Spatial analysis of atmospheric discharges in Lubelszczyzna in 2018

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Received: 1 September 2020 / Accepted: 27 April 2021 / Published online: 11 May 2021
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Abstract

The aim of the study was to analyse lightning discharges over the Lublin region in 2018 using GIS tools. The methods and systems for detection and location of lightning discharges were presented. The impact of terrain coverage, height above sea level, and location of transceiver stations of mobile operators on the occurrence of discharges was shown. The study provides knowledge of theoretically safer areas and those particularly vulnerable to lightning strikes. Additionally, statistics related to lightning discharges over the Lublin region in 2018 were presented. The analyses were carried out on vector data on the atmospheric discharges, vector data from the transceiver stations, vector data containing information on administrative units, and data from the CORINE Land Cover 2018 and on the digital elevation model. The results of the analyses confirmed that areas of airports are particularly exposed to lightning strikes, whereas beaches and sand dunes are the safest areas. It was also found that lightning strikes more often hit coniferous forests than deciduous forests. As indicated by the statistics, May is the month with the largest number of stormy days, while the largest number of lightning strikes is July.

Keywords Lightning discharges · Cloudy discharges · Lightning strikes · Spatial analysis · Lightning detection techniques · CORINE Land Cover · Digital elevation model

Introduction

Storms and accompanying electrostatic discharges, in particular cloud-to-ground discharges, are extremely interesting but unpredictable and dangerous weather phenomena occurring in the atmosphere.

On the one hand, it is possible to determine many various parameters of recorded and localised discharges; on the other hand, it is still impossible to predict accurately the formation of atmospheric discharges. Therefore, it seems necessary to conduct research on the spatial distribution of discharges in selected areas. The relationship between the occurrence of the electrostatic discharge phenomenon and land cover has been comprehensively analysed in the literature. Stallins and Rose (2008) reviewed the methodology for analysing ground discharge data in urban areas. Additionally, the authors assessed the impact of the urban heat island and

the increased amount of aerosols in the city air on the frequency of discharges. Their study also thoroughly described the lightning detection network in the USA. Kar and Liou (2019) presented the spatial distribution of atmospheric discharges recorded in Taipei, Taiwan. The spatial analysis was based on satellite data presenting the thermal-dynamic properties of the ground. They reported a strong spatial correlation between the frequency of atmospheric discharges and the thermal properties of the ground. In their paper, they also presented a relationship between the frequency of electrostatic discharges and the content of PM10 dusts and SO₂. A different approach was presented by Bentley and Stallins (2005), who carried out a statistical analysis of the frequency and spatial distribution of discharges in GA, USA. They analysed a 10-year period of 1994–2003. Additionally, they carried out a synoptic analysis of the formation of a large number of discharges in this state for selected days.

Special importance in the analysis of atmospheric discharges is ascribed to satellite observations. In their study, Albrecht et al. (2016) presented analyses based on high-resolution images recorded by satellite TRMM devices in 1998–2013. The data show the distribution of atmospheric discharges for the entire globe in the tropical zone. The authors analysed areas with the highest frequency of

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atmospheric discharges and presented accurate analyses on a monthly basis for these regions as well as the distribution of the frequency of discharges on a daily basis. The authors found the highest annual lightning frequency in the area of Lake Maracaibo in Venezuela, with 297 days in which the phenomenon occurred. Similar numbers of discharges were recorded in the eastern part of Africa. The authors associate the frequency of lightning discharges with the local landforms and distribution of winds.

Investigations of atmospheric discharges in Europe focused on the impact of landforms and ground cover were conducted by Kotroni and Lagouvardos (2008) and Rivas Soriano et al. (2019). Kotroni and Lagouvardos (2008) analysed the influence of land cover and landforms on the frequency of atmospheric discharges between June 2006 and May 2007 in the Mediterranean region. They observed an increase in the number of discharges at increasing altitudes, but only in spring months. The authors compared the number of discharges with the landforms and concluded that the number of discharges considerably increased towards

the foot of the slope in all months except winter. They also reported a positive correlation between the number of atmospheric discharges in summer and the presence of forest areas. These observations suggested that the higher humidity in forest areas in summer promotes the occurrence of atmospheric discharges in these areas.

In Polish literature, there are reports on atmospheric discharges, but they are mainly focused on methods for protection of various objects and elements from the impact of this phenomenon (Smalcerz et al. 2019, Strzyżewski 2019, Bugała and Bugała 2019). There are also studies presenting the lightning detection network designed at the Institute of Meteorology and Water Management. In his article, Łoboda (2013) highlighted differences in the accuracy and reliability of the atmospheric discharge data provided by the CELDN, PERUN, and LINET systems. The author also presented available information about atmospheric discharges in Poland after Stopa (1962), Markiewicz (1999), Instytut Meteorologii i Gospodarki Wodnej and Lorenc (2005), and Skomudek (2008). The study also included maps of the

Fig. 1 Location of the Lublin Province in relation to Poland

density of cloud-to-ground discharges registered with the use of various detection systems in Poland in 2008.

A compendium of knowledge about lightning detection systems was provided by Bodzak (2007). The author presented the physical aspect of the phenomenon as well as available measurement methods and techniques employed at the Institute of Meteorology and Water Management. Łoboda et al. (2009) described a new lightning detection system consisting of a dense network of sensors combined into a coherent network. The LINET system was also described in detail by Makar (2013).

In turn, in their article, Taszarek et al. (2015) analysed cloud-to-ground discharges registered by the PERUN system in 2002–2013. They showed maps with the location of stations comprised in this system and the accuracy of localisation of cloud-to-ground discharges in Poland. The average number of thunderstorm days per year was estimated at 151. Approximately 15% of cloud-to-ground discharges were found to occur at night and their percentage increased in subsequent years. Czernecki et al. (2016) presented a comparison of an automatic method for observation of storms (atmospheric discharges) with observations from synoptic stations. As shown by the analysis carried out by the authors, effective observation of atmospheric discharges can cover a distance of 16.9–18.3 km depending on the method employed. The distance over which observations of discharges are possible is associated with human perception abilities and strongly influences the quality of so-called manual observations carried out by man. Human limitations may result in large errors in data interpretation and processing and sometimes in erroneous conclusions.

Material and methods

The study was based on atmospheric discharge data from 2018. They were downloaded from the official website of the Institute of Meteorology and Water Management—National Research Institute <https://dane.imgw.pl/datastore#>. The downloaded data in the .txt format contained the following information: date, information about the status of the system, number of discharges, accurate time determination, latitude, longitude, identification of the type of discharge, localisation error, frequency of lightning, signal rise time, signal loss time, amplitude, current in the discharge channel, current error, and numbers of stations. The temporal resolution of the data was 10 min. According to Bodzak (2007), the accuracy of discharge detection in the PERUN network is about 95% and such accuracy is achieved within a range of up to 100 km from the receiving antenna. However, Taszarek et al. (2015) determined the actual accuracy at a range of 2 km to be just over 70%. The lightning discharge data was converted into the lightning density in the analysed area using

Fig. 2 Location of BTS (base transceiver station) stations in ranges of altitude used in the spatial analysis

the Kernel Density Estimation model (Fotheringham et al. 2000, Lloyd 2010). For statistical analyses, the discharge density was converted to a 1 km × 1 km grid using ArcMap v. 10.8 (Esri Inc 2019). The files in the native form were stored in the geographical system (WGS 84). Next, they were transformed into the 1992 layout in ArcMap software (Esri Inc 2019).

Administrative units in the .shp format were downloaded from the website of the Central Office of Geodesy and Cartography. Similar to the atmospheric discharge data, they were converted from WGS 84 to the 1992 coordinate system.

Data on the landforms provided by the CORINE Land Cover project (European Environment Agency 2020)

Table 1 Number and percent of the types of discharges

Type of discharge	Number of discharges	Percent
Cloud-cloud discharges	526,013	92.16%
Cloud-to-ground discharges	44,723	7.84%
All discharges	570,736	100.00%

Source: Own analysis based on data on atmospheric discharges

Table 2 Number and percentage of the types of discharges in individual months over the Lublin region

Month	Number of cloud-to-cloud discharges	Percent of cloud-to-cloud discharges in all types	Number of cloud-to-ground discharges	Percent of cloud-to-ground discharges in all types	Total number of atmospheric discharges
January	0	0.00%	0	0.00%	0
February	0	0.00%	0	0.00%	0
March	16	100.00%	0	0.00%	16
April	39,514	98.03%	793	1.97%	40,307
May	44,735	93.31%	3208	6.69%	47,943
June	32,142	90.21%	3490	9.79%	35,632
July	157,446	92.02%	13,659	7.98%	171,105
August	161,838	93.73%	10,821	6.27%	172,659
September	90,093	87.63%	12,720	12.37%	102,813
October	234	89.66%	27	10.34%	261
November	0	0.00%	0	0.00%	0
December	0	0.00%	0	0.00%	0

Source: Own analysis based on data on atmospheric discharges

were used in the study. These are publicly available data from a database covering the analysed area. The land cover classes in the CORINE Land Cover project are hierarchically created at three different levels of accuracy.

In order to check the thesis formulated by Kingfield et al. (2017) regarding the high probability of discharges in the close vicinity of transceiver stations, the number of discharges in terms of the distance from the station was analysed. Data on the location of all mobile operators in Poland in the WGS 84 system were downloaded from <http://beta.btsearch.pl/bts/export> (Niemczyk and Lorenz 2020).

The impact of the altitude and landform on atmospheric discharges was assessed in a terrain model created based on SRTM with 1-s spatial resolution version 3 (USGS 2020, Rodriguez et al. 2006). The downloaded files were saved in the GeoTIFF format in the WGS 84 coordinate system. The altitude data were mosaicked and cut to match the surface area of Lublin Province.

The analysis of the distance from the transceiver stations was performed using the buffer methodology. Seven buffer zones were established every 400 m in a distance range from 0 to 2800 m. In other cases, cloud-to-ground discharges were analysed by determination of their frequency in individual months, administrative units, and CORINE Land Cover land use forms at all levels of detail. The density of atmospheric discharges was recalculated per square kilometre in each case. Analyses associated with the digital terrain model were made based on NMT with a resolution of 30 m. The frequency was calculated for each basic plot and the data were presented in 30-m ranges.

Analysis of data

The Lublin region is an area lying in the zone where climate conditions with continental and oceanic features intertwine (Woś 1999); moreover, as noted by Makar (2013), Poland is divided into two parts related to the density of discharges (Fig. 1, Fig. 2). Both the location and the shape of the Lublin region make it an area representative of Poland, excluding the mountains.

Globally cloud-to-cloud (IC) discharges exhibit the highest frequency of occurrence among all types of discharges. They have been estimated at 60–90% of the total number of electric discharges occurring during storms (Bodzak 2007).

The analysed year 2018 was characterised by a substantially higher number of cloud-to-cloud (over 90%) than cloud-to-ground discharges (Table 1).

The analysis of the distribution of discharges in the particular months of the analysed year revealed the

Table 3 Relationship between the distance (in metres) from a BTS station and the density (number of discharges/km²) of cloud-to-ground discharges in the 400-m step zones around the BTS stations

Distance from the BTS station (m)	Density (no. of discharges/km ²)
0–400	1.598
401–800	1.801
801–1200	1.837
1201–1600	1.860
1601–2000	1.775
2001–2400	1.725
2401–2800	1.742

Source: Own analysis based on data on atmospheric discharges and BTS (base transceiver station) data

highest frequency of the phenomenon in August and July over the Lublin region. No electrical activity was observed in the atmosphere in the late autumn and winter months (Table 2).

The analysis of the deviation of the number of atmospheric discharges in the individual months from the mean value for the entire year 2018 over Lublin region demonstrated a similar frequency of the activity in April and June. The electrical activity in the atmosphere in August and July was over threefold higher than the average annual value. The

cloud-to-ground discharges represented the highest percentage (over 10%) in the total number in September and October. In March, only cloud-to-cloud discharges were recorded (Table 2).

Table 3 presents the results of analyses of the cloud-to-ground discharge density in seven buffer zones created at a 400-m step. The highest density was recorded in three zones located at the closest distance from the transceiver stations. This may indicate not only errors in the localisation of the discharges but also the fact that the lightning

Fig. 3 Map of the density (number of discharges/km²) of cloud-to-cloud discharges over the Lublin Province

tends to hit the stations as well as nearby areas. The results of the analyses are consistent with those presented by Kingfield et al. (2017). The three external buffers exhibited a lower discharge density per square kilometre. The selection of an appropriate distance step of the buffers was preceded by multiple empirical tests, which indicated the most optimal range of 400 m.

The spatial distribution of cloud-to-cloud discharges in Lubelszczyzna exhibited a relatively large diversity (Fig. 3). Communes in the eastern part of the Province were

characterised by a lower frequency of discharges than those located in the western part.

The lowest density of atmospheric discharges, i.e. over 4 discharges per square kilometre was recorded in south eastern part of region. The highest frequency was noted in the communes of the western and south-western parts of Lubelszczyzna. The highest density of cloud-to-cloud discharges, i.e. over 94 discharges per square kilometre, was reported from the Vistula valley in the western part of the Lublin region. The spatial distribution of cloud-to-cloud

Fig. 4 Map of the density (number of discharges/km²) of cloud-to-ground discharges over Lublin Province

discharges closely relates to the topography and the highest value is recorded in the jump zones of changes in relative heights.

The cloud-to-ground discharges were characterised by a slightly different spatial distribution, compared to the cloud-to-cloud discharges (Fig. 4). The northern part of the voivodeship is characterised by a lower lightning density than the southern part, which corresponds to the results presented by Makar (2013). The highest discharge density is recorded in the central part of the voivodeship and exceeds 11/km². Wyniosłość Giełczewska is a region with over 11 discharges/km². High discharge values are also characteristic of the south-western part of the Lublin region. The discharge density distribution corresponds to the main relief forms. Much lower values of the discharges are observed in the zone of depressions and plains than in the zone of elevations. Similar conclusions were formulated by, e.g. Royé et al. (2018). It is probably related to the areas of ascending convection

currents, where the formation of storm cells takes place (Bielec-Bakowska 2013).

The lowest density of cloud-to-ground discharges was recorded in the northern part of the voivodeship, in the area of Łuków Plain. In this area, the discharge density does not exceed one (Fig. 4).

The analysis of the density of atmospheric discharges in the individual land cover forms was based on CORINE Land Cover data. At each of the three levels, the density of atmospheric discharges was calculated per square kilometre of surface area (Table 4). The variation between the individual land cover forms at the most general first level was small. However, there was clear dominance of the density of cloud-to-ground discharges in the wetlands, i.e. almost 2.5/km². A slightly different correlation than that observed by Kotroni and Lagouvardos (2008) between the type of land cover and the number of lightning discharges was observed in the Lublin region in the case of forests. The lowest value of the frequency of discharges,

Table 4 Density of cloud-to-ground discharges (number of discharges/km²) at three levels of land cover specified by the CORINE Land Cover project

Level 1	Level 2	Level 3	Density in level I	Density in level II	Density in level III
Anthropogenic areas	Urban development	Compact urban development	1.758	1.746	2.883
		Loose urban development			1.742
	Industrial, commercial, and transport areas	Industrial or commercial areas		1.867	1.604
		Road and railway transport areas			1.319
		Airports			4.122
	Mines, excavation pits, and construction sites	Open-cut mines		1.949	2.357
		Dumping sites and waste heaps			3.058
		Construction sites			0.854
	Urban greeneries and recreational sites	Greeneries		1.738	0.428
Agricultural land	Arable land	Non-irrigated arable land	1.752	1.777	1.777
	Permanent crops	Orchards and plantations			2.038
	Meadows and pastures	Meadows, pastures			1.661
	Mixed crops	Complex systems of crops and allotments			1.716
		Agricultural land with a large proportion of natural vegetation			1.663
Forests and semi-natural ecosystems	Forests	Deciduous forests	1.839	1.846	1.716
		Coniferous forests			2.047
		Mixed forests			1.661
	Associations of tree and shrub vegetation	Grasslands and natural pastures		1.680	1.548
		Forests and changing shrub vegetation			1.682
	Open areas with no or sparse vegetation	Beaches, dunes, sands		0.000	0.000
Wetlands	Inland wetlands	Inland marshes	2.433	2.433	2.330
		Peat lands			2.882
Aquatic areas	Inland waters	Watercourses	1.936	1.936	1.429
		Water bodies			2.078

Source: Own analysis based on data on atmospheric discharges.

i.e. slightly over $1.8/\text{km}^2$, was observed in the forest and semi-natural ecosystems. At level II, no cloud-to-ground discharges were found to occur in the open areas with no or sparse vegetation in 2018. The highest density (over 2 discharges per square kilometre) was recorded in the inland wetlands and permanent crops. At level III providing the most detailed specification of the land cover, the highest density of atmospheric discharges in 2018 was recorded over airports: there were over 4 discharges per square kilometre. Slightly more than 3 discharges were

noted in the waste heaps and dumping sites. Interestingly, the number of atmospheric discharges above the urban compact development was quite high, i.e. almost 3 discharges per square kilometre. Similar relationships were reported by Stallins and Rose (2008).

In the next stage, data on the atmospheric discharges were analysed in relation to the altitude of the examined area (Fig. 5). The analysis revealed an increase in the density of discharges with the increasing altitude. The top parts noticeably diverged from the general trend of the increasing

Fig. 5 Map of the density (number of discharges/ km^2) of atmospheric discharges in the altitude ranges in Lublin Province

Table 5 Number and density (number of discharges/km²) of atmospheric discharges in the altitude ranges in Lublin Province

Altitude range (m a.s.l.)	Number of discharges	Surface area (km ²)	Density (number of discharges/km ²)
91–120	493	286.206	1.723
121–150	4231	3655.082	1.158
151–180	11,929	7726.266	1.544
181–210	10,289	5202.153	1.978
211–240	9800	4595.122	2.133
241–270	4729	2168.934	2.180
271–300	2411	1017.267	2.370
301–330	710	398.795	1.780
331–360	120	80.365	1.493
361–390	3	3.437	0.873

frequency of cloud-to-ground discharges with altitude (Table 5).

One of the most interesting elements visible on the map is the increase in the density of discharges in the Vistula River valley in the western part of Lubelszczyzna (Fig. 5, Scheme 1).

The absolute number of discharges in the individual altitude ranges was correlated with the surface area in each (Table 5). The analysis indicates the highest density of discharges (over 2 discharges/km²) at an altitude from 211 up to 300 m a.s.l. However, the density of discharges decreased gradually at altitudes located farther from this range. Interestingly, areas located in the lowest altitude range were characterised by a higher frequency of discharges than areas located slightly higher, i.e. in the range of 121–180 m a.s.l. The results obtained in the present analyses differ from those reported by Kotroni and

Lagouvardos (2008), but the non-linearity of this phenomenon observed for the Iberian Peninsula area has been confirmed (Royé et al. 2018).

Summary and conclusions

The present study describes the results of an analysis of atmospheric discharges recorded in Lublin Province in 2018 carried out with the use of GIS tools. The investigations mainly included cloud-to-ground discharges, but cloud-to-cloud discharges were presented as well.

The analyses revealed that cloud-to-cloud discharges were the most common and accounted for over 90%. Discharges that occur in March are cloud-to-cloud discharges, while those occurring in the autumn months are characterised by a greater number of cloud-to-ground discharges. The cloud-to-cloud discharge system is based on the local relief layout, with the density increasing from east to west. In turn, cloud-to-ground discharges are characterised by a slightly different spatial distribution but also a relationship with the terrain orography. The density of these discharges in the southern part of the voivodeship is higher than in the northern part, which is dominated by lowland landforms. An interesting relationship was found in the case of the airport area located in the central part of the Lublin region, which most likely contributes to the highest density of cloud-to-ground discharges. The altitude has an important effect as well. The density of discharges at an altitude from 211 up to 300 m a.s.l. is relatively high and exceeds 2 discharges/km². In turn, the density exhibits a significant proportional decrease above and below this range.

Scheme 1 Relationship between the altitude above sea level and the density of cloud-to-ground discharges. Source: Own analysis based on data on atmospheric discharges and digital terrain model

The findings have provided new insight into atmospheric discharges and partially confirmed the widely accepted theories postulating a higher frequency of the phenomenon in areas with higher humidity and elevation over flat terrain. Since the investigations were conducted in a relatively short period of 1 year, some of the results need to be corroborated in a larger sample of data. Nevertheless, the present study seems to have confirmed the complexity of the phenomenon, which requires further research.

Author contribution Conceptualization, M.S.; data curation, K.M., M.S.; formal analysis, K.M.; methodology, M.S., K.M.; project administration, K.M., M.S.; supervision, M.S.; visualization, K.M.; writing—original draft, K.M., M.S.; writing—review & editing, M.S. All authors have read and agreed to the published version of the manuscript.

Funding The study was financed by the NCN research project no. 2016/21/D/ST10/01947.

Declarations

Conflict of interest The authors declare no competing interests.

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