Bulletin of Geography. Physical Geography Series, No. 18 (2020): 25–39
http://dx.doi.org/10.2478/bgeo-2020-0003

# The origin and course of severe thunderstorm outbreaks in Poland on 10 and 11 August, 2017

ISSN 2080-7686

**Sławomir Sulik, Marek Kejna*** [a]

Nicolaus Copernicus University in Toruń, Faculty of Earth Sciences and Spatial Management, Toruń, Poland

* Nicolaus Copernicus University in Toruń, Faculty of Earth Sciences and Spatial Management, Toruń, Poland. E-mail: makej@umk.pl

[a] https://orcid.org/0000-0003-4815-9312

**Abstract.** This study documents the evolution of severe thunderstorm outbreaks that occurred on 10 and 11 August, 2017 in Poland. This study used cloud-to-ground lightning-strike data from the PERUN lightning detection network managed by the Polish Institute of Meteorology and Water Management – National Research Institute. In the description of storm phenomena the authors also applied synoptic maps, meteorological radar data, vertical atmosphere soundings and meteorological data from the station in Poland. The aim of this study was to trace the causes of the upward movement of supercells including the Mesoscale Convective System day by day, and to examine relationships between lighting distributions on 10 and 11 August, 2017. In Poland, on August 10, 2017, 154,524 cloud-to-ground flashes (CG) occurred, and 56,510 CG flashes the next day. On August 10, around 18% of all flashes had a positive current, but 29% the next day. The spatial distribution of the lightning in Poland was computed for 10×10-km grid cells. Based on the map analysis it was found that on those two days most of the positive flashes occurred in Greater Poland and Kuyavian-Pomeranian voivodeships, as well as on the border of Opolskie and Lower Silesia.

**Key words:**
thunderstorm,
lightning,
cloud-to-ground flashes,
mesoscale convective system,
natural disasters,
Poland

## Introduction

Thunderstorms pose a direct threat to human life, and they damage material goods. Thunderstorms usually form in unstable atmosphere conditions and with the development of convective clouds up to Cumulonimbus cloud. That is why thunderstorms frequently appear in the afternoon or evening. Storm clouds also form on atmospheric fronts. Therefore, in Poland, storms can occur at any time of the year, though there is a clear peak in their appearance in the warm half of the year (Bielec-Bąkowska 2013). Each year is slightly different from the last, and summer thunderstorms can undoubtedly be severe and dangerous.

Particularly dangerous are multi-cell storms, consisting of many storm clouds, which sometimes organise into a mesocyclone. In the mesocyclone the derecho phenomenon can be created – violent storms accompanied by strong winds, especially on the squall line. Its appearance is visible on meteorological radars as a “bow echo” (Trapp and Weismann 2003; Taszarek 2019).

Studies using observations at synoptic stations have shown that the annual number of days with thunderstorms in Poland increases in a south-easterly direction from the coast of the Baltic Sea (15–20 days) to the Carpathian Mountains (30–35 days) (Bielec-Bąkowska 2007). There are differences between human observations and those of the PERUN lightning detection network (Czernecki et al. 2016). In Poland there are approximately 4 flashes·km$^{-2}$ per year. This number is not high, as in the area of central Africa approximately 70 flashes·km$^{-2}$ occur (Holle et al. 2016).

In Poland, on average of 10 people are killed by lightning strikes every year, as demonstrated by the data of the Polish National Institute of Statistics (GUS 2019). However, according to the European Severe Weather Database (2019), between 2015 and 2017 Poland experienced more than 100 damaging lightning events, which killed 27 people. The discussed cloud-to-ground flashes are also associated with the loss of goods. During heavy strikes high voltage power lines and buildings are frequently damaged, and forest fires often occur (Mäkelä and Rossi 2013). In Poland, there are numerous dangerous storm-related phenomena, such as hail, severe squalls and tornadoes.

As global climate is constantly changing and air temperatures are rising, there is an increase in potential energy in the atmosphere, which results in higher incidence of severe thunderstorms (Michael et al. 2005; Dotzek et al. 2009; Púčik et al. 2017; Allen 2018). Convective Atmospheric Potential Energy (CAPE) is particularly important in the formation of storm clouds, which can be measured using vertical atmosphere surveys (Taszarek et al. 2017, 2018). Previous studies applying storm observations conducted in Poland demonstrate that there was no increase in number of days with thunderstorms over the years, but an increase in their severity and strength (Bielec 1998).

In Poland these dangerous phenomena have been the subject of a number of analyses (e.g. Bielec-Bąkowska 2013; Celiński-Mysław and Łoboda 2019). Particular attention was paid to the situation on August 11, 2017, when the derecho phenomenon occurred and a supercell storm did considerable damage. The genesis of this storm was described by Taszarek et al. (2019). The purpose of this study is to compare the two days of August 10 and 11, 2017, when strong storms and numerous lightning strikes occurred in Poland. There was not much damage on August 10, while the losses the next day were substantial. The research explores quantity, distribution and time development of supercells' movement, including the number of flashes, gust wind and damage.

## Database and methodology

A database of lightning strikes detected by the SAFIR/PERUN network was gathered, courtesy of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). This system detects lightning flashes in the categories cloud-to-cloud (CC) and cloud-to-ground (CG). Low frequency electromagnetic waves are used to measure electrical parameters and to distinguish between types of discharges.

The lightning detection system SAFIR (Surveillance et d'Alerte Foundre par Interferometrie Radioelectrique) was launched in Poland in 2002. Since then, the system has been nicknamed PERUN, after the god of thunder and lightning in Slavic mythology. It is a part of the European lightning detection system (Bodzak 2006; Czernecki et al. 2016) which creates new opportunities to conduct specific research on the spatial distribution of lightning.

The system mainly applies the technique of detecting the direction of arrival of the DF (Direction Finding) signal (Bodzak 2006). The whole measuring lightning network is combined into nine stations in different regions of Poland: Gorzów Wielkopolski, Częstochowa, Kalisz, Toruń, Sandomierz, Warsaw, Olsztyn, Białystok and Włodawa (Fig. 1). All of these stations are located in current meteorological stations managed by the IMGW-PIB. The centre of the network is the IMGW-PIB headquarters in Warsaw. This spatial distribution of stations was conceived to provide localisation precision to 1 kilometre and effective detection covering 95% of the country. Importantly, the system is capable of detecting up to 100 strikes per second. Detection stations are synchronised by the global positing system GPS. Each detection station performs an angular interferometric location lightning discharge (Bodzak 2006). Location of lightning strikes is saved in a lightning listing with other parameters, such as current charge time, numbers for recognising type of lightning (CC cloud-to-cloud, or CG cloud-to-ground), polarity, peak current estimate (kA) and multiplicity. As mentioned above, the location is given as latitude and longitude in WGS84 (World Geodetic System) and is written in decimal degrees. Because of Poland's location and local coordinate system, it was necessary to re-project the original WGS84 projection into the Polish CS92 (EPSG:2180) metric coordinate system.

The basic unit for this study was cloud-to-ground strokes. Daily number of cloud-to-ground lighting flashes densities on 10 and 11 August 2017 are computed for 10×10-km grid cells. To present hourly distribution of flashes, it was necessary to separate flashes in 1-hour steps with a different colour range. To mark number of flashes according to hour, we created a line chart that presents how many cloud-to-ground flashes occurred at different times, with maximum peaks, and with polarity current divided into negative and positive.

In addition, a Meteosat Second Generation (MSG) geostationary satellite image, and radar data from the POLRAD network, including reflectivity and radial velocity, were used. The POLRAD system operates in Poland, it consists of eight meteorological radars that scan the sky regularly. The system was constructed for military and scientific needs. The first meteorological radar was built in 1964 in Legionowo, near Warsaw (Barczyk 2013). Now, the system comprises eight radars, which are C-band Doppler radars, in different regions of Poland: Meteor 500C (Świdwin, Brzuchania, Poznań), Meteor 1500C (Gdańsk, Legionowo) and dual polarimetric Meteor 1600C (Pastewnik, Ramża, Rzeszów) of Selex SI Gematronic (Barczyk 2013) – see Figure 1.

In the analysis the authors also used synoptic surface maps published for 00 and 12 GMT by the IMGW-PIB (www.pogodynka.pl) and satellite images collected by the Meteosat Second Generation satellite (www.sat24.com).

To understand what happens in the highest parts of the troposphere, a vertical measuring system was used. A radiosonde is launched from some stations around the world every day at 00 and 12 UTC. In Poland, vertical measurements are taken at aerology stations in Łeba, Legionowo near Warsaw, and Wrocław. Vertical atmosphere surveys show dew point, air temperature and virtual temperature of rising air parcel. From this basic information, it is possible to define such parameters as Convective Atmospheric Potential Energy (CAPE) or Convec-

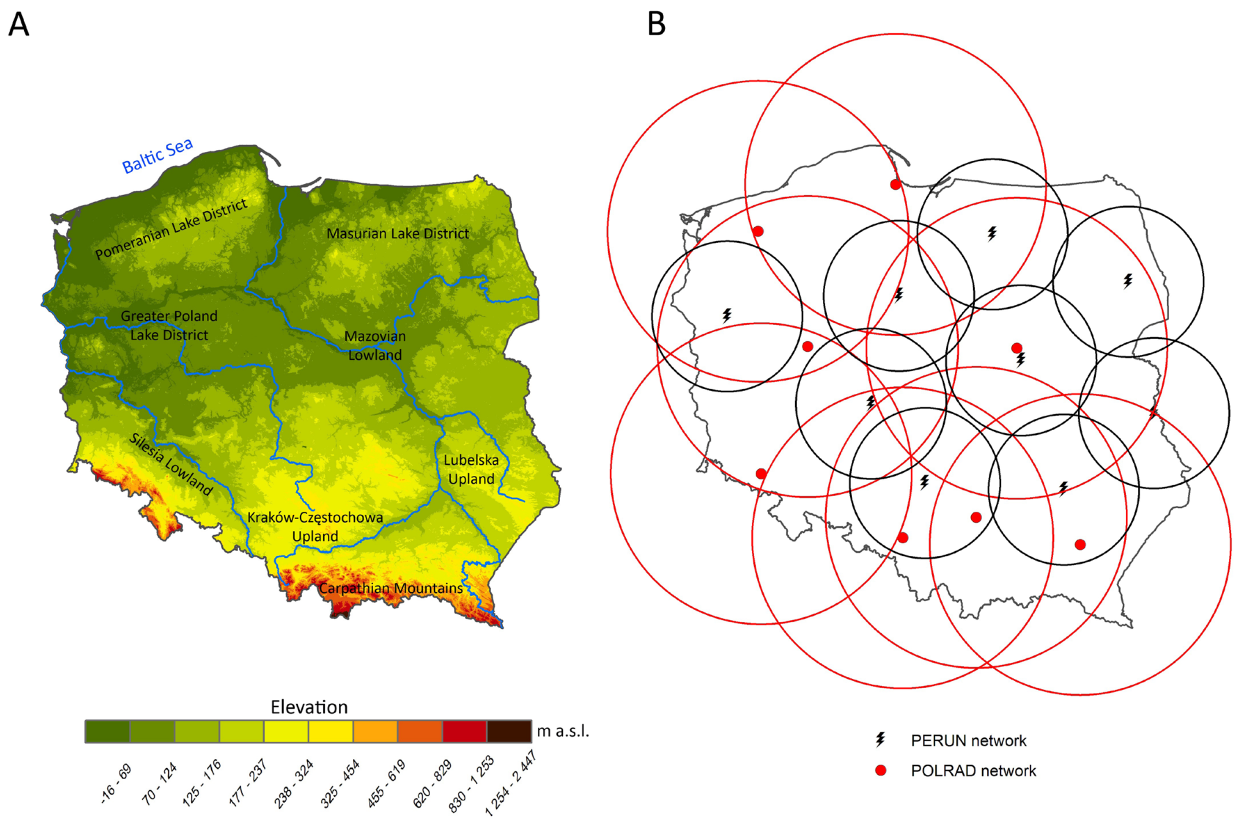


Fig. 1. A – Hypsometric map of Poland based on the Shuttle Radar Topography Mission Global Coverage (SRTM3) (source: Land Copernicus 2018). B – Locations of SAFIR3000 lightning sensors in the PERUN network with 100-km buffer zones (black circles) and locations of POLRAD meteorology radar network with 200-km buffer zones (red circles), Source: www.imgw.pl

tive Inhibition (CIN) (Taszarek et al. 2017). Severe thunderstorms are more likely if these factors are higher. Data from all stations are available at archives collected by the University of Wyoming.

Tracking and observing storms has been somewhat simplified by the development of the European Severe Weather Database (ESWD), aerial photography and other information on damage. The main aim of this database is to collect good quality reports on severe weather events. The database provides information on such phenomena as tornadoes, gusts of wind (above 90 kilometres per hour), large hail (above 2 cm), intensive rainfalls or downbursts, lightning strikes leading to damage, gustnadoes and severe icing or snowfall. This database makes it is possible to react quickly and to obtain information on where severe a phenomenon takes place (Brooks 2013).

## Results: events analysis

To emphasise the importance of what happened on 10 and 11 August, 2017, one of the most dangerous types of storm systems should be introduced. Under favourable conditions (i.e. high instability, large amounts of moisture in the lower troposphere and at least moderate amounts in the middle troposphere, especially in the layer 1–3 km above the ground) violent storm cells, including supercells, may be formed. Environments of low CAPE and strong low level-shear can produce those systems as well. A distinction can be made between multi-cell clusters and multi-cell lines or squall lines (Dahl and Parker 2012). If an additional flow of cool air occurs, squall lines are often formed in high flow environments. Precipitation carried by storms cools the air, creating an area stain of cool air behind the squall line. This type of storms often becomes linearly organised when their outflows merge and a large deep cold pool forms. At the same time, cool air – heavier and additionally "pressed" to the ground by the back zone of descending current – pushes the front of the systems. A rear-inflow jet is created, which, if strong enough, bends the storm system into an arc. This formation, visible best on radar scans, is called a "bow echo" (Atkins and St. Laurent 2009).

## August 10, 2017

For several days preceding the events of 10 August, 2017, a very unstable tropical air mass was advected to Poland and central Europe, creating a basis for dynamic convection. Air temperatures of around 28–34°C in the daytime and around 12–23°C at night, depending on region, prevailed over the territory of Poland. As seen in Figure 2 on the synoptic map, from 00 UTC of 10 August, 2017, a large portion of polar-maritime air mass in the western part of Poland and tropical air mass are clearly visible, and separated by a convergence line. The former air mass contains a considerable amount of moisture and it is definitely cooler than the surrounding masses.

On 10 August a huge thermal gradient appeared between the western and eastern part of Poland. Through a waving atmospheric front, total tropospheric water saturation was over 50 mm, which is quite a large value considering the climate of Poland (Taszarek et al. 2019). Dealing with high air temperature gradients, humidity and atmospheric front, even a small and weak storm cell can grow into one big cluster. Such factors led to CAPE (Convective Atmospheric Potential Energy) values up to 2,500 $J \cdot kg^{-1}$ and CIN (Convective Inhibition) to -200 $J \cdot kg^{-1}$ led to convection currents reaching values of approximately 20–25 $m \cdot s^{-1}$, which created mesoscale convective systems from one day to the next (Fig. 3). Despite this, another even stronger structure was created the next day by an average relative humidity of around 55–80% (even higher in some areas) and temperatures exceeding 30°C over a significant area of the country.

Directly above Poland there was an active zone of wavy, quasi-stationary atmospheric front with significantly increased potential for the development of waves, rising to the form of low-pressure mesoscale systems. These were individual disorders that contributed to the emergence of violent storm formations. Around midnight on August 10, cells from the Czech–German border were still a loose cluster of storms. An hour later it was a fairly well organised cluster, slowly merging with an area of night-time convection from Lower Silesia. The system was moving slowly along the front axis to the north-east, pushing the convergence line in front of

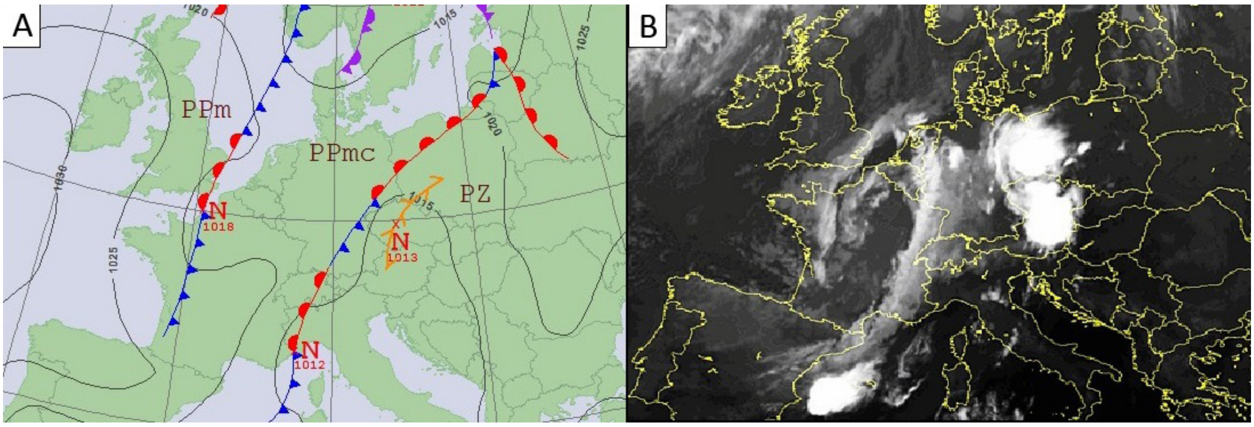


Fig. 2. A – Synoptic map at 00 UTC 10 August 2017; W – high pressure, N – low pressure, PZ – tropical air mass, PPmc – polar maritime air mass (source: the Polish Institute of Meteorology and Water Management). B – Meteosat Second Generation High-Resolution Visible (MSG HRV) image from the same date and time as the previous one (source: Sat24.com)

it. The storms increased rapidly and began to form a squall line. Around 2:30 a rapid convection development occurred in the area of Jelenia Góra, which initiated the further construction of storms over the peaks of the Sudetes, up to the Kłodzko Valley, over which the storm line from the Czech Republic entered at around 3:30. The central and northern parts of the system intensified further over the next hour and a half (i.e. the belt from the central and southern Lubuskie Land, through south-western Greater Poland) (Fig. 4).

After this, around 6:00 the system started to rise, which was the cause of the bow echo formation clearly detected by radars and the PERUN system as

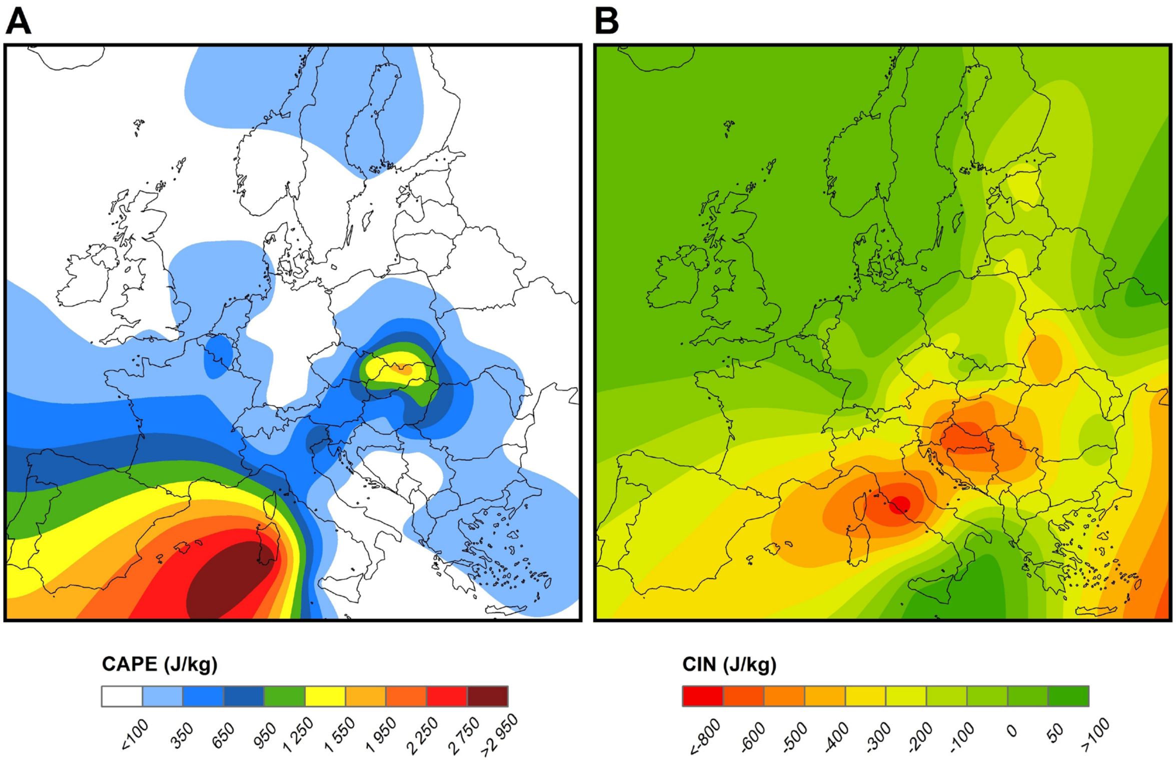


Fig. 3. A – Spatial distribution of Convective Atmospheric Potential Energy (CAPE) at 00 UTC 10 August, 2017. B – Spatial distribution of Convective Inhibition (CIN) at 00 UTC 10 August, 2017. Source: vertical atmospheric surveys archives of the University of Wyoming

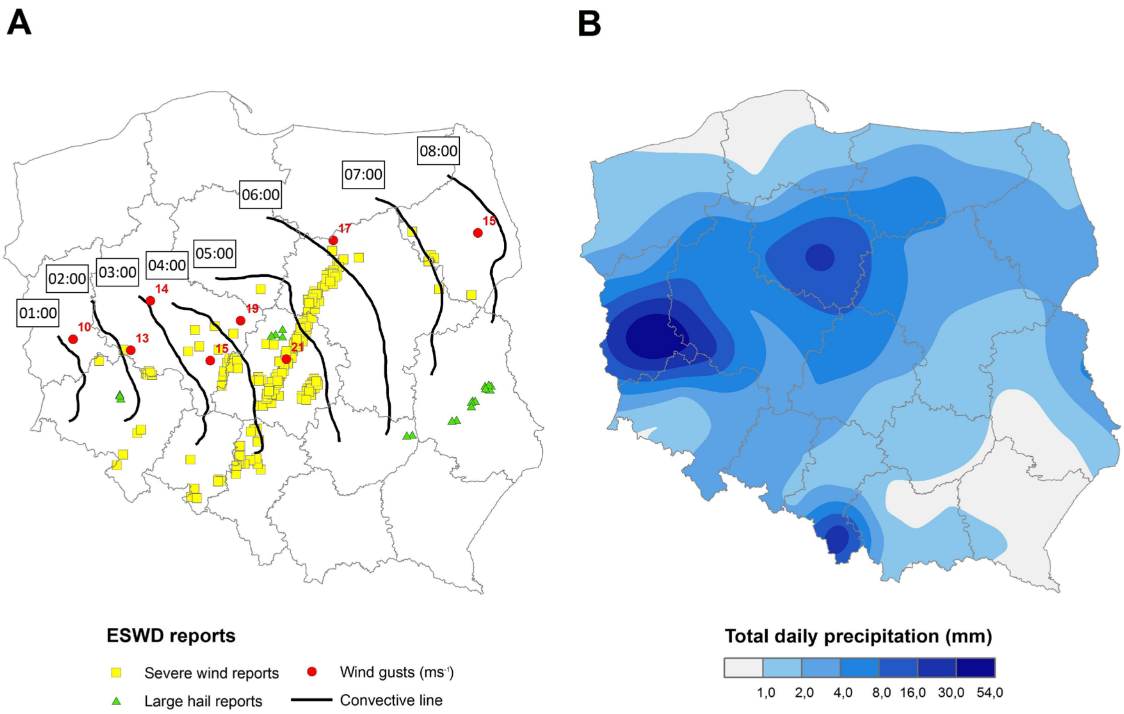


Fig. 4. A – Hourly displacement of supercell on 10 August, 2017 with 1-hour steps through convective line (black line), severe wind reports (yellow squares), large hail reports (green triangle), severe wind gusts registered at meteorological stations (red dots) derived from the European Severe Weather Database (ESWD). B – Total daily precipitation (mm) on 10 August, 2017. Measurement data derived from meteorological stations managed by IMGW-PIB

a large number of lightning strikes (Fig. 6). It may have been created by the influx of the polar-maritime air mass and the most unstable air parcel at 500–600 hPa, including a freezing level at the same altitude. A powerful multi-cell system in the form of a high-rise bow echo with a zone of extensive large-scale precipitation and storms in the northern part, and about 200–300 km wide, moved in the first half of the day from the Poznań–Katowice line, through Łódź, the northern part of Upper Silesia, eastern and central Greater Poland, Mazovia, south of Kuyavia, southern and eastern Masuria and the northern Lublin region, up to Podlasie. The rest of the system accelerated rapidly and gained strength.

In Poland, on August 10, 2017, there occurred 154,524 cloud-to-ground flashes. Most occurred between 3:00 and 6:00 when the system was above the Greater Poland, Kuyavian and Pomeranian, and Łódź voivodships. In one hour (4:00–5:00) the supercell produced over 39,000 cloud-to-ground flashes (Fig. 5).

Thunderstorm phenomena caused numerous instances of wind damage and heavy rain and hailstorms, mainly in the central part of the Łódź Province, in the west and centre of Mazovia, as well as on the border of the Łódź Region, Greater Poland and Lower Silesia (Fig. 4). The storm was moving along the convergence line of the wind. The supercell left our country at around 10:00, entering Lithuania and Belarus, but this was not the end of the storms. Around the same time, storms began to build up over Moravia and western Slovakia, slowly heading towards Poland. They entered our country after 13:00, quickly growing stronger and becoming supercells, but soon falling apart.

## August 11, 2017

On August 11, 2017, the weather did not differ much from the previous few days. After another tropical night with air temperature ranging around 22°C, hot moist air still covered most parts of the country. The temperature during the day in south-east Poland was almost 35°C. In Kraków, the observatory station recorded a maximum of 36.2°C, with an average humidity of 70%. Air humidity exceed-

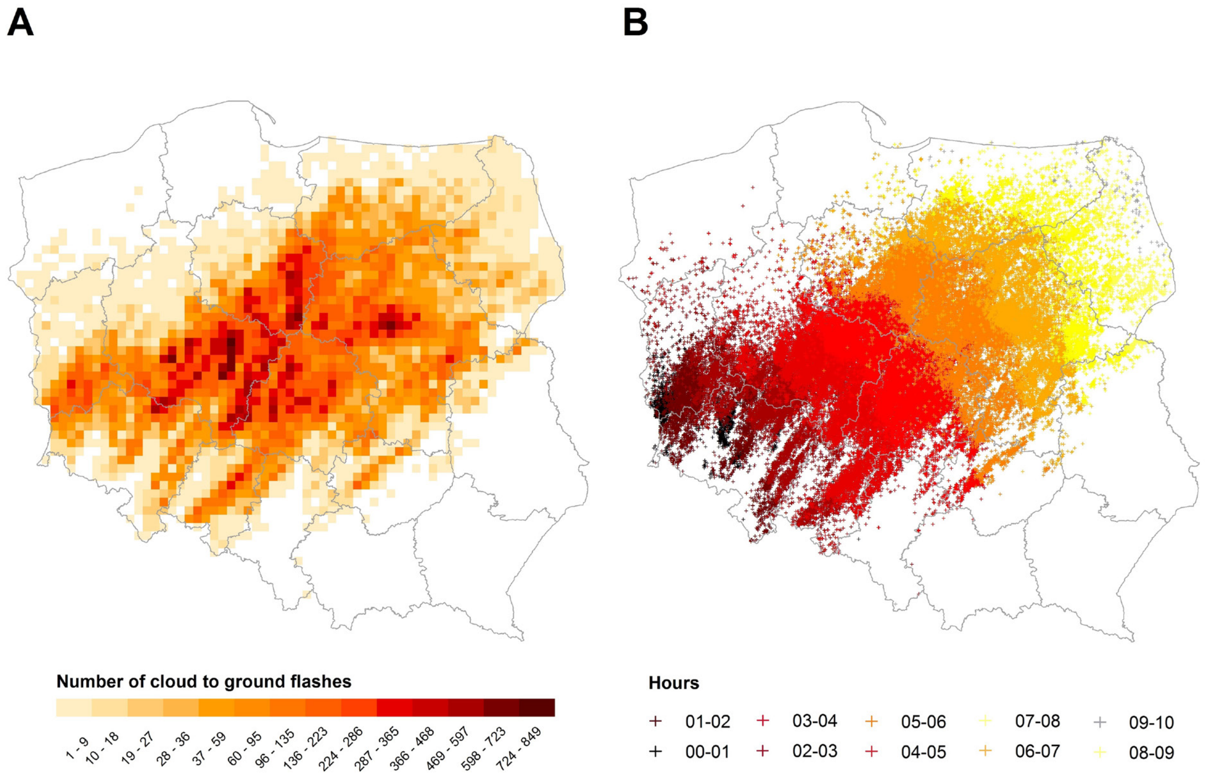


Fig. 5. A – Daily number of cloud-to-ground lightning flashes on 10 August, 2017. Lightning densities are computed for 10×10-km grid cells. B – Hourly distribution of cloud-to-ground lightning flashes on 10 August, 2017. Colour crosses denote time of occurrence of flashes. (source: based on lightning data derived from the PERUN network)

ed 80% in many places. The farther north, the colder it was: in Pomerania, the maximum temperature was about 25–28°C. Behind the front, in Germany, it was only 18°C at that time, and in Świnoujście around 21–22°C.

In the morning the warm front slowly left Poland, moving further north, while the cold front line retreated behind the Oder. Within its reach, as well as to the east of it over Hungary, northern Croatia and Slovakia, strong storms began to form early in the morning, led by the moist and hot mass of tropical air (Fig. 7).

Even before 7:00, from the Sudetes to the Lower Silesia voivodship, storms occurred on the aforementioned wind convergence line. Shortly after entering Poland, the line disappeared, probably blocked by cloud cover, and a patch of cool air after the morning passing of storms. However, new cells were still forming in the vast area stretching from the shores of the northern Adriatic, through Slovenia, northern Croatia, western Hungary, Austria, and the Czech Republic. Vertical atmospheric surveys revealed high instability in the rising air parcel. The CAPE values ranged around 3,000 $J \cdot kg^{-1}$ but the instability value LI (Lifted Index) was around -5°C to -10°C (Fig. 8).

Strong processes supporting the development of storm cells were forecast especially in the area of waviness and potential lowlands. There was also considerable water atmosphere (PW 40–45 mm), and also the Mixing Ratio indicator was 10–14 $g \cdot kg^{-1}$, which indicated a large amount of water vapour in the air. This combination of thermodynamic parameters resulted in torrential rainfall. Due to the sharpening of the wave over the country, a stronger flow appeared; thus, larger vertical wind faults DLS (Deep Layer Shear) 0–6 km (15–25 $m \cdot s^{-1}$) LLS (Low Lever Shear) 0–1 km (10–15 $m \cdot s^{-1}$) and wind rotation SRH (Storm Relative Helicity) 0–3 km (100–300 $m^2 \cdot s^{-2}$). The combination of these parameters resulted in the formation of strong storm supercells, and later a linear system.

That day, the IMGW-PIB issued hot-weather alerts that continued to apply for south-eastern Poland at the highest, third degree. First- and second-degree storm warnings were also issued for the west and south-west of the country.

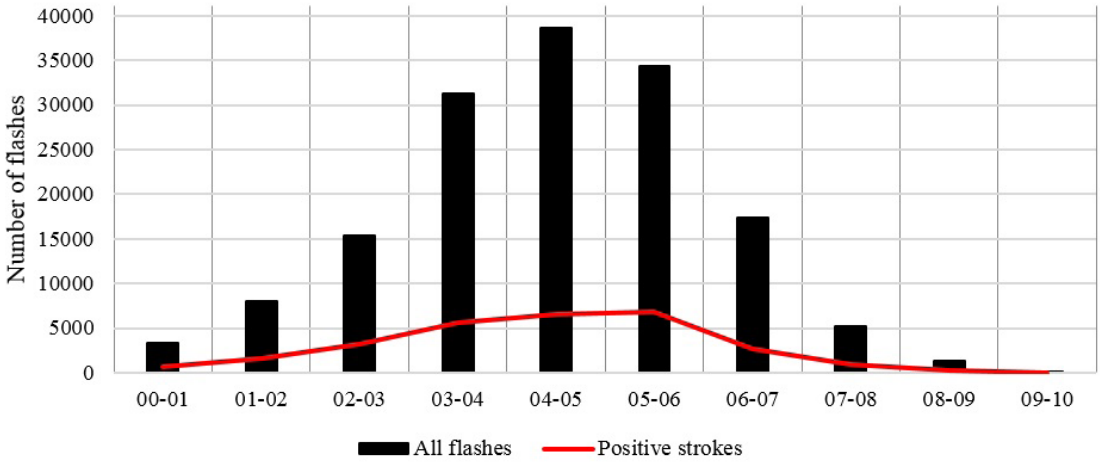

Fig. 6. Hourly cloud-to-ground flash density chart (black bars) and positive strokes (red line) with 1-hour steps on 10 August, 2017. Source: based on lightning data derived from the PERUN network

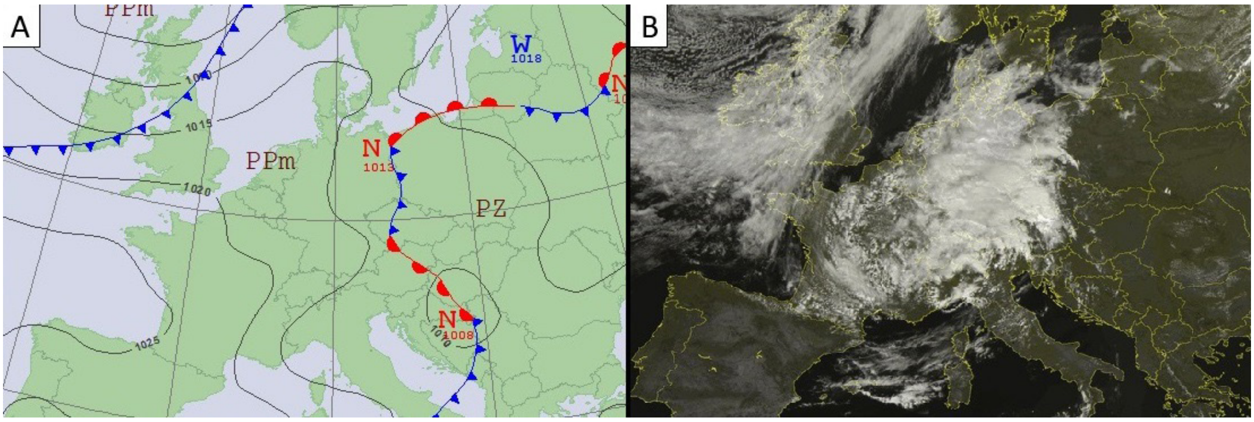

Fig. 7. A – Synoptic map at 12 UTC 11 August, 2017; W – high pressure, N – low pressure, PZ – tropical air mass, PPm – polar maritime air mass (source: Polish Institute of Meteorology and Water Management). B – Meteosat Second Generation High-Resolution Visible (MSG HRV) image from the same date and hours as previous. Source: Sat24.com

Single storms clusters were visible on radars from 15:00. Around 17:00, the system began clearly to turn, instead of continuing north-eastwards. At around 18:30 the system entered the area of Poznań. The system ran along the line of convergence within the shallow lowlands on the wavy front. It was a classic, progressive bow echo, going parallel to the axis of the stationary (wavy) front provided by strong flow in the troposphere. Around 19:00 the northern part of the system increased, while the southern part began to break away and soon fell apart. The system flipped north, straight to Pomerania. The storm entered Kuyavia shortly after 20:00, where it began to rise rapidly. There was a characteristic bulge in the central part of the storm, which suggests very strong gusts of wind (Fig. 9).

In Poland, on August 11, 2017 there occurred 56,510 cloud-to-ground flashes (Fig. 10). This number is considerably smaller than that for the previous day. The lower electrical activity was due to the smaller difference in the upper troposphere and the lower freezing point.

A high peak is also visible the hour before maximum electric activity, from 7,000 to 10,000 flashes (Fig. 11). It is worth mentioning that 29% of all flashes that day had a positive charge.

Due to the high speed of the system, the most dangerous part of the storm was preceded by a squall of just two to three minutes. The first impact in the Pomeranian Voivodship took place at around 21:00, south of Chojnice. Later, a strip of storms stretching from west to east for a section of over 150 kilometres hit the south-western part of

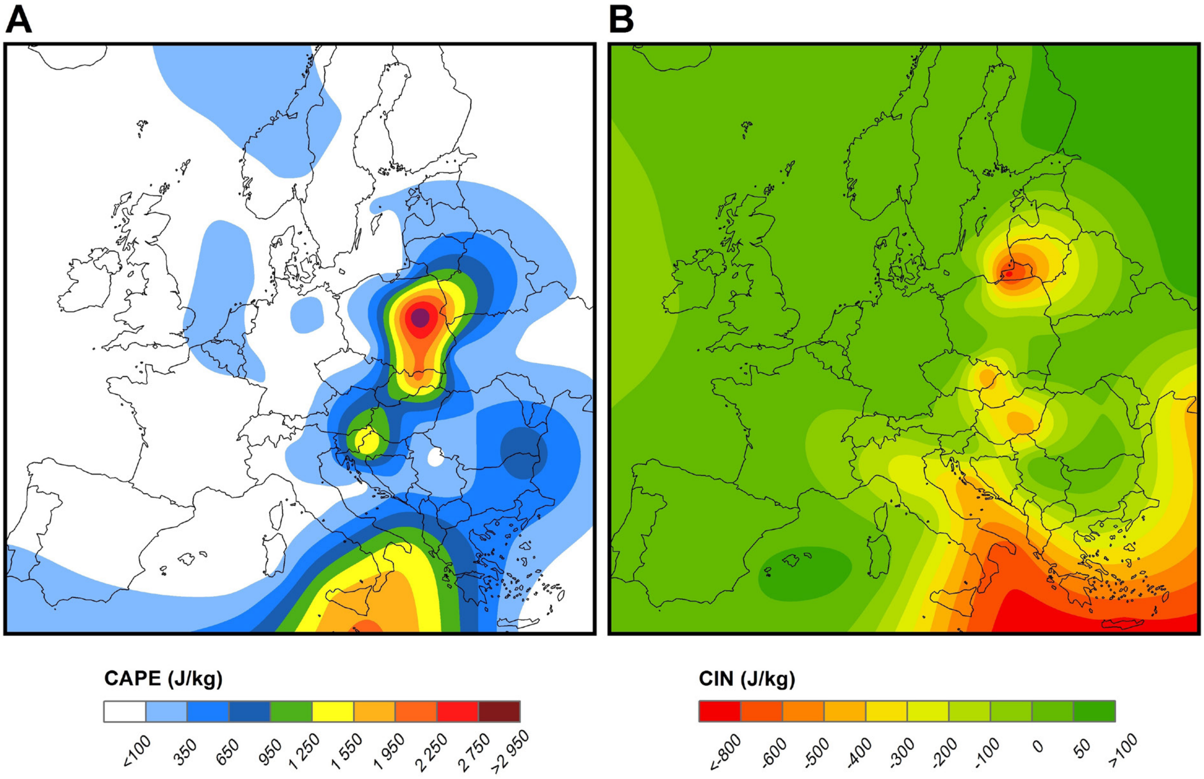


Fig. 8. A – Spatial distribution of Convective Atmospheric Potential Energy (CAPE) at 12 UTC; 11 August, 2017. B – Spatial distribution of Convective Inhibition (CIN) at 12 UTC; 11 August, 2017 (source: vertical atmospheric surveys archives of the University of Wyoming)

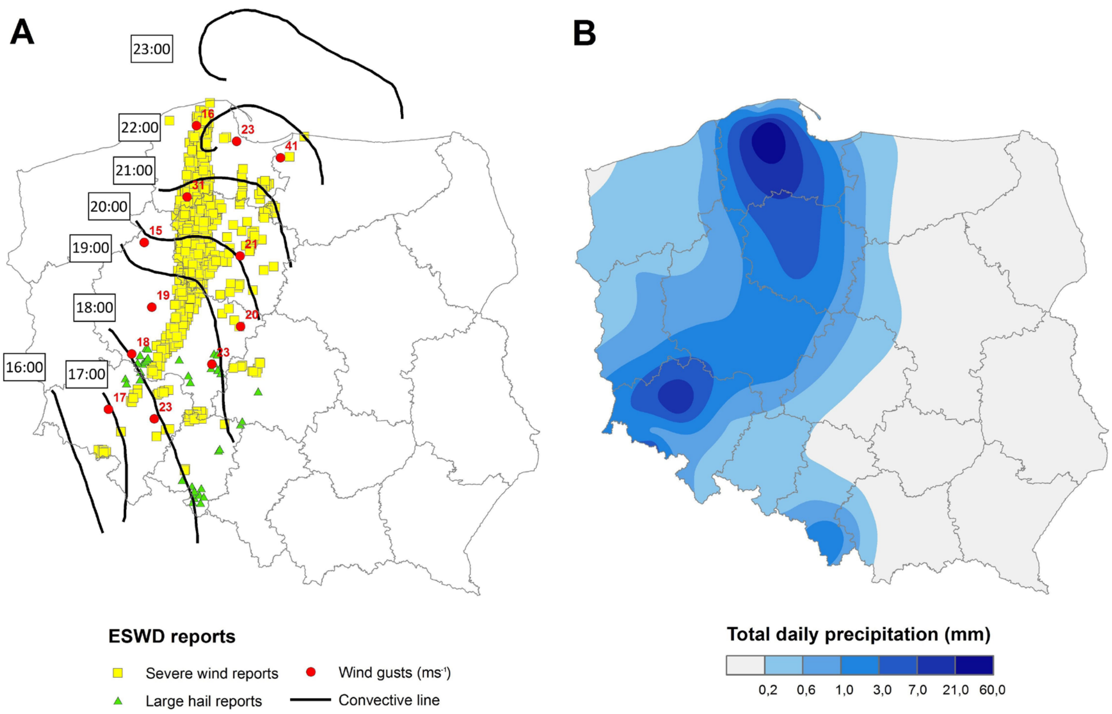


Fig. 9. A – Hourly displacement of supercell on 11 August, 2017 with 1-hour steps through convective line (black line), severe wind reports (yellow squares), large hail reports (green triangle), severe wind gusts registered at meteorological stations (red dots) derived from the European Severe Weather Database (ESWD). B – Total daily precipitation (mm) on 11 August, 2017. Measurement data derived from meteorological stations managed by the IMGW-PIB

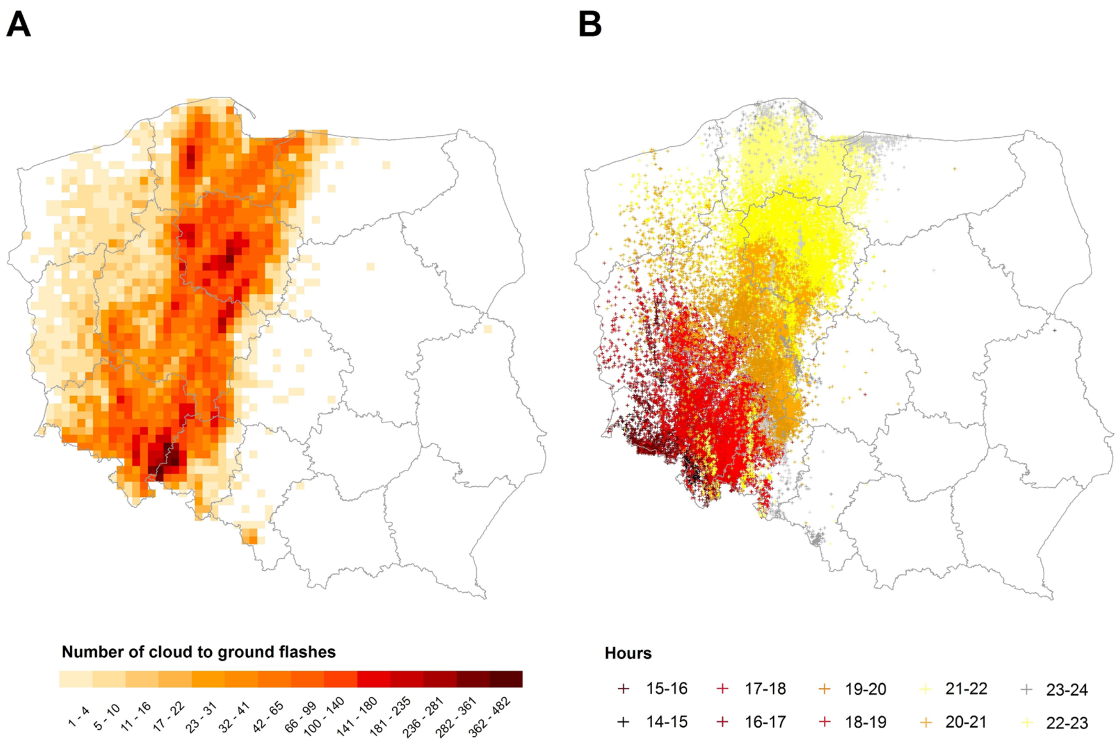


Fig. 10. A – Daily number of cloud-to-ground lightning flashes on 11 August, 2017. Lightning densities are computed for 10×10-km grid cells. B – Hourly distribution of cloud-to-ground lightning flashes on 11 August, 2017. Colour crosses denote time of occurrence of flashes. Source: based on lightning data derived from the PERUN network

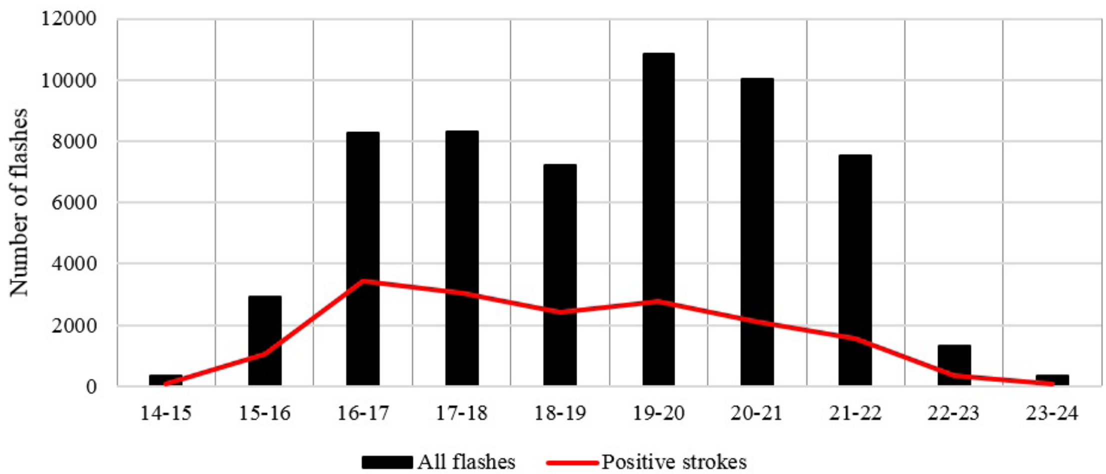


Fig. 11. Hourly cloud-to-ground flash density chart (black bars) and positive strokes (red line) with 1-hour steps on 11 August, 2017. Source: based on lightning data derived from the PERUN network

the province with great violence. Just 10 minutes after the derecho reached Pomerania, a squall occurred around the northern border of the Kuyavian-Pomeranian voivodship. Immediately behind the huge, low-suspended shelf cloud and a zone of quite strong squall (about 70 $km \cdot h^{-1}$) came a precipitation zone associated with one of the component storms, which turned out later to be a supercell. This cell generated an extremely intense macroburst of about 10 kilometres wide that lasted over an hour and whose strength was compounded by the enormous speed of the system. The wind components could be up to 170 $km \cdot h^{-1}$ in places, while Doppler scans from the radar in Gdańsk indicated almost 160 $km \cdot h^{-1}$. In exactly the middle of this macroburst route (wind gust over 60 $m \cdot s^{-1}$) there was a scout camp in Suszek where two scouts lost their lives when a tree fell on their tent. The next three hours were the system's "journey" through Pomerania, during which dozens of towns and forests were devastated (Fig. 12). The greatest damage to buildings was documented in the area of Nakło on the Noteć, Sępólno Krajeńskie, Tuchola and Kościerzyna. The most violent storm left Poland only around midnight. However, before this happened, an MCV (mesoscale convective vortex) appeared in the western part of the system. This phenomenon, as already mentioned, sometimes arises when the bow echo phase is mature (then the hook echo signature is formed), often with violent downburst phenomena or whirlwinds. It is best seen on radar scans from around 22:00 (Fig. 13).

## Comparison of 2017's August 10 and August 11 storm phenomena

This study documents two different thunderstorm days (August 10 and 11, 2017) considering the synoptic situation, atmospheric condition, spatial distribution of lightning flashes and the evolution of the outbreak of severe thunderstorms in Poland in such a short time (Table 1 and Fig. 13).

On 10 August a violent storm formed at the convergence line due to the moist and humid part of polar-maritime air merging with the tropical air mass. Unstable air flow in the top of the troposphere layer and big differences in dew point, including freezing level, caused such quantities of lightning strikes to occur. The amount of polar-maritime air mass and a high air temperature gradient at ground surface played an extremely important role in this process. However, the moisture and instability variables were not surprising for August, given the climatology of central Europe (Taszarek et al. 2018). On August 10, CAPE values were not much higher than CIN values. Within a short time, the system developed from smaller clusters of storms into a one big and fast moving system that at some point produced almost 40,000 cloud-to-ground lightning strikes per hour. During August 11, the system produced only up to 10,000 flashes per hour. On the 11$^{th}$, with the development of the supercell, the storm began to use the strong flow of the jet stream carrying amounts of cold air, which further enlarged the storm system. According to this, the jet stream current allowed severe wind gust – but not lightning – to develop. Interestingly, the supercells produced severe wind damage after reaching the hourly maximum of lightning distribution in both cases.

Fig. 12. Tracts of forest damaged by storm downburst (source: General Directorate of the State Forests)

Celiński-Mysław and Łoboda (2019) evaluated thermodynamic and cinematic conditions of 91 bow echo cases in Poland, and derived 1,750 J kg$^{-1}$

Table 1. Comparison of significant supercell features with secondary factors

| Parameters | 10 August, 2017 | 11 August, 2017 |
|---|---|---|
| Duration | 10 hours | 10 hours |
| Main direction | North-east | North |
| Estimated supercell velocity | 71 $km \cdot h^{-1}$ | 88 $km \cdot h^{-1}$ |
| Electric activity peak | 04:00–05:00 | 19:00–20:00 |
| Number of flashes at activity peak | 38,575 | 10,840 |
| Total daily number of cloud-to-ground flashes | 154,524 | 56,510 |
| Highest number of cloud-to-ground flashes at 10×10-km grid cell | 849 | 482 |
| Percentage of positive lightning flashes | 18% | 29% |
| Highest CAPE value measured around Poland border (radius 450 km) | 1750 $J \cdot kg^{-1}$ (Poprad, Slovakia) | 2982 $J \cdot kg^{-1}$ (Legionowo, Poland) |
| Highest CIN value measured around Poland border (radius 450 km) | –480 $J \cdot kg^{-1}$ (Lviv, Ukraine) | –503 $J \cdot kg^{-1}$ (Kaliningrad, Russia) |
| Maximum freezing level | 560 hPa | 500 hPa |
| Average humidity | 80% | 70% |
| Air temperature gradient during day time (SE–NW) | 14.1°C | 20.2°C |
| Highest daily synoptic measured precipitation | 54.0 mm | 60.0 mm |
| Highest synoptic measured gust of wind | 21 $m \cdot s^{-1}$ (75.6 $km \cdot h^{-1}$) | 41 $m \cdot s^{-1}$ (147.2 $km \cdot h^{-1}$) |
| Number of ESWD reports | 481 | 1279 |
| Storm-damaged forest area | ~11,000 ha | ~80,000 ha |

MU CAPE per bow echo event. In those cases, on August 11, CAPE values were even higher, as determined by measured CIN values (Table 1). Moreover, on the first day, the activity and occurrence of positive flashes was confirmed by the occurrence of mature Cumulonimbus clouds with electric peak from 4:00 to 5:00. However, the next day, the maximum occurrence of positive flashes was noted at the early stage of Cumulonibus cloud, when the main cloud form was not yet developed. It is worth noting that, even with a moderately high freezing level in the cloud base, there were not many cases of large hail.

The main threats were the high amount of lightning flashes and wind gusts. A considerably lower number of severe wind events were reported in the central and eastern parts of the bow echoes. This suggested that meso-vortices on the edge of a bow echo may cause a rear inflow jet to descend and subsequently produce damaging winds (Fig. 13).

## Conclusion

In Poland, 10 and 11 August, 2017 were undeniably very dynamic, severe and terrifying days, especially for those who lost their homes and even their lives. Over several hours, two rising supercells formed and 211,034 cloud-to-ground lightning strikes occurred, while 1,658 wind reports were entered into the ESWD database. Generally, storms destroyed and partially damaged over 91,000 ha of forests (source: General Directorate of the State Forests), damaged over 20,000 buildings (source: Main Building Control Inspectorate) and cut off electricity to around 510,000 residents. To highlight the differences between those two thunderstorm outbreaks it is worth noting that a significant share of all flashes had a positive current. A positive lightning strike is much powerful than a negative one because of

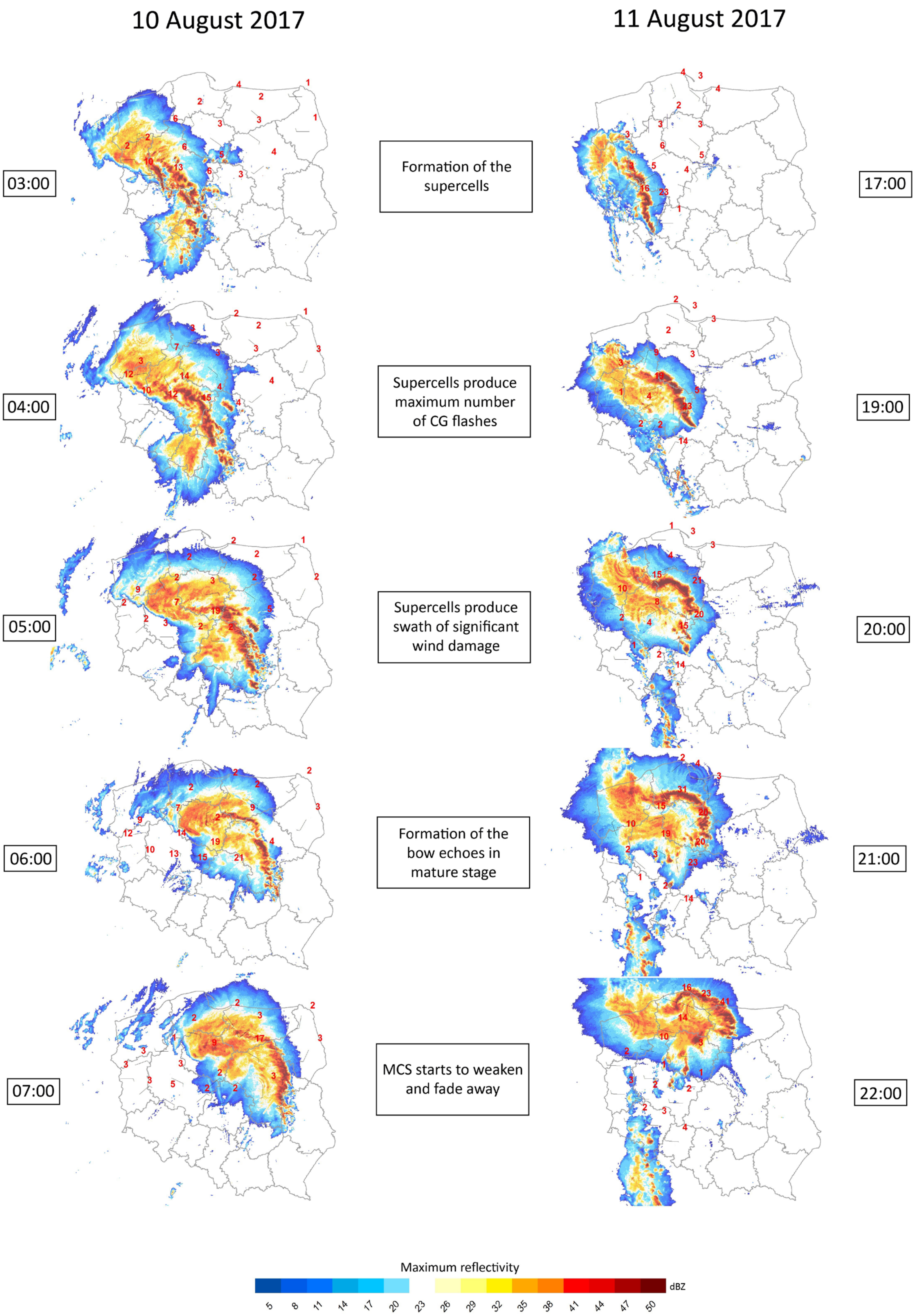


Fig. 13. Timeline of the most important events in MCS's evolution (from top to bottom). Surface synoptic maximum gusts of wind speed ($m \cdot s^{-1}$) (red digits) and direction (black vanes) with 1-hour steps. Shaded transparent area denotes maximum reflectivity from the POLRAD network

the high voltage, of even up to one billion volts in one strike (Bodzak 2006). This type of flashes mainly damaged forests and buildings and started haystack fires. In both cases, positive strokes occurred in the front and middle of the convective line, just from the top of a Cumulonimbus anvil cloud (Nag and Rakov 2012). The maximum intensity of cloud-to-cloud strikes did not occur at the same time as the maximum of all cloud-to-ground flashes. On August 10, positive current flashes were noticed 1 hour after the clouds produced their maximum of all cloud-to-ground flashes. On August 11, the maximum number of positive flashes occurred in the initial stage of Cumulonimbus cloud. As mentioned before, many people were injured and six people lost their lives as a result of the natural disaster.

Due to current climate change, which includes increased supply of hot and unstable air masses, we may expect the phenomenon of 10 and 11 August, 2017 to be repeated. The intensity of these MCSs may suggest that this was an extremely rare phenomenon in Poland, considering the frequency and intensity of thunderstorms (Trapp and Weisman 2003; Brooks 2013; Allen 2018; Taszarek et al. 2019). Due to climate changes the magnitude of such factors as the CAPE is also changing. In this situation, violent storms with high electric activity are likely to become more common in this part of Europe. Even with low CAPE and wind shear, multi-cell storms can develop, including bow echo signatures with squall lines (Brooks 2013). Preliminary results from climate projections for Europe indicate that an increase in the most unstable CAPE values and a slight increase in shear are expected in the next 100 years (Púčik 2017). To sum up, thunderstorms capable of producing severe and extremely severe phenomena may become more frequent. Consequently, we should all take this into consideration and be prepared for this phenomenon as it may occur again in the near future. Therefore, it is necessary to predict the impending threat and understand its strength.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Author contributions

Study design: SS, MK; data collection SS; statistical analysis: SS; result interpretation SS, MK; manuscript preparation SS, MK; literature review: SS, MK.

## References


ALLEN JT, 2018, Climate change and severe thunderstorms. *Oxford Research Encyclopedia of Climate Science.* Oxford University Press, 1–37, DOI: https://doi.org/10.1093/acrefore/9780190228620.013.62.

ATKINS NT and ST. LAURENT M, 2009, Bow echo mesovortices. Part I: Processes that influence their damaging potential. *Monthly Weather Review* 137: 1497–1513, DOI: https://doi.org/10.1175/2008MWR2649.1

BARCZYK M, 2013, Wykorzystanie radaru meteorologicznego do detekcji i prognozy zjawisk meteorologicznych. Instytut Meteorologii i Gospodarki Wodnej, Warszawa, 4–24.

BIELEC Z, 1998, Long-term variability of the thunderstorm frequency in Szczecin, Łódź, Kraków and Kasprowy Wierch in the period 1954–1993. *Acta Universitatis Lodziensis*, *Folia Geographica Physica* 3: 449–453.

BIELEC-BĄKOWSKA Z, 2007, Wyznaczanie regionów burzowych w Polsce. *Annales Universitatis Mariae Curie-Skłodowska* B 61(6): 57–64.

BIELEC-BĄKOWSKA Z, 2013, Burze i grady w Polsce. *Prace Geograficzne Instytutu Geografii i Gospodarki Przestrzennej* 132: 99–132.

BODZAK P, 2006, Detekcja i lokalizacja wyładowań atmosferycznych. *Seria: Instrukcje i podręczniki*, Wydawnictwo IMGW, Warszawa.

BROOKS HE, 2013, Severe thunderstorms and climate change. *Atmospheric Research* 123: 129–138, DOI: https://doi.org/10.1016/j.atmosres.2012.04.002

CELIŃSKI-MYSŁAW D and ŁOBODA Ł, 2019, Kinematic and thermodynamic conditions related to convective systems with a bow echo in Poland. *Theoretical and Applied Climatology* 137: 2109–2123. DOI: https://doi.org/10.1007/s00704-018-2728-6

CZERNECKI B, TASZAREK M, KOLENDOWICZ L and KONARSKI J, 2016, Relationship between human observations of thunderstorms and PERUN lightning detection network in Poland. *Atmospheric Research* 167: 118–128.

DAHL JML and PARKER MD, 2012, Uncertainties in trajectory calculations within near-surface mesocyclones of simulated supercells. *Monthly Weather Review* 140 (9): 2959–2966.

DOTZEK N, GROENEMEIJER P, FEUERSTEIN B and HOLZER AM, 2009, Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmospheric Research* 93: 575–586.

General Directorate of the State Forests, 2019, https://www.lasy.gov.pl/pl

HOLLE RL, CUMMINS K and BROOKS WA, 2016, Seasonal, monthly, and weekly distribution of NLDN and GLD360 cloud-to-ground lightning. *Monthly Weather Review* 144(8), DOI: https://doi.org/10.1175/MWR-D-16-0051.1

Main Building Control Inspectorate, 2019, https://www.gunb.gov.pl

MÄKELÄ A and ROSSI P, 2011, The daily cloud-to-ground lightning flash density in the contiguous United States and Finland. *Monthly Weather Review* 139(5): 1323–1337.

NAG A and RAKOV VA, 2012, Positive lighting: An overview, new observation and inferences. *Journal of Geophysical Research Atmosphere* 117, DOI: https://doi.org/10.1029/2012JD017545

PÚČIK T, GROENEMEIJERA P, RÄDLERA AT, TIJSSENA L, NIKULIND G, PREINE AF, VAN MEIJGAARDG E, FEALYH R, JACOBI D and TEICHMANNI C, 2017, Future changes in European severe convection environments in a regional climate model ensemble. *Journal of Climate* 30: 6771–6794, DOI: https://doi.org/10.1175/JCLI-D-16-0777.1

TASZAREK M, BROOKS HE and CZERNECKI B, 2017, Sounding-derived parameters associated with convective hazards in Europe. *Monthly Weather Review* 145: 1511–1528.

TASZAREK M and CZERNECKI B, 2015, A cloud-to-ground lightning climatology for Poland. *Monthly Weather Review* 143: 4285–4304, DOI: https://doi.org/10.1175/MWR-D-15-0206.1

TASZAREK M, PILGUJ N, ORLIKOWSKI J, SUROWIECKI A, WALCZAKIEWICZ S, PILORZ W, PIASECKI K, PAJUREK Ł and PÓŁROLNICZAK M, 2019, Derecho evolving from a mesocyclone – A study of 11 August 2017 severe weather outbreak in Poland: Event analysis and high-resolution simulation. *Monthly Weather Review* 145: 1511–1528.

TASZAREK M, SZUSTER P and FORTUNIAK K, 2018, Climatological aspects of convective parameters over Europe: A comparison of ERA-Interim and sounding data. *Journal of Climate* 31: 4281–4308, DOI: https://doi.org/10.1175/JCLI-D-17-0596.1

TRAPP RJ and WEISMAN ML, 2003, Low-level mesovortices within squall lines and bow echoes. Part II: Their genesis and implications. *Monthly Weather Review* 131: 2804–2823, DOI: https://doi.org/10.1175/1520-0493(2003)131%3C2804:LMWSLA%3E2.0.CO;2

Univeristy of Wyoming, 2019, http://weather.uwyo.edu/upperair/sounding.html

*Received 17 January 2020*
*Accepted 12 May 2020*