter, the number of thunderstorm days slowly increased up to the early 21st century, reaching 31 days (in the 1994/95 season) and 14 days (2001/02) respectively, after which the number decreased significantly. Nevertheless, the increase in the number of winter days with a thunderstorm was worthy of note, amounting to 0.35 days in ten years (a significance level of $p=0.05$).

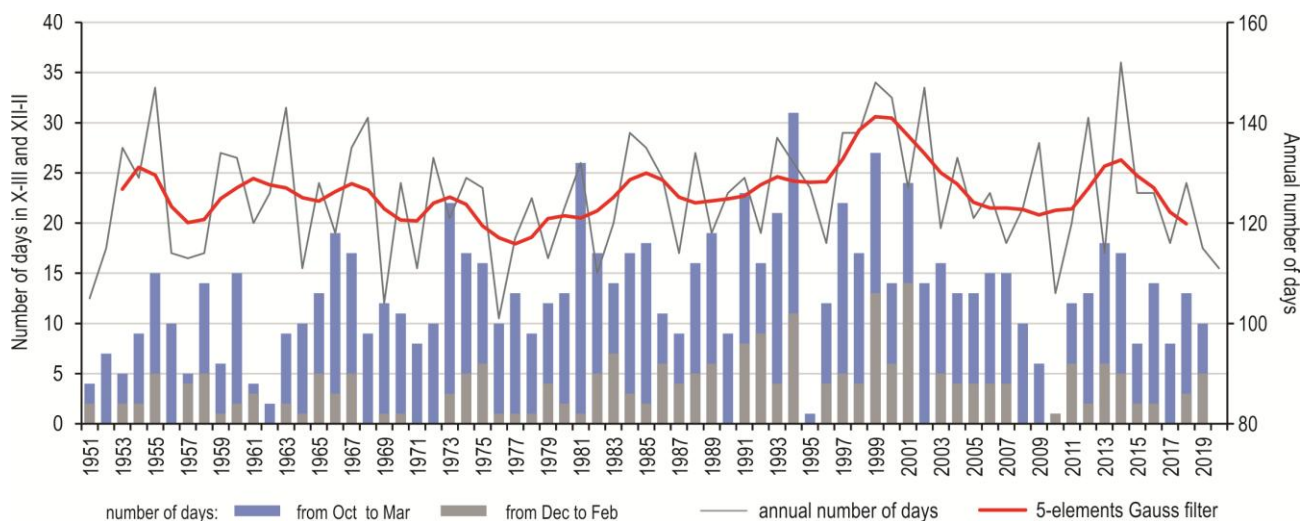


Fig. 4. Number of days with a thunderstorm in Poland during the years 1951-2020 - annual values, from the period October-March and December-February (1951 - means the season 1951/1952)

As already presented in previous studies, long-term changes to thunderstorm occurrence at particular stations are insignificant, particularly in the cool season (BIELEC-BĄKOWSKA ET AL., 2021). In the long-term period analysed, an increase in the number of thunderstorm days was principally recorded in the eastern half of Poland, with the greatest increase of 2.0 days in 10 years being recorded in Terespol (Fig. 5). The greatest decrease, however, was observed at the station on Śnieżka Mountain (-1.26 days/10 years). In the cool season, as well as in winter, almost every station experienced an increase in the number of thunderstorm days, but these changes were very small and usually not statistically significant. They do not exceed 0.26 days per 10 years in Katowice and 0.11 days per 10 years in Olsztyn and Katowice. Due to the small number of days considered, the results obtained should be treated only as signals of changes taking place.

Usually, thunderstorms are recorded in a small country area during one day. From 1951 to 2020,

in approximately 54% of cases, in a single day, they were recorded at 1 to 6 stations, and in approximately 27% of cases, at 7 to 15 stations. There were a few days in which thunderstorms were recorded at at least 30 stations (about 3%), and they usually occurred from April to September, and only in summer were they recorded at more than 40 stations (during 8 days). In the study period, thunderstorms covered practically the entire territory of Poland only twice: on 20 June 1968 and 6th June 1982, when they were recorded at 43 out of 46 stations. In the cold half of the year, in approximately 68% of thunderstorm days in Poland, thunderstorms were recorded at 1–2 stations and only in about 3% – at more than 10 stations. The most outstanding days were 27 March 1955 and 1995, when thunderstorms were recorded at 19 stations, 4 October 1978 – at 21 stations, and 26 February 1990 – at 22 stations. A low-pressure system with an active cold front moved over Poland in all these cases.

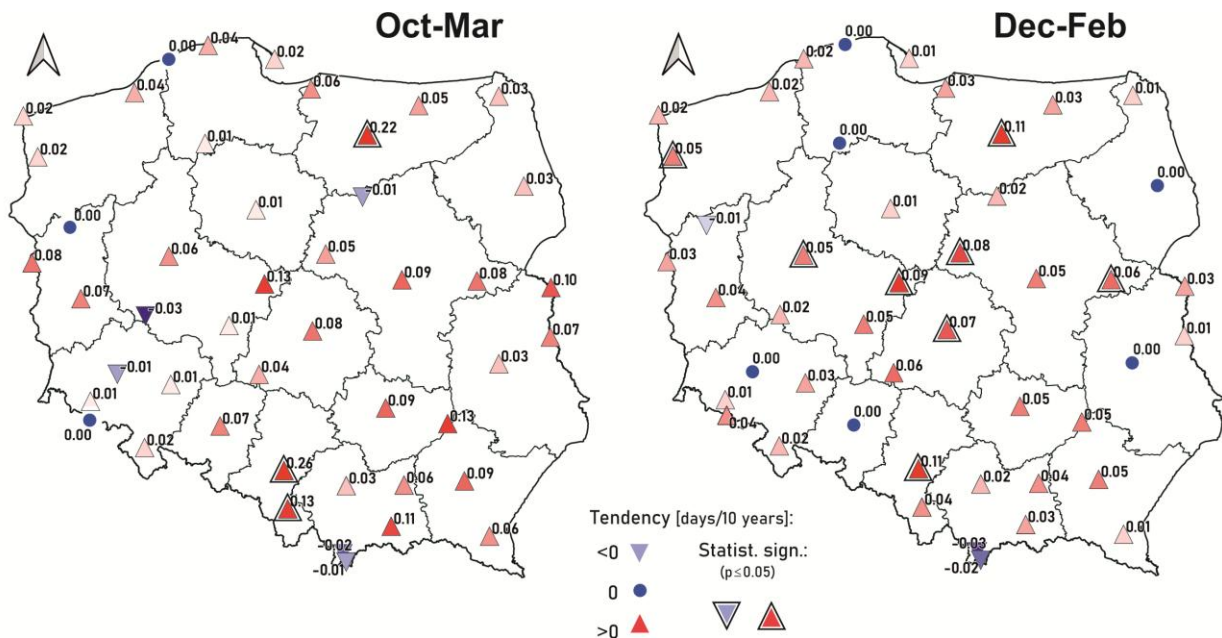


Fig. 5. Long-term changes in the number of days with a thunderstorm in Poland [days/10 years] from October to March and from December to February during the period 1951-2020

4. Cool-season and winter thunderstorms

In the period from October to March thunderstorms are rare in Poland and the conditions for their development are limited. In cool seasons during the period 1951–2020, thunderstorms were most prevalent in October (4.6 days on average) and in March (3.3 days), namely in months where

temperatures are higher and thus there is more humidity in the troposphere (Table 1). Fewer thunderstorms take place in the remaining months, from 1.0 days in December to 1.8 in November. There are, however, years with more thunderstorm activity in which there can be as many as 16 days with a thunderstorm in a month (October 1981) or 8 days with a thunderstorm in winter (January 1993).

Table 1. Maximum and average number of days with a thunderstorm in Poland in subsequent decades in months of the cold season in the period 1951-2020

Years	Number of days with thunderstorm							
	X	XI	XII	I	II	III	X-III	XII-II
Average								
1951-1960	3.9	0.6	1.1	0.5	0.8	2.1	9.0	2.3
1961-1970	4.1	2.3	0.6	0.1	1.3	2.3	10.6	2.1
1971-1980	5.1	2.2	1.1	0.9	0.3	3.4	13.0	2.3
1981-1990	5.3	2.3	1.2	1.8	1.0	3.8	15.6	3.9
1991-2000	5.0	1.9	1.1	2.3	2.5	5.4	18.4	6.4
2001-2010	4.2	1.9	0.8	1.5	1.7	3.2	12.7	3.6
2011-2020	4.4	1.2	1.0	1.4	0.8	3.1	12.6	3.4
1951-2020	4.6	1.8	1.0	1.2	1.2	3.3	13.1	3.4
Maximum								
1951-1960	9	2	4	2	3	5	15	5
1961-1970	9	6	5	1	4	8	19	5
1971-1980	9	9	4	6	1	6	22	6
1981-1990	16	6	3	6	4	7	26	7
1991-2000	10	4	3	8	7	10	31	13
2001-2010	9	4	4	5	9	7	24	14
2011-2020	9	3	4	3	4	7	18	6
1951-2020	16	9	5	8	9	10	31	14

In Poland most thunderstorms in the cool season were recorded in the south (Katowice – on average 1.6 days, Lesko – 1.0 days, Kraków – 1.0 days, Bielsko-Biała – 1.0 days; Fig. 6) and in the Baltic coast belt (Łeba – 1.8 days, Koszalin – 1.4 days, Ustka – 1.2 days). In the west and in the centre of Poland, on average 0.5-0.8 of such days are usually observed, with the fewest thunderstorms occurring in the north-eastern part, at Suwałki (0.3 days). During the meteorological winter, thunderstorms are extremely rare. In the entire history of measurements, there were individual cases of thunderstorms, although their number slowly increased over the long period covered. It was observed that their average total ranged from 0.01 days in Suwałki (1 day in the long-term period) to 0.59 days in Katowice (41 days) (Fig. 7). At the remaining synoptic stations, the number of days with a thunderstorm throughout the study period ranged between 3 and 23 days.

In the cool season, there is significantly less energy available from incoming solar radiation, which limits

access to the energy needed to trigger convective processes in the troposphere. The absence of such energy must be supplemented with the kinetic energy of shear winds in the troposphere, processes occurring at atmospheric fronts, or supported with land orography. Lower temperatures mean that there is less humidity in the atmosphere (characterized by parameters such as the Mixing ratio, PWAT-precipitable water, and steam pressure in the atmosphere). For this reason, thunderstorms in the cool season are accompanied by weather conditions that provide low convective available potential energy (CAPE) and high values of wind shear (SHEAR). Thunderstorms formed in such meteorological conditions are referred to in the literature as LCHS thunderstorms (Low CAPE, High Shear). They are dynamic and are usually connected with atmospheric fronts that move fast and are less developed in the vertical dimension (WADE ET AL., 2021).

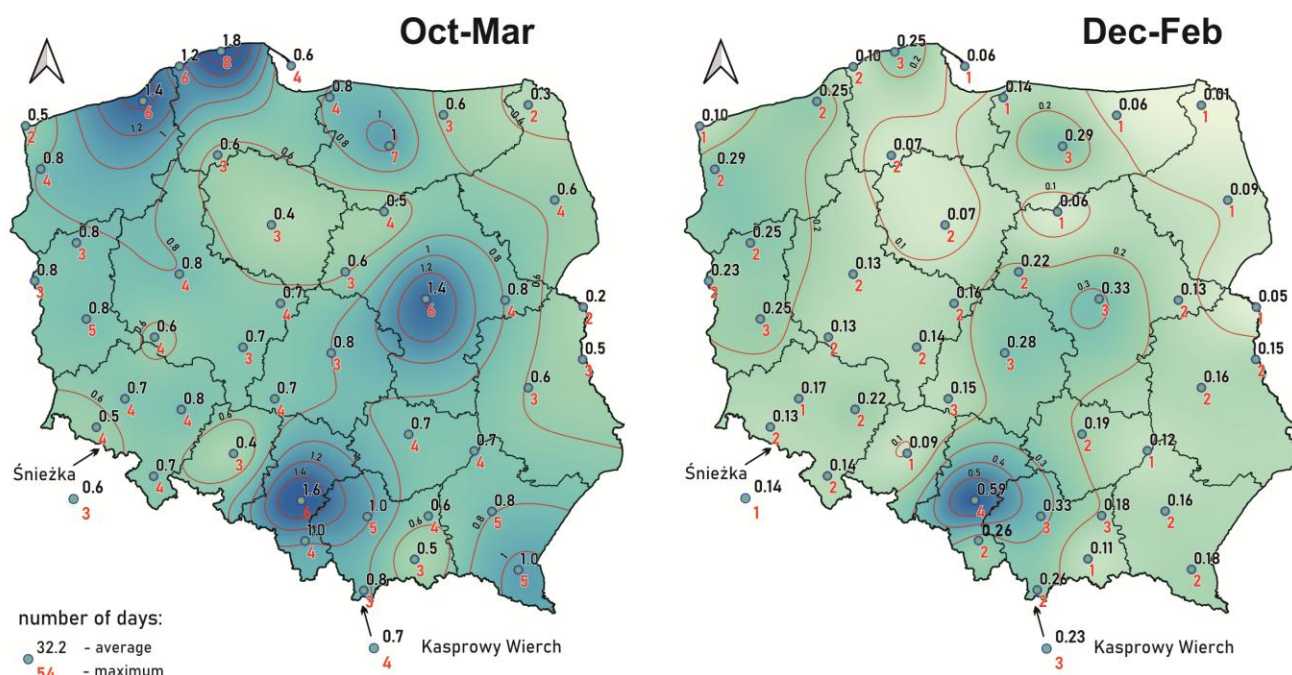


Fig. 6. Average and maximum number of days with a thunderstorm from October to March and from December to February during the period 1951-2020

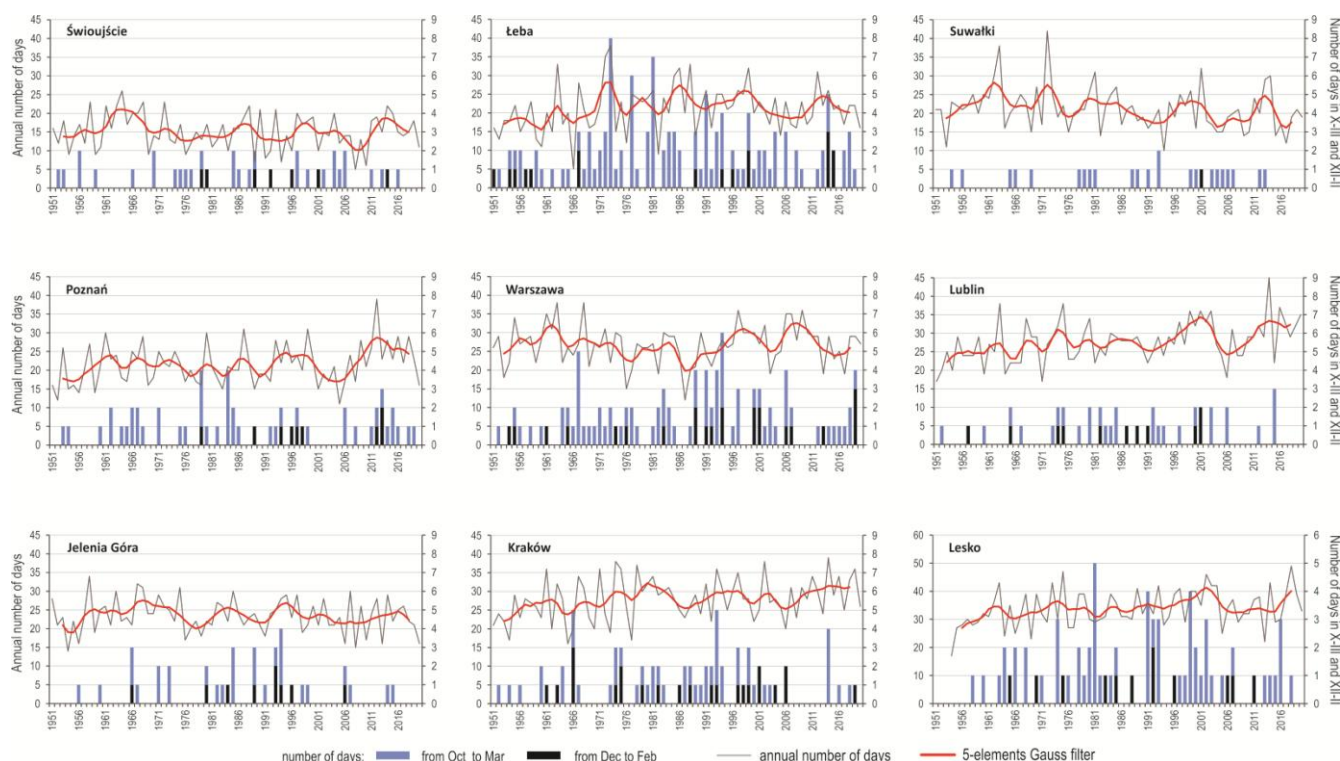


Fig. 7. Long-term variability of the number of days with a thunderstorm at the selected meteorological stations during the period 1951-2020 (number of days e.g. 2015 for the period Oct-Mar means sum of days from Oct-Dec 2015 and from Jan-Mar 2016)

In some cases, the abovementioned meteorological conditions are supported by the impact of local conditions. The most important factors include the impact of water reservoirs and orography. It is for

this reason that the impact of the Baltic Sea is so significant, as it gives back energy to the atmosphere in autumn and winter, causing a simultaneous increase in moisture in the air. Similar processes,

although on a smaller scale, occur in the lake districts, including the Upper Silesian Anthropogenic Lake District. Examples of stations with a visible impact from the Baltic Sea include Koszalin, Ustka and Łeba whereas the impact of lakes is observed in Olsztyn. In the case of stations in the south of Poland (Kraków, Katowice, Bielsko-Biała, Zakopane, Kasprowy Wierch), the large number of thunderstorms recorded in the cool season is related to orography which, in the case of excessive stability of an air parcel next to the land surface or a temperature inversion, additionally supports convection. It is also worth highlighting the greater number of thunderstorms taking place in urbanised areas (including: Warsaw, Łódź, Zielona Góra, Kraków, Katowice – on average at least 0.25 days with a thunderstorm in 10 years), which may be related to anthropogenic heat supplied to the atmosphere and a greater number of ice nucleating particles.

What seems puzzling is the high incidence of thunderstorms in the cool season and winter in Katowice, which is visibly higher than in the other regions of Poland. This may be a result of many factors, such as the high lake density of the area, or the presence of the Moravian Gate which allows the inflow of warm and moist air from the south. Analysis of the synoptic situations for the 27 days with a thunderstorm in Katowice in the cool season in the period 2004–2020 revealed that most thunderstorms were related to low pressure systems with their centre over the Baltic Sea, directly over Poland or central Scandinavia. On 8 out of the days analysed, thunderstorms occurred exclusively in Katowice, on 7 – both in Katowice and in the south and south-east of Poland, while on 12 days – they were recorded even at stations located in the north and west of Poland. This may suggest that a major part of the aforementioned thunderstorms could be related to local conditions enhancing the development of convection, although this requires more detailed research.

Variation in circulation and local conditions are also confirmed with the long-term variability in the number of thunderstorm days in the cool season and winter (Fig. 7). As one can see, there are significant differences in their number depending on station location and their changes do not allow one to point to a visible trend, or even to shorter periods that stand out with an increased, or

decreased, total of thunderstorms over a major area of Poland.

5. Selected cases of winter thunderstorms in Poland

In order to gain a better understanding of the mechanisms of winter thunderstorm formation in Poland, a thorough analysis was carried out for three selected cases of this phenomenon. The analysis involved thunderstorms taking place on:

- 18 January 2007 – related to the passage of a strong linear system across Poland with strong gusts of wind (classified as a *derecho*) and with local whirlwinds,
- 17 January 2022 and 17 February 2022 – strong wind thunderstorms in the form of a quasi-linear convective system (QLCS), occurring along or ahead of a cold front.

5.1. The thunderstorm of 18 January 2007

In January 2007, the Kyrill deep low-pressure system moved across Europe from over the Atlantic. This involved a system of fronts closed by an active cold front with a QLCS developing ahead of it with an in-built squall line (Fig. 8a). Its presence was sensed almost across all of Europe, with particularly violent weather phenomena moving through the centre of the continent where the thunderstorm caused major damage in the United Kingdom, the Benelux countries, Germany, Poland, the Czech Republic, Austria, and Slovakia. This was linked to strong gusts of wind and the occurrence of many whirlwinds (LUDWIG ET AL., 2015). The most violent weather phenomena related to the thunderstorm crossed western, central, and northern Germany. The accompanying thunderstorm clouds were not particularly towering in character. Ahead of the cold front, there was a shallow convection phenomenon with the temperature of the cloud tops reaching approximately -30°C , whereas radar images showed values reaching up to 54 dBZ, which means a very high accumulation of hydrometeors per thunderstorm cell and heavy rain (the meteorological station in Berlin recorded 25 mm of rain on that day at 17:15–17:45 hours UTC; FINK ET AL., 2009).

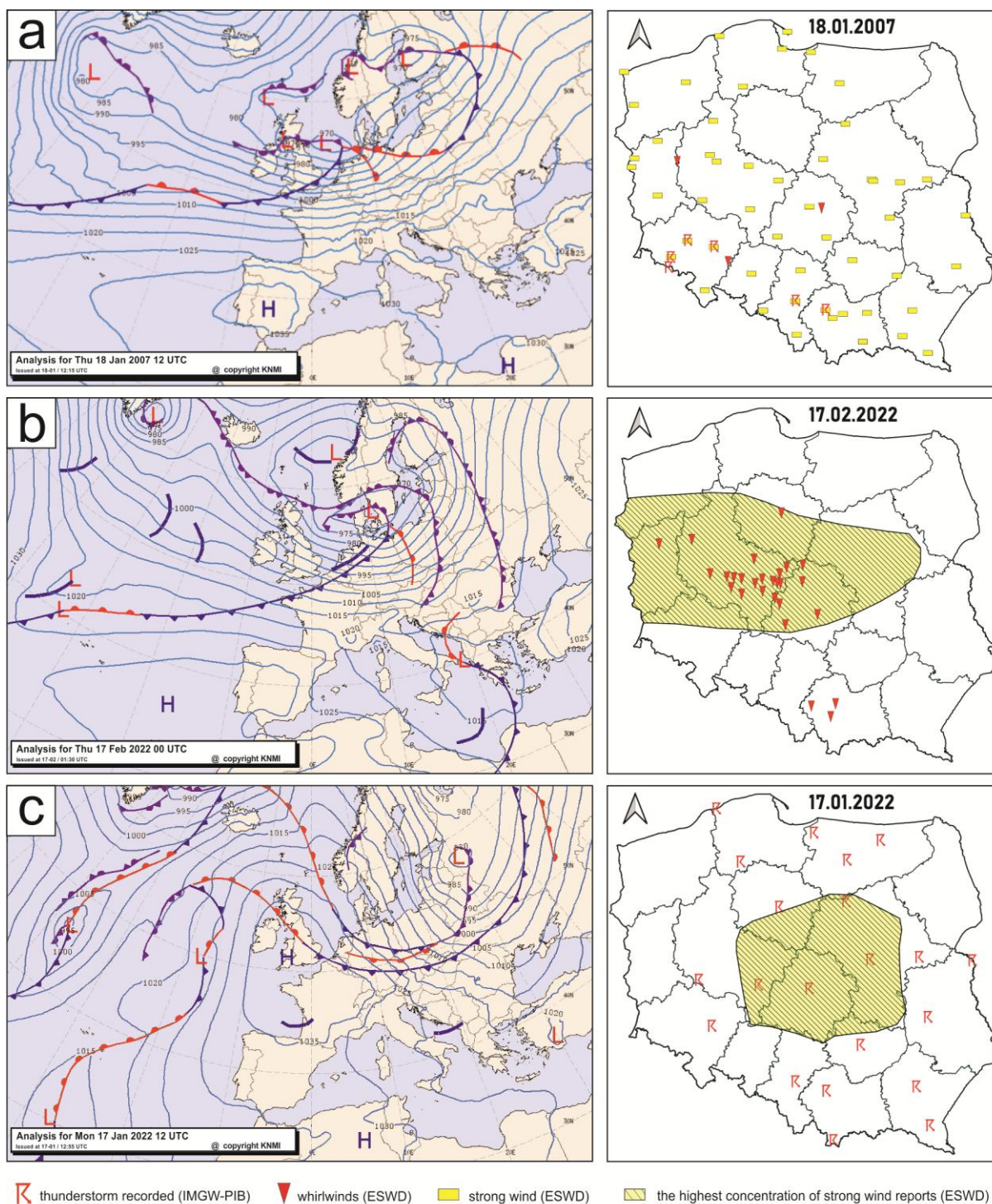


Fig. 8. Synoptic map (source: KNMI) and map of strong winds, and reports of thunderstorms and tornadoes (own elaboration based on data from IMGW-PIB synoptic stations and ESWD reports) from: a) 18.01.2007, b) 17.02.2022 and c) 17.01.2022

By about 18:00 hours UTC on 18 January, the leading edge of the cold front was over Poland, and its passage caused significant damage in the form of roofs ripped off, broken power lines, as well as damage to trees. This was confirmed by over 50 reports from the ESWD database. On the day analysed, three whirlwinds occurred in Poland,

including two classified as F2 (Andrespol and Osiek) and one as F1 (Silna), all separated by significant distances from one another (by over 100 kilometres; Fig. 8a). The whirlwinds were related to the QLCS with in-built meso-scale whirls. Meteorological conditions accompanied by the most violent weather phenomena occurring west of Poland (near

Wittenberg) indicating minor instability in the lower troposphere (Most Unstable Convective Available Potential Energy: MUCAPE = 69), high temperature at ground level for January (approximately 14°C) and conditional instability of the atmosphere (temperature laps rate: LR 0–1 km = 6.7°C/km, LR 0–3 km = 6.3°C, and LR 3–6 km = 7.2°C). This prevailed up to an altitude of approximately 5.5 km above ground level (equilibrium level: MUEL = 5455 m) (Table 2– presents values selected for areas representing conditions during the passage of thunderstorms west of Poland and the moment of passage of the system with tornadoes in Poland). An additional factor involved the possibility of a high accumulation of hydrometeors, which is confirmed by a PWAT of 22 mm and high air relative

humidity (RH 0–2 km and 2–5 km over 90%). According to ERA5 reanalysis, the estimated potential energy (MUCAPE) value near the cold front was 200–300 J/kg with SHEAR06 (SHEAR in a layer up to 6 km) at the level of 40–45 m/s. Such extreme kinematic conditions are rarely observed in Europe, particularly in conjunction with such CAPE values. Furthermore, storm relative helicity: SRH01 and SRH03 parameters exceeded 500 m²/s². These are exceptionally high values for Europe, where values of 300–400 are considered extremely high. Over Poland, the conditions for the development of convection were slightly weaker than in Germany, principally due to a later time of day and a temperature inversion at ground level, which inhibited the convective process (Table 2).

Table 2. Selected values of atmospheric instability indices during particular winter thunderstorms in Poland (sources: http://rawinsonde.com/ERA5_Europe, http://rawinsonde.com/thunder_app) – (explanations in the text)

Index	Place and time				
	18.01.2007		17.02.2022		17.01.2022
	Wittenberg 18:00 UTC	Oleśnica 21:00 UTC	Lindenberg 00:00 UTC	Pleszew 04:00 UTC	Częstochowa 12:00 UTC
	52.00°N 12.50°E	51.25°N 17.25°E	52.22°N 14.12°E	52.00°N 17.75°E	50.75°N 19.00°E
Thermodynamic indices					
MUCAPE [J·kg ⁻¹]	69	56	245	124	0
MUEL [m]	5455	4210	7605	5010	0
LR 0-1 km [°C]	6.7	6.8	5.3	6.7	7.0
LR 0-3 km [°C]	6.3	6.7	4.8	6.5	6.5
LR 3-6 km [°C]	7.2	7.0	7.4	6.8	3.9
MULCL [m]	1170	1165	1680	820	3255
Kinematic indices					
SHEAR01 [m/s]	28.8	27.5	29.4	24.7	16.6
SHEAR06 [m/s]	44.1	33.9	35.4	28.0	58.1
SRH01 [m ² /s ²]	544	500	752	369	148
SRH03 [m ² /s ²]	698	618	832	393	205
Moisture parameters					
PWAT [mm]	22	20	23	19	9
RH 0-2 km [%]	94	88	83	69	66
RH 2-5 km [%]	91	89	95	94	90
Temperature asl					
T [°C]	14	15	12	12	3

5.2. The thunderstorm of 17 February 2022

A similar case was presented by the thunderstorm of 17 February 2022, principally covering Poland and Germany. This was related to an active cold atmospheric front of a deep low-pressure system which, as with Kyrill, moved from over the North Sea to cross the Baltic Sea (Fig. 8b), with the main hazards also posed by the strong gusts of wind and whirlwinds, the latter totalling 27 cases in Poland (data as of 24.04.2024, ESWD), mostly in Wielkopolskie and Łódzkie provinces. Also in this case, an extensive and dynamic QLCS system with meso-scale whirls was developed. The two thunderstorms, 17 February 2022 and 18 January 2007, have many characteristics in common and do not significantly differ. The common features include a secondary low-pressure system with its centre over the Baltic Sea, near Bornholm, and high kinematic values plus high humidity (Table 2). In both cases, there was also a moist warm low-pressure system sector with convective parameters that favoured the development of violent thunderstorms. What differentiates the 2007 thunderstorm from the 2022 one is the method of formation of the low-pressure system. In 2007, this was cyclogenesis at the occlusive front and formation of a secondary low-pressure system, while the low-pressure system from 2022 originated at the cold front.

5.3. The thunderstorm of 17 January 2022

On 17 January 2022, in the morning and around noon, a strong thunderstorm system crossed Poland with a QLCS ahead of a cold front (Fig. 8c). The cold atmospheric front was related to a dynamically moving secondary low-pressure system with its centre over Estonia and with the main centre over north-east Scandinavia. The thunderstorm was first recorded by stations on the Baltic coast (Elbląg and Ustka). The thunderstorm system ahead of the cold moved from north to south and the wind associated with it (at 10:00 UTC, the synoptic station at Warszawa-Okęcie recorded a gust of wind with a velocity of 26 m/s) caused severe damage across Poland (roofs ripped off, damage to telecommunications infrastructure, uprooted trees). The system moved with high velocity, which is confirmed by the fact that the thunderstorm was recorded in Elbląg at 6:00 UTC and started in Warsaw a few minutes after 10:00 UTC whereas, at 13:00 UTC, it was recorded, inter alia, in Katowice

and Kraków. In the south of Poland, strong gusts of wind were observed around 12:00 UTC (in Katowice, with a velocity of 16 m/s), with lightning as well as intense precipitation, initially of rain, then of rain with snow pellets, and finally of snow at the rear of the thunderstorm where the precipitation was related to post-convective clouds (cumulonimbogenitus).

Conditions for the development of convection were similar to the examples discussed above with a few exceptions. An inversion and a significantly drier air mass blocking the development of more towered *Cumulonimbus* clouds occurred at an altitude of approximately 4 km (Table 2), and the cells formed at the head of the atmospheric front were less towered than in other cases resulting in a milder course of the thunderstorm. The air mass at the head of the atmospheric front was less humid and, due to high kinematic parameters (SHEAR06 = 58 m/s), meso-scale whirls developed inside the system as it passed. Changes to wind velocity and direction, as well as the small vertical size of the cells, allowed the generation of gusts that were locally strong. At the head of the atmospheric front, the horizontal temperature gradient was not too high, which caused the air mass to be pushed upwards in a less violent manner. The spatial distribution of the reports of damage caused by the wind forming lines suggests the occurrence of locally strong wind phenomena within the meso-scale whirls where convection was supported by kinematic conditions (high SHEAR06 and SHEAR01 values accompanied with high SRH01 and SRH03 values; Table 2).

6. Discussion and conclusion

The study has presented the occurrence of thunderstorms in Poland, giving special consideration to thunderstorms in the cool season and the meteorological winter, in the period 1951–2020. The research conducted revealed that, as in other areas at similar latitudes, thunderstorms occurring in the cool season and meteorological winter usually constitute less than 5% and up to 2% of all thunderstorms, respectively (FÖRCHTGOTT, 1969; MUNZAR & FRANC, 2003; SCHULTZ & VAVREK, 2009). Their spatial differentiation is not high, although there is a notable impact of the Baltic Sea in the north and varied topography in the south. This is reflected in the total number of thunderstorm days and their annual course. An additional factor may be provided by urban heat islands which, within

large cities, may support convection with anthropogenic heat and an increased number of ice nucleating particles that may encourage more intensive cloud formation. This is confirmed by studies on clouds which indicate that there has been a notable increase in the frequency of *Cumulonimbus* clouds recorded over cities since the 1970s in many regions of the World (MATUSZKO ET AL., 2001; SUN ET AL., 2001; WIBIG, 2008). The comparison of the incidence of thunderstorm clouds in the non-urban and strongly urbanised areas also indicated a more frequent occurrence over cities in the cool season (MATUSZKO, 2014).

Long-term changes to the number of days with a thunderstorm recorded at at least one station in Poland do not reveal a visible trend. In the case of thunderstorms in the cool season, however, and in particular winter thunderstorms, an increased frequency has been observed since the beginning of the 21st century, which is confirmed by a statistically significant increase in winter thunderstorms, totalling 0.35 days per 10 years. Similar changes have also observed in other areas of Central Europe (RACKO ET AL., 2002; MUNZAR & FRANC, 2003).

Changes to the occurrence of thunderstorms at particular stations indicate regional variation, although such changes are not all statistically significant. In the western part of Poland, the number of thunderstorm days is declining, whereas they are on the increase in the eastern part of the country. In the case of cool-season thunderstorms, many stations record signals of their increased frequency, but this is only evident at individual stations, which confirms regularities known from the literature (BIELEC-BĄKOWSKA ET AL., 2021). It is also worth remembering that conditions favouring the formation of cool-season thunderstorms are rare and usually related to atmospheric fronts. For this reason, in about 68% of all cases, such thunderstorms were recorded at 1–2 stations on one day, and only in about 3% at more than 10, which also confirms regularities known from the literature (MARKET ET AL., 2002). It is also worth pointing out that winter thunderstorms in this part of the continent are very often more frequent in January and February than in December (FÖRCHTGOTT, 1969; MUNZAR & FRANC, 2003).

Thunderstorms in the cool season and meteorological winter are formed under different conditions from those causing thunderstorms occurring in the warm season, in particular, when compared to thunderstorms in the summer.

Sufficiently strong convection in this season is mainly provided by the processes evolving in active cold fronts. They can be enhanced by local conditions (MARKET ET AL., 2002; LETCHER & STEIGER, 2010). This is probably related to the fact that, despite the front passing across the country, cool-season thunderstorms are usually recorded at several stations that are often significantly distant from one another.

The fundamental factors responsible for the incidence of lightning in winter include the vertical size of *Cumulonimbus* clouds. This is predominantly determined by the height of the tropopause and intrusions of drier and warmer air masses in the central troposphere, which often causes a temperature inversion at an altitude of 500 hPa or lower air layers, limiting the potential for convective cell formation. The research and results provided in the literature indicate that the top of thunderstorm clouds in the cold season rarely exceed an altitude of 5–6 km (FÖRCHTGOTT, 1969). Such a cloud structure is related to the low altitude of the mixed-phase region in clouds (with a temperature between -10 °C and -40 °C in which supercooled liquid water and ice co-exist). This is located lower (between 1–3 km above ground) than in the summer period which, among other factors, is responsible for the low number of lightning events (KONARSKI ET AL., 2008; SCHULTZ & VAVREK, 2009).

The cases of violent and dynamic winter thunderstorms described in the literature and considered in this study indicate that they usually involve advections of humid air masses located in the warm sectors of the low-pressure systems, enclosed by an active cold front. This situation produces large horizontal gradients of air pressure and temperature that contribute to the violent upwelling of air masses (KONARSKI ET AL., 2008). This in turn leads to strong gusts of wind at the leading edge of the cold front within which (depending on the conditions) violent thunderstorms may form that cause wind-related damage and occasionally also whirlwinds. Conditions for the development of hail are usually very poor in such cases, but there is precipitation in the form of fine snow pellets, snow, or rain. Some of the most violent winter thunderstorm incidents which were examined were a result of the passage of a dynamic secondary low-pressure system together with a system of atmospheric fronts. Such low-pressure systems are fresh and formed at a lower level, which produces stronger wind shear in the bottom

and middle troposphere in which in the main convective processes take place (convective processes in the upper troposphere are subject to significant limitation due to the small size of the thunderstorm cells). Additional factors supporting thunderstorm development include high humidity in the lower troposphere and a low level of the lifting condensation level (Most Unstable Lifting Condensation Level – MULCL much lower than 2 km or even 1 km; Table 2) which, together with high wind shear, may cause conditions encouraging strong convection and even supercells and whirlwinds (DUNIEC ET AL., 2023). However, it should be remembered that to assess the conditions in which winter thunderstorms occur thoroughly, an in-depth synoptic analysis is necessary, covering all cases of this phenomenon occurring in a given area over a long observation period.

The results presented point to increasingly visible changes of thunderstorm incidence in Poland, which also refer to thunderstorms in the cool season. They are another indicator of climate change that has been observed which is principally related to an increase in air temperature and changes in atmospheric circulation. Nevertheless, the complex impact of individual factors preconditioning convective phenomena, which include local conditions, make it difficult to identify scenarios for future changes to such phenomena, both in Poland and on a global scale (PÚČIK ET AL., 2017; TASZAREK ET AL., 2021; GHASEMIFARD ET AL., 2024).

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