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Wpływ niestabilności termodynamicznej atmosfery na rozkład przestrzenno-czasowy występowania wyładowań doziemnych w Polsce w latach 2002-2020

Influence of atmospheric thermodynamic instability on spatial and temporal distribution of cloud-to-ground flashes occurrence in Poland (2002-2020)

Rozprawa doktorska

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W tym miejscu kieruję podziękowania dla
Promotora **dr hab. Marka Kejny prof. UMK**
za okazałe wsparcie, wszelkie cenne wskazówki i uwagi.

Małżonce, za nieoceniony entuzjazm i wiarę w dążeniu do celu.

Wszystkim bliskim osobom za dobre słowo i udzielone wsparcie na drodze kształcenia.

Spis treści

Autoreferat

Autoreferat pt. „Wpływ niestabilności termodynamicznej na rozkład przestrzenno-czasowy występowania wyładowań doziemnych w Polsce w latach 2002-2020" został przygotowany na podstawie cyklu pięciu oryginalnych, powiązanych tematycznie, artykułów naukowych. Cztery artykuły zostały opublikowane w latach 2021-2024 w czasopismach znajdujących się w wykazie czasopism naukowych i recenzowanych materiałów z konferencji międzynarodowych Ministerstwa Edukacji i Nauki oraz posiadających wskaźnik cytowań Impact Factor (IF). Jeden artykuł został złożony do czasopisma Meteorology, Hydrology and Water Management i jest na etapie recenzji. Łączna liczba punktów zgodnie z punktacją MEiN wynosi 365, a sumaryczny wskaźnik IF jest równy 10,5.

Cykl publikacji składa się z następujących prac:

Lp.	Dane bibliograficzne publikacji (układ chronologiczny)	MEiN	IF
P1	**Sulik Sławomir**, **2021**. Formation factors of the most electrically active thunderstorm days over Poland (2002-2020). *Weather and Climate Extremes* 34: 1-13.	140 pkt.	8,0
P2	**Sulik Sławomir**, Marek Kejna, **2022**. Spatial diveristy of cloud-to-ground lightning flashes in the Kujawsko-Pomorskie Voivodeship (Poland), 2002-2019 *Geographia Polonica* 95: 5-23	100 pkt.	0.9
P3	**Sulik Sławomir**, **2022**. A cloud-to-ground lightning density due to progressing climate change in Poland *Environmental Challenges* 9: 1-12	5 pkt.	0.2
P4	**Sulik Sławomir**, Marek Kejna, **2023**. Comparison of thunderstorm days in Poland based on SYNOP reports and PERUN lightning detection system *Miscellanea Geographica* 27: 134-146	100 pkt.	0.8
P5	**Sulik Sławomir**, Mateusz Taszarek, **2024**. Kinematic and thermodynamic environment during cloud-to-ground lightning occurrence in Poland *Meteorology, Hydrology and Water Management* (złożona do czasopisma)	20 pkt.	0.6
		365 pkt.	**10.5**

Pozostałe publikacje naukowe autorstwa/współautorstwa S. Sulika z punktacją MEiN nie wchodzące w skład osiągnięcia naukowego:

Lp.	Dane bibliograficzne publikacji (układ chronologiczny)	MEiN	IF
A1	**Sulik Sławomir**, Marek Kejna, **2020**. The origin and course of severe thunderstorm outbreaks in Poland on 10 and 11 August, 2017 *Bulletin of Geography: Physical Geography Series* 18: 25-39.	40 pkt.	0.9
A2	**Sulik Sławomir**, **2022**. Convective environment and development of a tornadic supercell in the Czech Republic on 24 June 2021. *Meteorology, Hydrology and Water Management* 10: 60-72	20 pkt.	0.6
A3	Sanjana Dutt, Amit Batar Kumar, **Sulik Sławomir**, Mieczysław Kunz, **2024**. Forest ecosystem on the edge: mapping forest fragmentation susceptibility in Tuchola Forest, Poland *Ecological Indicators* 1-15	200 pkt.	6.9
		260 pkt.	**8.4**

Streszczenie

Burza to ekstremalne zjawisko atmosferyczne należące do elektrometeorów. Położenie geograficzne Polski, ukształtowanie terenu, zmienna cyrkulacja atmosferyczna, przejściowość klimatu, czy złożoność procesów zachodzących w atmosferze, definiują burze jako zjawisko lokalne, uwarunkowane przez wiele zmiennych. Powoduje to znaczną zmienność liczby dni z burzą oraz wyładowań atmosferycznych w Polsce z roku na rok i w ciągu roku. Postępujące zmiany klimatu objawiające się wzrostem temperatury powietrza wpływają na częstość i intensywność burz. Każdego roku zjawiska współtowarzyszące burzom stwarzają realne zagrożenie dla życia i zdrowia człowieka oraz powodują znaczne straty materialne. Tak jak w przypadku innych zjawisk meteorologicznych, również w przypadku burz do obserwacji tego typu zjawiska niezbędny jest długookresowy monitoring. Badania te są również konieczne do zrozumienia zasad funkcjonowania systemu środowiska konwekcyjnego, niezbędnego do rekonstrukcji warunków panujących w atmosferze. Określenie parametrów stanu atmosfery umożliwi lepsze i bardziej precyzyjne prognozowanie tego typu zjawisk w przyszłości. Aby zdefiniować środowisko konwekcyjne generujące występowanie doziemnych wyładowań atmosferycznych (CG - cloud-to-ground) na terenie Polski wykorzystano dane pochodzące z systemu detekcji i lokalizacji wyładowań atmosferycznych PERUN (IMGW-PIB) z lat 2002-2020. Na tej podstawie zbadano rozkład przestrzenno-czasowy występowania wyładowań CG oraz liczby dni z burzą w Polsce. Dokonano również szczegółowej analizy dni o podwyższonej aktywności elektrycznej oraz liczby generowanych wyładowań CG. Na podstawie reanaliz ERA5 (ECMWF) zdefiniowano parametry środowiska konwekcyjnego sprzyjające powstawaniu wyładowań CG. Stały wzrost temperatury na kuli ziemskiej wpływa również na środowisko konwekcyjne, co prezentuje widoczny wzrost parametru WMAXSHEAR. W wyniku analizy stwierdzono, iż zmieniający się klimat wpływa na wzrost ilości wyładowań CG oraz liczby dni z burzą. Najbardziej sprzyjające warunki do rozwoju chmur *Cumulonimbus* występują przy CAPE ok. 1300 $J \cdot kg^{-1}$ oraz jednoczesnej obecności ścinania wiatru wynoszącej ok. 15 $m \cdot s^{-1}$ w profilu od 0 do 6 km AGL. Dodatkowymi czynnikami wspierającymi konwekcję jest zachowanie stosunku zmieszania pary wodnej wynoszącego 13 $g \cdot kg^{-1}$ oraz temperatury powietrza ok. 28-29°C i temperatury punktu rosy przekraczającej 18°C. Utrzymanie lub/i przekroczenie wartości podanych parametrów skutkowało wystąpieniem na przestrzeni lat 2002-2020, ośmiu dni z burzą podczas, których wystąpiło ponad 60.000 wyładowań doziemnych/dzień. Dalszy wzrost temperatury powietrza może przyczynić się do zwiększenia częstości i gwałtowności zjawisk burzowych, również ze względu na znaczne osłabienie oddziaływania prądu strumieniowego w umiarkowanych szerokościach geograficznych.

Słowa kluczowe: burza, wyładowanie atmosferyczne, konwekcja, CAPE

Abstract

A thunderstorm is an extreme atmospheric phenomenon belonging to the electrometeors. The geographical location of Poland, terrain, variable atmospheric circulation, transient climate, or the complexity of atmospheric processes define thunderstorms as a local phenomenon, conditioned by many variables. This results in significant variability in the number of thunderstorm days and lightning in Poland from year to year and throughout the year. Progressive climate change manifested by rising air temperatures affects the frequency and intensity of thunderstorms. Every year, the phenomena accompanying thunderstorms pose a real threat to human life and health and cause significant property damage. As with in the case of other meteorological phenomena, long-term monitoring is necessary to observe this type of phenomenon. This research is also necessary to understand the principles of the convective environment system, necessary for reconstructing the conditions of the atmosphere. Defining the parameters of the atmospheric state will enable better and more precise forecasting of such phenomena in the future. In order to define the convective environment generating the occurrence of cloud-to-ground (CG) lightning flashes in Poland, data from the from the PERUN lightning detection and localization system (IMGW-PIB) from 2002-2020. On this basis, the spatial-temporal distribution of CG flashes occurrence and the number of thunderstorm days in Poland were examined. A detailed analysis of days with increased electrical activity and the number of CG flashes generated was also carried out. On the basis of ERA5 (ECMWF) reanalyses, the parameters of the convective environment favorable for CG flashes were defined. A constant increase in the temperature of the globe also affects the convective environment, as presented by an apparent increase in the WMAXSHEAR parameter. As a result of the analysis, it was found that the changing climate affects the increase in the number of CG flashes and the number of thunderstorm days. The most favorable conditions for the development of Cumulonimbus clouds occur at a CAPE of about 1300 $J \cdot kg^{-1}$ and the simultaneous presence of wind shear of about 15 $m \cdot s^{-1}$ in the profile 0-6 km AGL. Additional factors supporting convection are the maintenance of a water vapor mixing ratio of 13 $g \cdot kg^{-1}$ and an air temperature of about 28-29°C and a dew point temperature exceeding 18°C. Maintaining and/or exceeding the values of the given parameters resulted in the occurrence, over the 2002-2020 period, of eight thunderstorm days during which more than 60.000 CG flashes/day occurred. Further increases in air temperature may contribute to an increase in the frequency and violence of thunderstorm events, also due to a significant weakening of the impact of the jet stream in mid-latitudes.

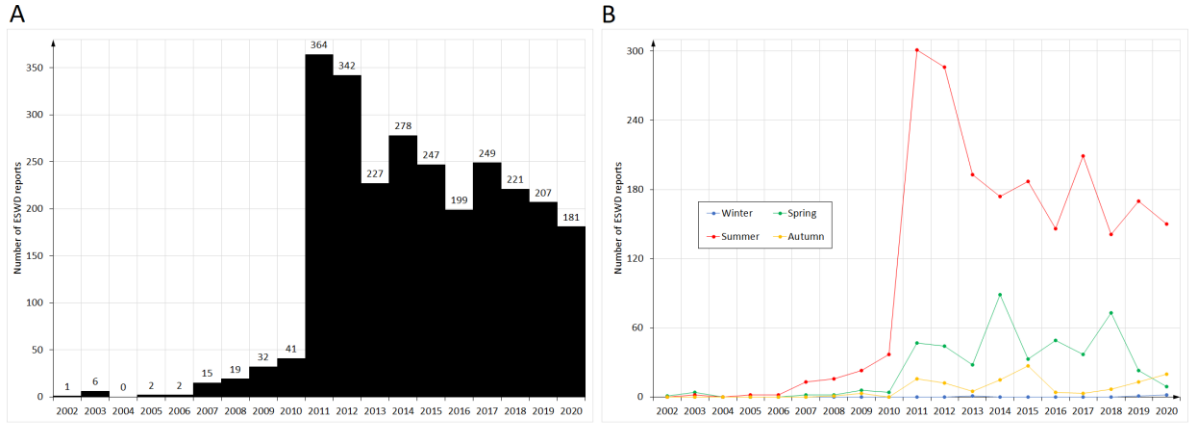
Keywords: thunderstorm, lightning, convection, CAPE

Motywacja podjęcia badań

Burze, jako zjawiska elektryczne, od zawsze fascynują ludzi. Pierwotnie utożsamiano je z obecnością bogów, a zwłaszcza ich gniewem. Wyładowania atmosferyczne pojawiające się prosto z nieba kojarzyły się głównie z boskimi atrybutami i karą wymierzoną za grzechy (Gieysztor 2006). Wynikiem burz były liczne pożary lasów, domów i miast, czy też lokalne podtopienia przez nawalne opady atmosferyczne powstające w chmurach *Cumulonimbus* (*Cb*). Burzom często towarzyszą opady gradu niszczące uprawy i sady. W dawnych zapiskach klasztornych można odnaleźć również wspomnienia o ciemnych lejach zstępujących z nieba i powodujących zniszczenia okolicznych zabudowań – trąby powietrzne. Współcześnie, dzięki stopniowemu rozwojowi metod i technik badawczych zjawisko burzy stało się tematem wielu rozpraw naukowych, lecz w dalszym ciągu nie wszystkie kwestie związane z tym fenomenem zostały w pełni wyjaśnione czy zbadane.

Definicja burzy zaproponowana przez Byersa i Brahama w 1949 jest nadal aktualna. Według *Glossary of Meteorology* jest to zjawisko meteorologiczne związane bezpośrednio z obecnością chmury typu *Cumulonimbus* (*Cb*) i objawiające się zawsze w postaci wyładowań atmosferycznych. Dodatkowymi zjawiskami współtowarzyszącymi burzom są często krótkotrwałe, lecz silne porywy wiatru, nawalne opady deszczu, czy też opady gradu. W chmurach *Cb* powstaje również tornado/trąba powietrzna, zjawisko relatywnie rzadko występujące w Polsce. Podobna definicja burzy zawarta jest w *Słowniku Meteorologicznym* Instytutu Meteorologii i Gospodarki Wodnej (2003), która jasno stanowi, że wystąpienie tego zjawiska jest związane z chmurami *Cb* i wyładowaniami atmosferycznymi oraz zjawiskami akustycznymi, w postaci grzmotu. Burze dzielimy na wewnątrzmasowe, powstające w gorącej, wilgotnej i chwiejnej masie powietrza oraz frontowe, tworzące się zwłaszcza na chłodnym froncie atmosferycznym. Jednak złożoność procesów zachodzących w troposferze podczas inicjacji konwekcji i rozwoju chmur *Cb* wymaga szczegółowych badań parametrów sprzyjających powstawaniu komórek burzowych.

Każdego roku w całej Europie burze powodują szkody o wartości milionów euro, a tylko w Polsce w latach 2002-2020 w wyniku uderzeń piorunów zginęło 50 osób, a 408 zostało rannych. Dzięki systemowi European Weather Observer (EWOB) zarządzanemu przez European Severe Storms Laboratory (ESSL) zbierane są dane o różnego rodzaju ekstremalnych zdarzeniach pogodowych. Raporty pokazane na ryc. 1A i 1B odzwierciedlają wystąpienie zjawiska definiowanego w tej bazie jako „niszczycielskie wyładowania atmosferyczne", które powodują znaczne i rozległe szkody materialne.



__Rycina 1.__ A – Liczba raportów o niszczycielskim wyładowaniu atmosferycznym dla obszaru Polski pochodząca z bazy danych o niebezpiecznych zjawiskach atmosferycznych ESWD. B – Liczba raportów ESWD w podziale na pory roku.

Na częstość i siłę ekstremalnych zjawisk pogodowych wpływa rosnąca temperatura na kuli ziemskiej. Wraz z postępującym globalnym ociepleniem wzrastają zasoby energii w atmosferze. W Polsce w latach 1966-2018 wzrost temperatury powietrza osiągnął 0.33°C na dekadę. Najszybciej wzrost temperatury postępuje na obszarze centralnej i zachodniej części kraju (Kejna i Rudzki, 2021). Ocieplenie występuje we wszystkich porach roku, a zwłaszcza latem i zimą (Ustrnul i in. 2021). Stąd też jakże aktualne stają się badania ekstremalnych zjawisk atmosferycznych, w tym określenie warunków termodynamicznych i kinematycznych atmosfery, które inicjują gwałtowne burze z wyładowaniami doziemnymi (Allen, 2018). W badaniach nad zmiennością przestrzenno-czasową wyładowań atmosferycznych niezbędny jest rozwój nowych metod i technologii pozwalających na ich detekcję. Ponadto wymagane są badania stanu termodynamicznego atmosfery, a zwłaszcza troposfery, gdzie następuje inicjacja konwekcji i rozwój komórek burzowych. Dane te są dostępne w czasie rzeczywistym, jednak ciągle nie są wystarczające, aby skutecznie prognozować pojawianie się burz i ostrzegać ludność przed zagrożeniem. Konieczne jest również zastosowanie numerycznych modeli meteorologicznych oraz reanaliz stanu atmosfery.

Stan dotychczasowych badań

Początkowo badania burz prowadzono na podstawie danych ze stacji synoptycznych, na których odnotowywano fakt pojawienia się burzy poprzez zaobserwowanie wyładowania atmosferycznego lub/i usłyszenie grzmotu. Na tej podstawie wydzielano dni z burzą. Metodyka ta jest stosowana również współcześnie w sieci Instytutu Meteorologii i Gospodarki Wodnej PIB (IMGW). Obserwacje tego typu umożliwiły prowadzenie badań w zakresie klimatologii burz na terenie Polski. Pierwsze prace powstały dopiero w latach 90. XX wieku i dotyczyły rozkładu przestrzennego dni z burzą (Kolendowicz, 1996; Bielec, 1998, 2002, Bielec-Bąkowska, 2013). Zwrócono uwagę na cyrkulacyjne uwarunkowania występowania burz (Kolendowicz, 1997, 1998, 2005, Bielec-Bąkowska, 2012, Kolendowicz i in., 2017). Analizowano przy tym zmiany częstości i tendencje występowania burz w Polsce (Bielec-

Bąkowska, 2002, 2003, 2013, Bielec-Bąkowska i in., 2021). Najdłuższą serię obserwacyjną (od 1901 r.) posiada Kraków (Bielec-Bąkowska i in., 2021).

Wraz z rozwojem technologicznym, a zwłaszcza metod teledetekcyjnych, zwiększyły się możliwości badania burz. Informacje o lokalizacji wyładowań atmosferycznych pochodzące z systemów teledetekcyjnych umożliwiły rozpoczęcie kolejnego etapu badań nad burzami. Na świecie szczegółowo badano te zjawiska w Stanach Zjednoczonych m.in. Koehler (2020), (Taszarek i in., 2020) oraz w Europie (Taszarek i in., 2019). Dla Europy powstało szereg opracowań regionalnych. Dla południowej Europy m.in. Biron i in., 2009, Feudale i in., 2013; Kotroni i Lagouvardos 2016, w tym dla Półwyspu Iberyjskiego Santos i in., 2012 czy Soriano i in., 2005. Dla Europy środkowej badania prowadzili Betz i in., 2009; Schulz i in., 2005; Wapler 2013; Novák i Kyznarová, 2011. Dla Europy północnej Enno 2011; Mäkelä i in., 2011; Pohjola i Mäkelä, 2013. Również dla obszaru Polski powstało szereg prac, np. Taszarek i in., 2015; Bielec-Bąkowska i in., 2021; Sulik 2022; Sulik i Kejna, 2023. Analizie poddawane zostały również mniejsze jednostki terytorialne, takie jak województwo kujawsko-pomorskie (Sulik i Kejna, 2022). Na świecie bada się również wyładowania atmosferyczne na terenie metropolii miejskich (Wu i in., 2016). W badaniach wyładowań atmosferycznych wykorzystywano informacje pochodzące z różnych systemów detekcyjnych. Analizy prowadzono w różnym zakresie czasowym i przestrzennym. Najczęściej wybieranym polem podstawowym była siatka złożona z kwadratów o wymiarach 1 km x 1 km, 5 km x 5 km, 10 km x 10 km, 20 km x 20 km, 0.1° x 0.1° czy też 0.2° x 0.2°. Ponadto w badaniach próbowano określić determinanty wpływające na formowanie się chmur burzowych, wykorzystując reanalizy meteorologiczne (ERA5) do określenia parametrów konwekcji (Taszarek i in., 2021).

Cel badań

Głównym celem zrealizowanych badań była analiza czasowo-przestrzenna wyładowań atmosferycznych w Polsce oraz określenie parametrów konwekcyjnych termodynamicznego stanu atmosfery generujących ich występowanie na terenie Polski. Analiza objęła zakres lat od 2002 do 2020.

Biorąc pod uwagę stan dotychczasowej wiedzy oraz główny cel pracy postawiono poniższe hipotezy badawcze:

H1: na terenie Polski występuje zróżnicowanie przestrzenne wyładowań doziemnych uwarunkowane czynnikami geograficznymi,

H2: rozkład przestrzenny wyładowań atmosferycznych w Polsce pozytywnie koreluje z rodzajami pokrycia terenu,

H3: liczba wyładowań atmosferycznych wykazuje zmienność w ciągu roku,

H4: w latach 2002-2020 wzrost temperatury powietrza wpływa na liczbę wyładowań doziemnych oraz liczbę dni z burzą w Polsce,

H5: silne układy burzowe generujące podwyższone wartości wyładowań doziemnych mogą tworzyć się w środowisku umiarkowanego wskaźnika CAPE i relatywnie niskiego ścinania wiatru w warstwie 0-6 km AGL - DLS,

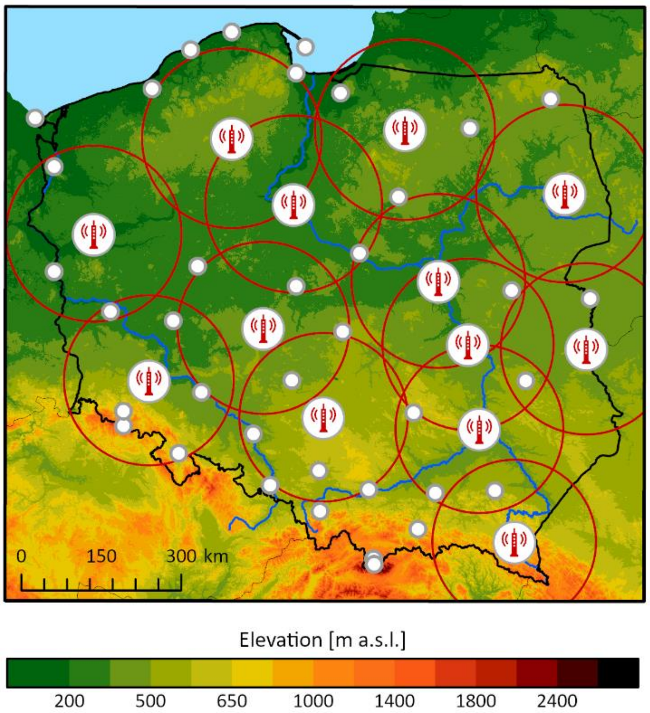
H6: obecność opadu gradu o średnicy do 2 cm świadczy o intensywności komórek burzowych i jest pozytywnie powiązana z ilością generowanych wyładowań doziemnych.

Bazy danych

Realizacja celu badań wymagała zgromadzenia danych ze specjalistycznych baz pochodzących z systemu detekcji i lokalizacji wyładowań atmosferycznych PERUN oraz raportów o liczbie dni z burzą ze stacji synoptycznych IMGW-PIB (raporty SYNOP). Do określenia parametrów termodynamicznych i kinematycznych wykorzystano reanalizy warunków meteorologicznych ERA5.

System PERUN (IMGW-PIB)

Działający w Polsce system detekcji i lokalizacji wyładowań atmosferycznych rozpoczął pracę w 2002 roku i początkowo składał się z kilku jednostek (masztów/detektorów), zlokalizowanych bezpośrednio przy stacjach synoptycznych na terenie kraju. Obecnie system składa się z 13 detektorów: Chojnice, Olsztyn, Toruń, Gorzów Wielkopolski, Legnica, Kalisz, Legionowo, Białystok, Kozienice, Włodawa, Częstochowa, Sandomierz oraz uruchomiony ostatnio detektor znajdujący się w Lesku (ryc. 2).



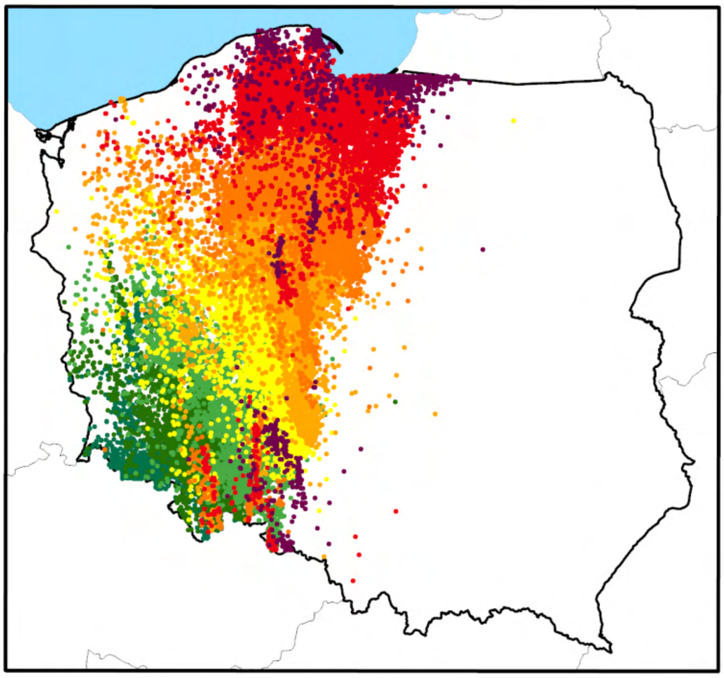
Rycina 2. *Mapa hipsometryczna Polski wykonana na podstawie Shuttle Radar Topography Mission Global Coverage (SRTM3; Farr i in. 2007). Białe punkty oznaczają lokalizację stacji synoptycznych Instytutu Meteorologii i Gospodarki Wodnej – Państwowego Instytutu Badawczego. Punkty z symbolem radaru oznaczają lokalizację masztów systemu detekcji i lokalizacji wyładowań atmosferycznych PERUN wraz z buforem o promieniu 100 kilometrów.*

System ten wchodzi w skład Europejskiego systemu detekcji SAFIR. W Polsce system ten nazwano PERUN od imienia słowiańskiego boga piorunów. System wykrywa i lokalizuje wyładowania atmosferyczne w podziale na doziemne (CG - cloud-to-ground lightning) oraz chmurowe (CC – cloud-to-cloud lightning). W ich detekcji wykorzystywane są fale elektromagnetyczne o niskich częstotliwościach oraz technika DF (ang. Direction Finding), która lokalizuje pozycję wyładowania na zasadzie triangulacji (Bodzak, 2006).

Dane o wykrytych i zlokalizowanych wyładowaniach atmosferycznych przesyłane są do siedziby głównej IMGW-PIB w Warszawie. Stopniowy rozwój i udoskonalanie całości systemu wiązał się z zapotrzebowaniem na zwiększenie dokładności detekcji wyładowań. Po wymianie czujników starszej generacji na detektory TLS200 firmy Vaisala udało się osiągnąć precyzję lokalizacji wyładowań w centralnej części kraju dochodzącą do 0.5 km. System PERUN dostarcza informacje o dacie i czasie wystąpienia wyładowania, jego współrzędne geograficzne w układzie WGS84, rodzaj wyładowania, krotność prądu w kanale natężenia wyładowania (kA). W niniejszej pracy wykorzystano dane o wyładowaniach doziemnych CG w podziale na przenoszony ładunek: dodatni, ujemny.

Stwierdzono, że w przypadku wyładowań międzychmurowych (CC) występują błędy w promieniu 16 kilometrów od lokalizacji masztu systemu detekcji. Dlatego też podjęto decyzję o analizie danych o wyładowaniach doziemnych (CG) w podziale na dodatnie i ujemne. Dodatkowo z bazy danych zawierającej informacje o wyładowaniach doziemnych usunięto rekordy o ładunku poniżej 10 kA ze względu na możliwość fałszywej detekcji przez system. Jak pokazało opracowanie Cumminsa i in. (1998) niektóre wyładowania doziemne tego natężenia mogą być wykrywane jako wyładowania międzychmurowe. Również wyładowania o ładunku ujemnym składające się z wielu uderzeń w to samo miejsce połączono pozostawiając jedynie pierwsze zarejestrowane wyładowanie doziemne. Ze względu na format współrzędnych (układ odniesienia WorldGeodeticSystem 84) przeliczono koordynaty do powszechnie używanego w Polsce układu odniesienia PUWG94 (układ metryczny). Całość procesów związanych z ujednoliceniem i finalnym przygotowaniem bazy danych o wyładowaniach została przeprowadzona za pomocą języka programowania Microsoft PowerShell oraz R (R Core Team, 2014), natomiast wizualizacje wykonano za pomocą oprogramowania ESRI ArcGIS PRO oraz RStudio.

W sumie w Polsce w latach 2002-2020 wystąpiło 8.626.200 takich wyładowań CG. Przykładową wizualizację wyładowań w dniu 11 sierpnia 2017 r. przedstawiono na ryc. 3. Wystąpiło w nim ponad 50 tysięcy wyładowań CG.



Rycina 3. *Wizualizacja zarejestrowanych przez system PERUN wyładowań doziemnych w dniu 11.08.2017 r. w przedziale godzinnym. Kolory odpowiadają interwałom 1-godzinnym (kolor zielony godzina 1500, kolor fioletowy godzina 2200). Opracowano na podstawie danych systemu PERUN.*

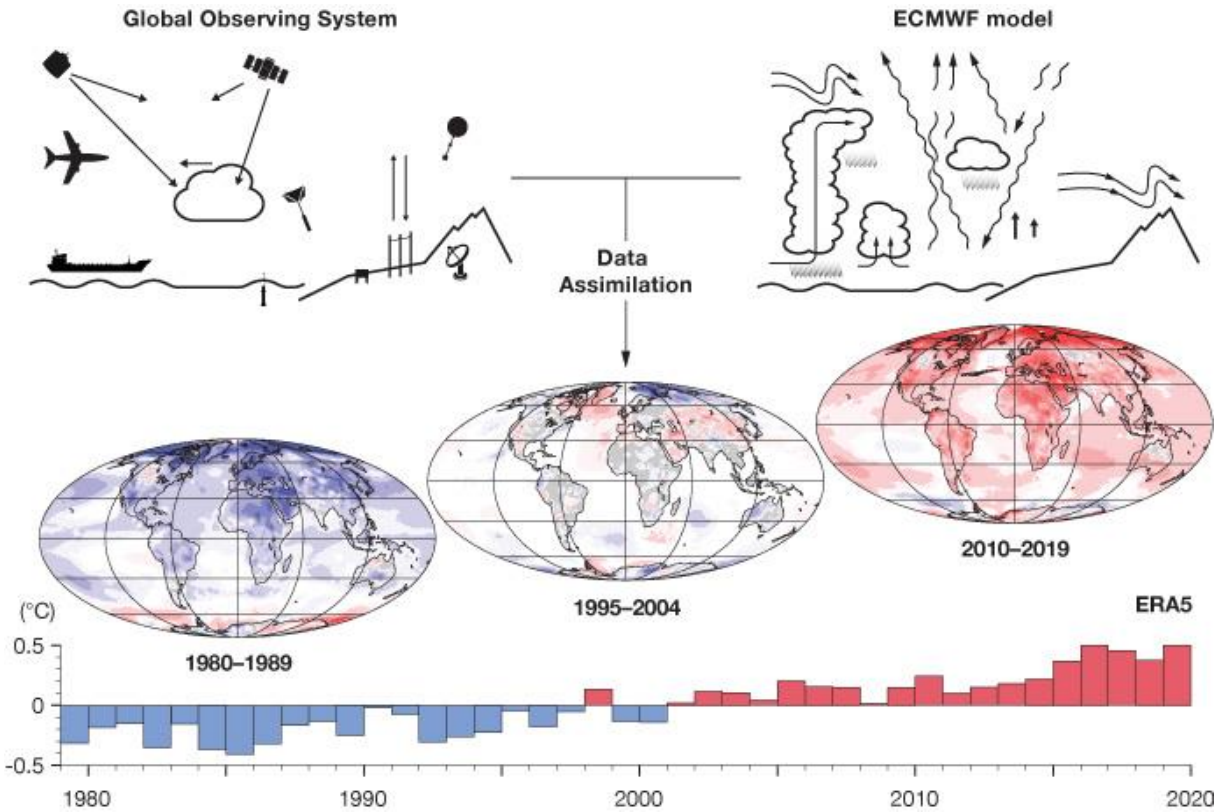
Raporty SYNOP (IMGW-PIB)

Obserwacje burz dokonywane na stacjach synoptycznych są obarczone dość dużym błędem. Wynika to między innymi z subiektywności oceny obserwatora. Na otwartym terenie, odległa burza widoczna jest z wielu kilometrów (szczególnie w nocy). Czynnikami ograniczającymi obserwację jest zakrycie horyzontu przez zabudowę, drzewa i wzniesienia w bliskim sąsiedztwie stacji czy miejski hałas (Lechner i Arns, 2013). Na obszarze Polski, na tego typu błędy szczególnie narażone są górskie obszary na południu. Systematyczne obserwacje prowadzone na stacjach synoptycznych IMGW-PIB zawierają informacje o liczbie dni z burzą oraz czasie ich trwania. Niestety nie wszystkie serie danych są homogeniczne, ze względu na przeniesienie stacji w inne miejsce, zmianę otoczenia i warunków obserwacji burz. Wystąpiły też przerwy w działalności kilku stacji lub też po wprowadzeniu pomiarów automatycznych zakończono obserwacje burz. W analizie liczby dni z burzą wykorzystano dane z 48 stacji synoptycznych IMGW (ryc. 2). Istotnym problemem badawczym było porównanie wyników z dwóch systemów pomiarowych SYNOP i PERUN.

Reanalizy meteorologiczne ERA5 (ECMWF)

Niezwykle przydatnym, wręcz niezbędnym narzędziem w rekonstrukcji warunków panujących w troposferze są modele matematyczne – reanalizy. Przy prognozowaniu głębokiej konwekcji najczęściej wykorzystywane są modele typu GFS (ang. Global Forecasting System), WRF (ang. Weather Research and Forecasting Model), ICON-EU (ang. ICOsahedral Nonhydrostatic), ECMWF (ang. European Centre for Medium Weather Forecasts), czy też SWISS.

Reanalizy meteorologiczne bazują głównie na wyliczeniach modelowych na kilka czy kilkanaście godzin w przód. Weryfikuje się ich poprawność na podstawie danych ze stacji meteorologicznych, sondowań aerologicznych, danych satelitarnych czy teledetekcyjno-telemetrycznych (ryc. 4).



__Rycina 4__. Schemat przygotowania reanaliz meteorologicznych produktu ERA5. Źródło: European Centre for Medium-Range Weather Forecasts.

W finalnym produkcie ERA5 wykorzystuje również korekcję zgodną z prawami fizyki w interwale co 1 godzinę (tab. 1).

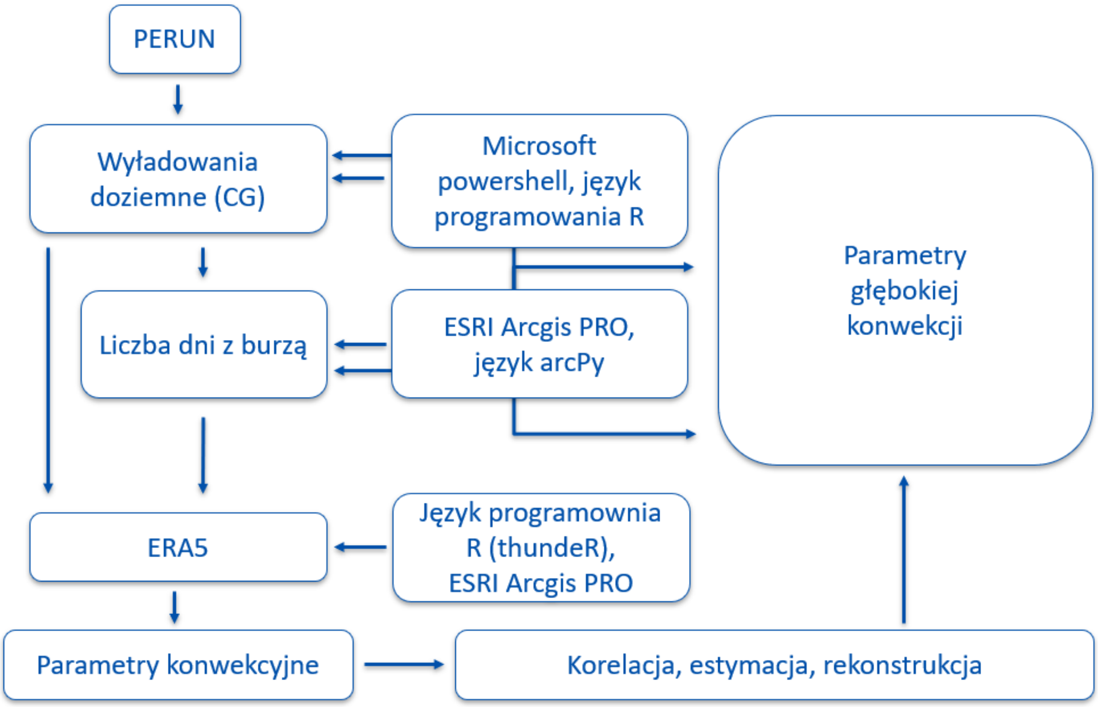
__Tabela 1.__ Parametry przestrzenno-czasowe reanalizy ERA5.

Typ danych	Grid
Rozmiar	0.25° x 0.25°
Odwzorowanie	długość-szerokość
Interwał czasowy	1-godzina
Pokrycie przestrzenne	Polska
Przedział czasowy	1940-2022 2002-2020
Liczba gridów	500 195
Szerokość geograficzna	48.75° - 55.25°
Długość geograficzna	13.75° - 24.50°

Produkt ten jest pochodną kompilacji wielu składowych: takich jak dane z naziemnych stacji meteorologicznych, dane satelitarne czy sondowania aerologiczne. Do procesu rekonstrukcji warunków panujących w troposferze podczas generowania przez chmurę *Cb* wyładowań CG wykorzystano reanalizy najnowszego do tej pory produktu jakim jest ERA5 (ECMWF) o zakresie przestrzennym 0.25° x 0.25° obejmującego w sumie 500 195 punktów grid.

Metodyka badań

Zgromadzony zasób danych umożliwił dogłębną analizę zarówno aspektów związanych z klimatologią wyładowań CG, jak i konkretnych przypadków wystąpienia burz generujących znacznie podwyższone wartości tych wyładowań. Schemat procedury badawczej wyładowań atmosferycznych PERUN zaprezentowano na ryc. 5.



Rycina 3. *Algorytm procedury badawczej w zakresie analiz teledetekcyjnych PERUN.*

Produktem wyjściowym były dane pochodzące z systemu PERUN. W pierwszym etapie prac należało wydzielić informacje o wyładowaniach (CG). Wyładowania międzychmurowe (CC) zostały celowo odrzucone ze względu na błędną detekcję przez system. Dodatkowo, z bazy usunięte zostały wyładowania o natężeniu 10 kA ze względu na prawdopodobieństwo błędu podczas detekcji. Kolejnym etapem było przekształcenie systemu odniesienia z zapisu dziesiętnego (WGS84) na metryczny (PUWG92). Prace wykonano za pomocą Microsoft PowerShell oraz języka programowania R.

Przygotowana baza składająca się z ponad 8 milionów punktów została poddana analizie klimatologicznej. Do tego celu wykorzystano siatkę grid składającą się z kwadratu o wymiarach 10 x 10 km. Obszar 100 km^2 został wybrany celowo ze względu na podobną rozdzielczość wcześniejszych opracowań w innych krajach Europy (Diendorfer, 2008). Jedynie dla województwa kujawsko-pomorskiego zmniejszono oczko siatki grid do wymiarów 5 x 5 km

[P2]. Zabieg ten zastosowano ze względu na relatywnie mały obszar badań. Klimatologię wyładowań CG dla Polski w podziale na poszczególne lata, miesiące czy ładunek (dodatni, ujemny) przedstawiono w odrębnym opracowaniu [P3]. Wykonano również analizę dni o odbiegającej od normy liczbie wyładowań CG. Wybrano osiem dni z burzą, podczas których wystąpiło więcej niż 60 tysięcy wyładowań w ciągu jednego dnia [P1].

Liczbę dni z burzą opracowano na podstawie danych obserwacyjnych (SYNOP) oraz danych detekcyjnych (PERUN). Konieczne przy tym było powiązanie percepcji ludzkiego organizmu w zakresie obserwacji burz z faktycznie występującymi wyładowaniami [P4]. Jako dzień z burzą przyjęto wystąpienie przynajmniej 1 wyładowania w rejonie stacji. W wyniku szeregu testów polegających na znalezieniu optymalnego bufora wokół stacji synoptycznej stwierdzono, że najlepszą zgodność pomiędzy obserwacjami SYNOP, a detekcją PERUN zapewnia bufor o promieniu 15 kilometrów. Porównano wyniki obserwacji i wystąpienie wyładowań na tym obszarze. W ten sposób, wykorzystując precyzyjne dane z systemu teledetekcyjnego, możliwe było ustalenie faktycznej liczby dni z burzą na obszarze Polski oraz określenie zmian w czasie i ich trendu w Polsce [P4]. Uwolniono się dzięki temu od ograniczeń związanych z obserwacjami stacjonarnymi, prowadzonymi bezpośrednio przez człowieka. Przy analizie liczby dni z burzą zastosowano z kolei siatkę o wymiarach 1 x 1 km.

W artykule [P5] przeanalizowano warunki kinematyczne oraz termodynamiczne występowania wyładowań doziemnych w Polsce. Wykorzystano przy tym wyniki reanaliz ERA5. Produkt ten zawiera rekonstrukcję rozmaitych wskaźników meteorologicznych na danym obszarze. ERA5 zawiera szczegółowe dane o poszczególnych parametrach na różnych poziomach izobarycznych, analiza tych parametrów umożliwia rekonstrukcję warunków konwekcyjnych w profilu pionowym troposfery. Na potrzeby szczegółowej analizy przeanalizowano ponad 500 tysięcy gridów.

Procesy fizyczne zachodzące w atmosferze potrzebne do inicjacji burz i ich późniejszego rozwoju są skomplikowane, a do ich oceny niezbędne są odpowiednie wskaźniki. Pierwotne dane z reanaliz przekształcono za pomocą wzorów matematycznych.

Wskaźnik CAPE (ang. Convective Available Potential Energy) określa energię dostępną drogą konwekcji, wyliczono go ze wzoru:

$$CAPE = \int_{zf}^{z_n} g\left(\frac{T_{v_{parcel}} - T_{v_{environment}}}{T_{v_{environment}}}\right) dz$$

CAPE jest wyrażany w J/kg. Dodatnie wartości tego wskaźnika określają potencjalną zdolność do pojawienia się konwekcji w przypadku jej inicjacji. CAPE jest wskaźnikiem określającym niestabilność atmosfery, w przypadku gdy parcela powietrza jest cieplejsza od otoczenia, a więc posiada zdolność do wznoszenia. Znacznik Z_n we wzorze oznacza poziom swobodnej konwekcji, natomiast Z_f wysokość do której zdolna jest wypiętrzyć się potencjalna komórka burzowa. CAPE określa chwiejność atmosfery za pomocą temperatury wirtualnej w odniesieniu do temperatury otoczenia uwzględniając siłę grawitacji. W ten sposób numeryczne modele pogody wyznaczają parametry, które niezbędne są do późniejszego oszacowania warunków termodynamicznych panujących w atmosferze podczas wyładowań atmosferycznych. Parametr CAPE jest również jednym z podstawowych parametrów wykorzystywanych w prognozowaniu burz. W niniejszym opracowaniu wykorzystano również szereg innych wskaźników niezbędnych do zrozumienia przebiegu procesów podczas tworzenia chmury *Cb* i generowania wyładowań atmosferycznych (tabela 2).

Tabela 2. *Parametry i wskaźniki meteorologiczne użyte w opracowaniu.*

Skrót	Opis	Jednostka
MUCAPE	Potencjalna energia dostępna drogą konwekcji	$J \cdot kg^{-1}$
MUCIN	Zahamowanie konwekcji	$J \cdot kg^{-1}$
MULI	Indeks wyniesienia	K
MUMIXR	Stosunek zmieszania pary wodnej	g/kg
MUHGT	Wysokość geopotencjału	m AGL
MUWMAXSHEAR	Wskaźnik energii konwekcyjnej oraz jednoczesna wartość ścianania wiatru w profilu 0-6 km. Formuła zaimplementowana przez Taszarek i in. (2017)	m^2/s^2
ISO 0 H	Izobara 0°C	m AGL
PW	Szacowana zawartość wilgoci w troposferze	mm
BSEFF	Ścinanie wiatru na odcinku 0-6 km	$m \cdot s^{-2}$
HSI	Indeks rozmiaru gradu zaimplementowany przez Czernecki i in. (2019)	cm
T2M	Temperatura powietrza na wysokości 2 m	°C
TD2M	Temperatura punktu rosy na wysokości 2m	°C
CP	Opad konwekcyjny	$mm \cdot h^{-1}$

Wyniki badań

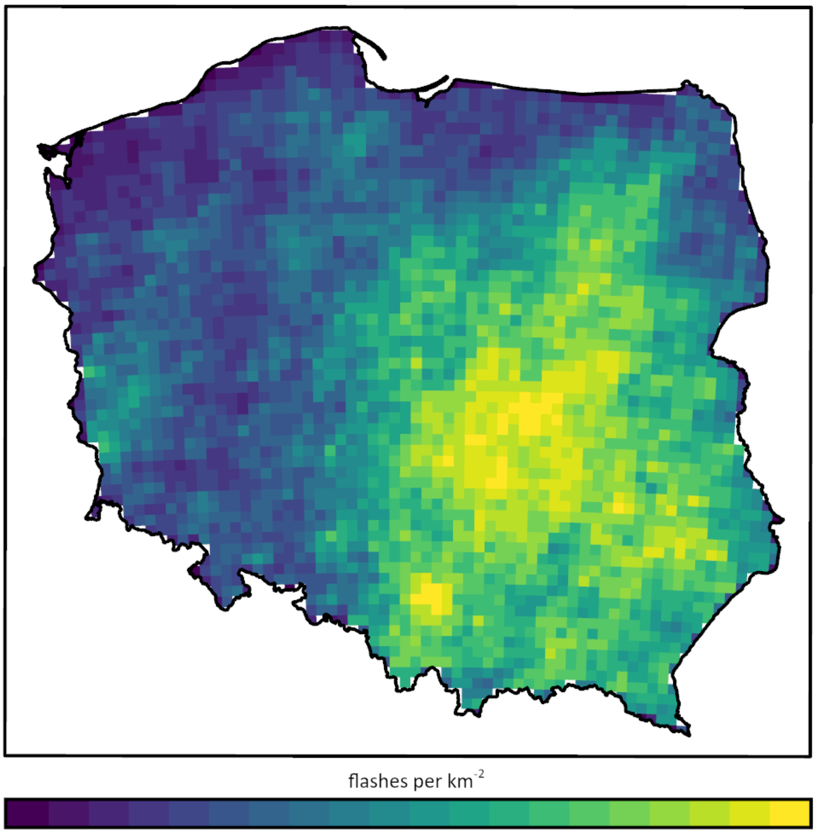
W niniejszej rozprawie doktorskiej, autoreferat zawiera zbiór pięciu publikacji tworzących logiczny ciąg badawczy. W pierwszym artykule [P1] przeanalizowano czynniki wpływające na aktywność elektryczną atmosfery w Polsce w wybranych dniach. Następnie zbadano zróżnicowanie przestrzenne wyładowań doziemnych na przykładzie województwa kujawsko-pomorskiego [P2]. W kolejnym artykule [P3] przeanalizowano częstość wyładowań CG w warunkach zmieniającego się klimatu. Istotne w dalszych badaniach było powiązanie dotychczasowych serii obserwacyjnych burz (SYNOP) z danymi detekcyjnymi wyładowań atmosferycznych (PERUN) [P4]. Warunki tworzenia chmur burzowych oraz towarzyszących im wyładowań atmosferycznych przeanalizowano w artykule [P5].

Najważniejsze wyniki badań przedstawiono z podziałem na kilka problemów badawczych.

Rozkład przestrzenno-czasowy wyładowań CG i liczby dni z burzą

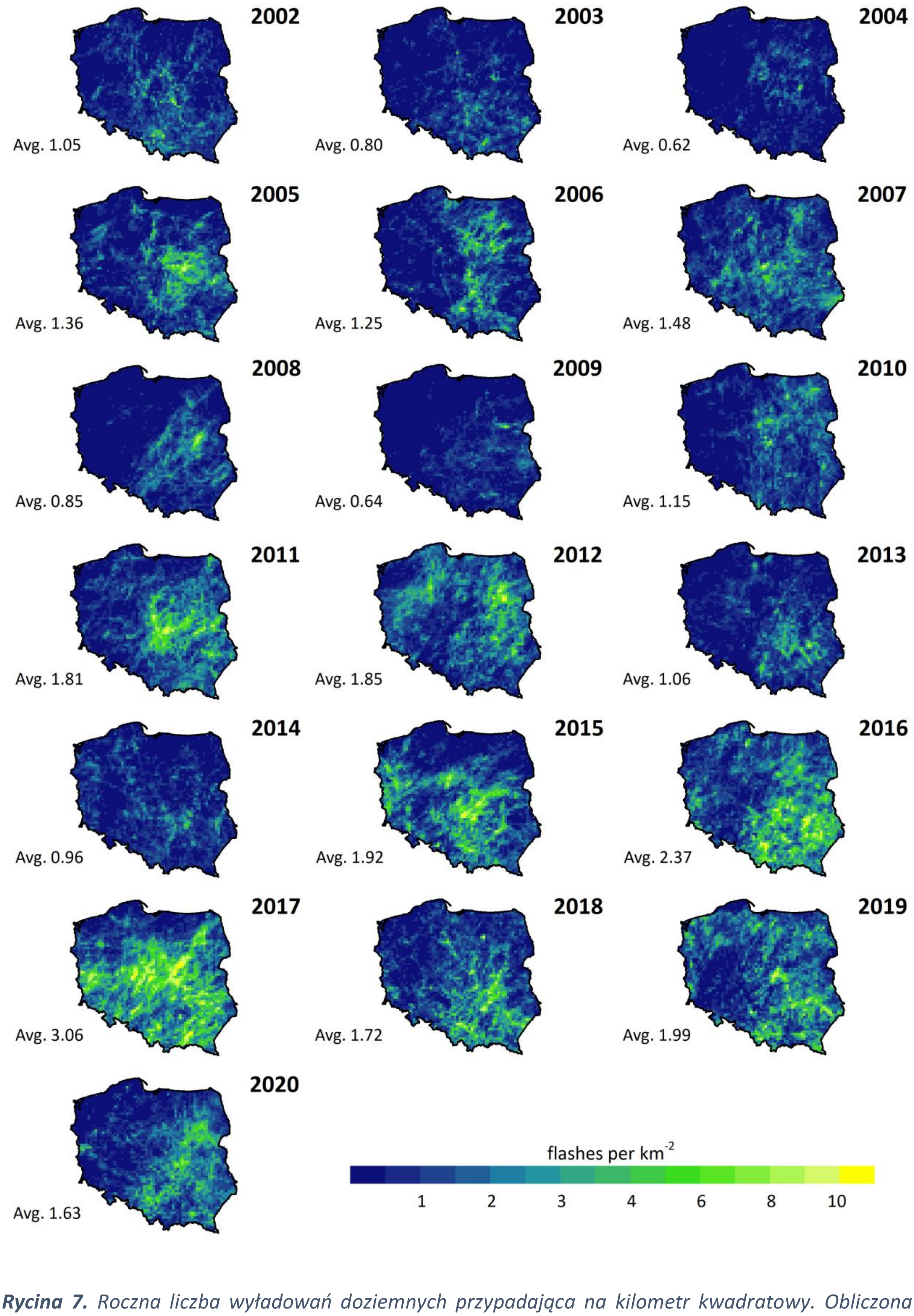
W latach 2002-2020 na obszarze Polski zarejestrowanych zostało przez system PERUN ponad 8 milionów wyładowań CG [P3]. Największa ich koncentracja przypadała na obszary

Mazowsza, Lubelszczyzny oraz Górnego Śląska (ponad 3 wyładowania na 1 km^2). Najmniejszą liczbę wyładowań odnotowano natomiast na wybrzeżu Morza Bałtyckiego oraz w zachodniej i północnej Polsce, w niektórych gridach <0.5 wyładowania na 1 km^2 (ryc. 6).



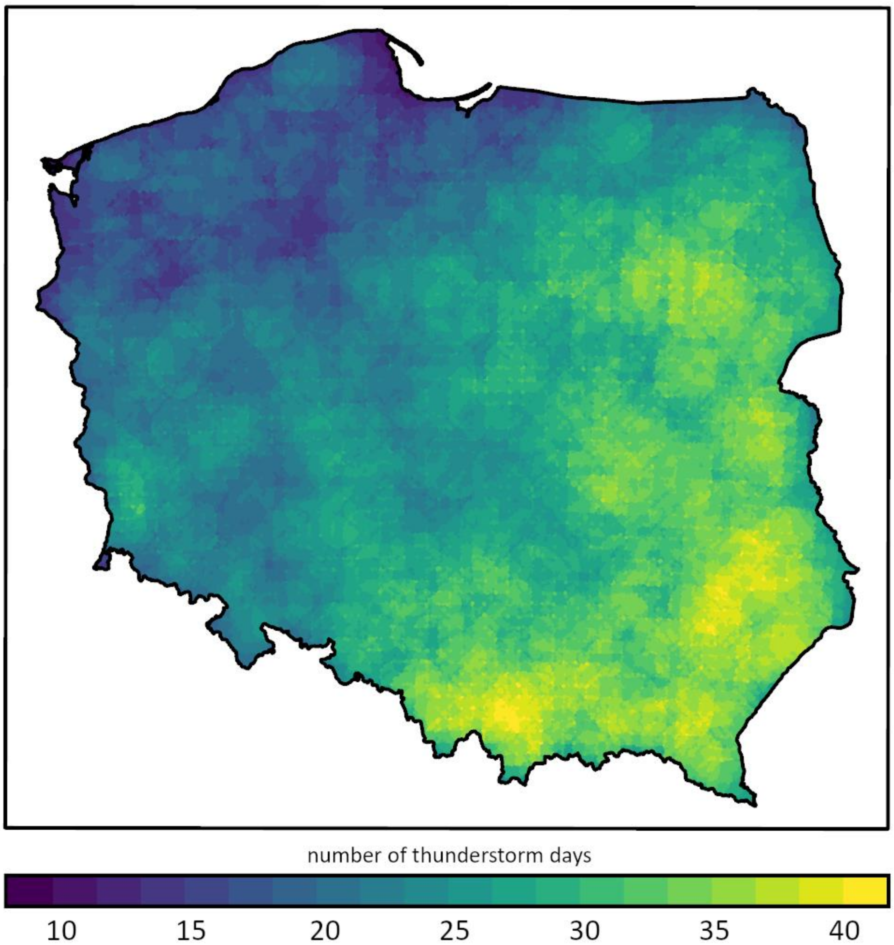
Rycina 4. *Średnia roczna liczba wyładowań doziemnych przypadająca na kilometr kwadratowy. Obliczona w siatce grid o wymiarach 10 x 10 km dla lat 2002-2020. Opracowano na podstawie danych PERUN.*

Stwierdzono przy tym znaczne zróżnicowanie rozkładu przestrzennego wyładowań CG z roku na rok. Związane jest to z położeniem i rodzajem ośrodków barycznych, rodzajem mas powietrza oraz frontami atmosferycznymi, które determinują warunki termodynamiczne i kinematyczne w troposferze oraz warunki sprzyjające rozwojowi chmur burzowych i zjawisk elektrycznych. Fronty atmosferyczne oraz napływ niestabilnej masy powietrza, szczególnie w ciepłej porze roku, zwiększa prawodopodobieństwo wystąpienia burz. Na przestrzeni lat 2002-2020 wystąpiły lata o mniejszej aktywnosci atmosfery, np. 2002-2004, 2009 i 2014 (ryc. 7). Na rozkład przestrzenny wyładowań istotny szczególny wpływ wywierają pojedyncze epizody rozwoju komórek burzowych w postaci mezoskalowych układów konwekcyjnych [P1]. Szczególnie w okresie letnim burze mogą generować nie tylko nawalne opady deszczu, ale również silne porywy wiatru wzdłóż linii szkwałów i ogromną liczbę wyładowań elektrycznych. Przykładem może być rok 2017, w którym to system PERUN zarejestrował w dniach 10 i 11 sierpnia łącznie ponad 200 tysięcy wyładowań doziemnych.



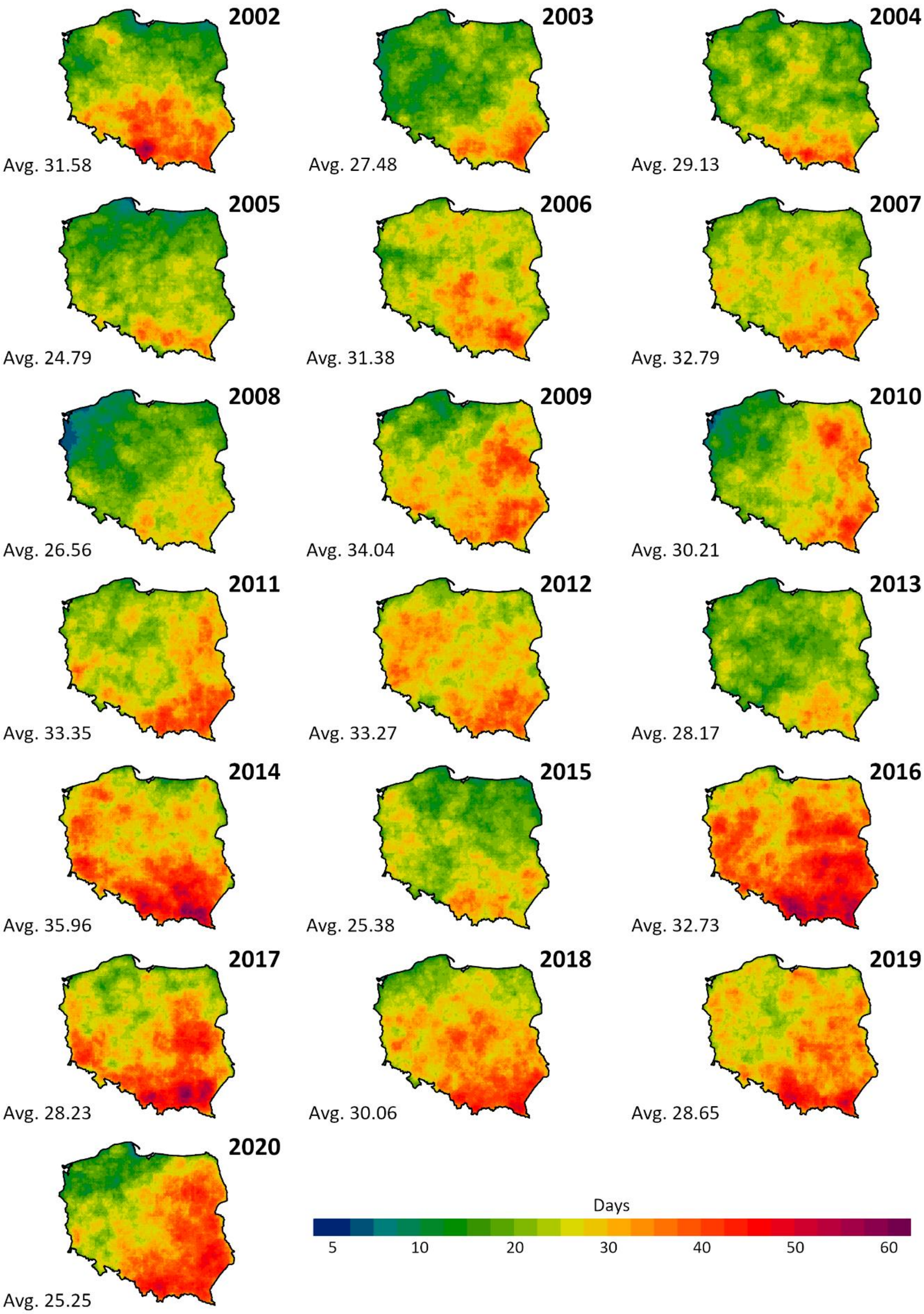
Rycina 7. *Roczna liczba wyładowań doziemnych przypadająca na kilometr kwadratowy. Obliczona w siatce grid o wymiarach 10 x 10 km dla lat 2002-2020. Opracowano na podstawie danych PERUN.*

Liczba dni z burzą uzyskana na podstawie detekcji wyładowań atmosferycznych jest większa w porównaniu do obserwacji prowadzonych w sieci SYNOP (IMGW-PIB). Jak wykazała analiza każdego roku na obszarze Polski występuje około 160 dni z burzą, oczywiście nie pojawiają się one jednocześnie w całym kraju. Natomiast średnia liczba dni z burzą wykazuje znaczne zróżnicowanie przestrzenne, wzrasta w kierunku południowo-wschodnim od mniej niż 10 dni na wybrzeżu Morza Bałtyckiego po ponad 40 dni w Karpatach [P4]. Więcej dni z burzą występuje we wschodniej niż zachodniej części kraju, co wiąże się z narastającym kontynentalizmem klimatu (ryc. 8).



Rycina 8. *Średnia liczba dni z burzą w latach 2002-2020. Obliczona w siatce grid o wymiarach 1 x 1 km z buforem 15 kilometrów ze środka komórki grid. Opracowano na podstawie danych PERUN.*

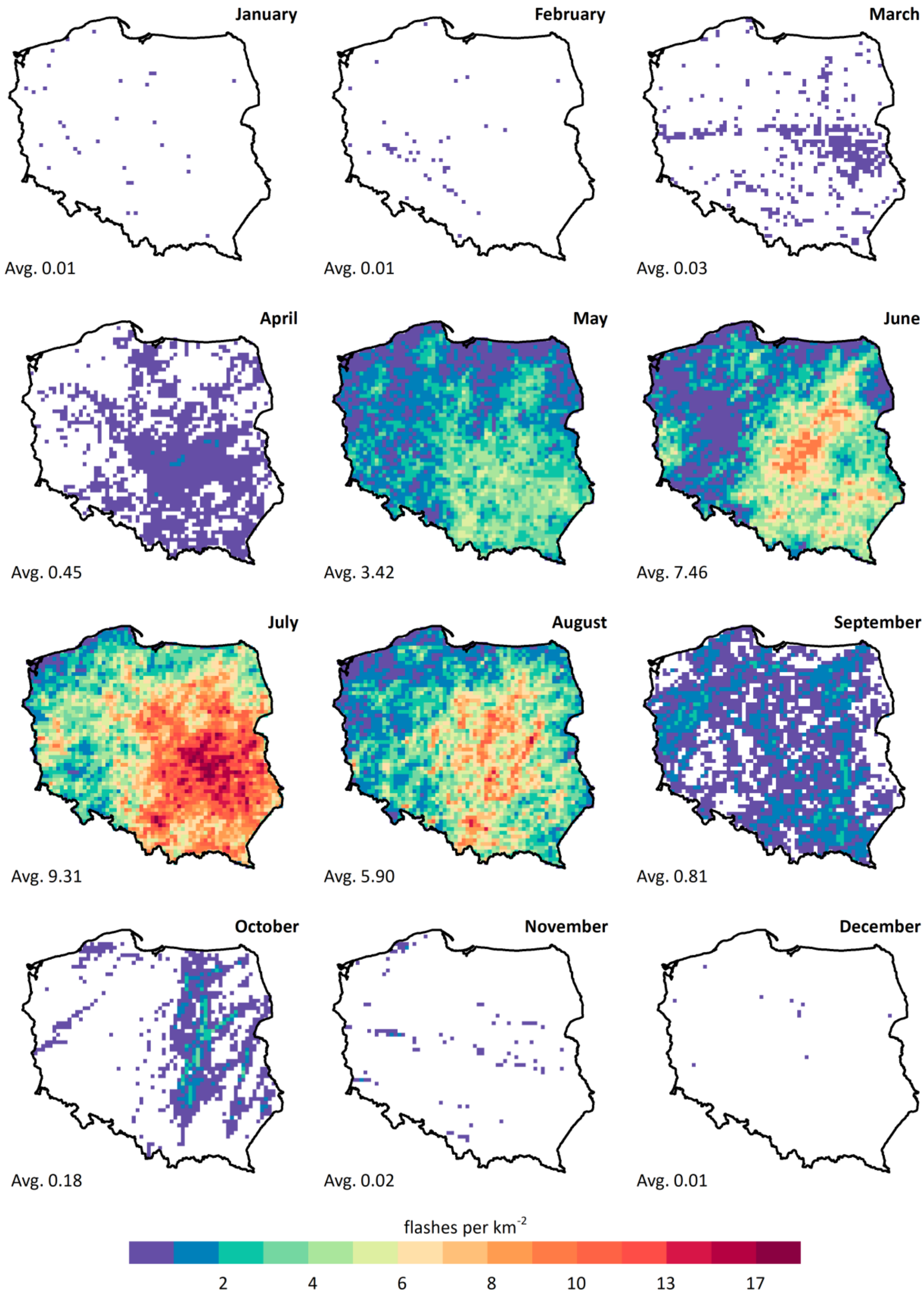
Również liczba dni z burzą na obszarze Polski wykazuje dużą zmienność z roku na rok. Średnio w analizowanym okresie wystąpiło 30 dni z burzą, wartość ta zmieniała się od 25.3 dni w 2020 r. do 36.0 dni w 2014 r. (ryc. 9). Jednak rozkład przestrzenny tego zjawiska charakteryzuje się dużą powtarzalnością w kolejnych latach [P4]. Występują przy tym znaczne różnice między poszczególnymi rejonami kraju np. w 2016 i 2017 r. od <10 dni na NW Polski do 60 dni z burzą na SE kraju.



***Rycina 9**. Roczna liczba dni z burzą obliczona na podstawie danych z systemu PERUN w latach 2002-2020.*

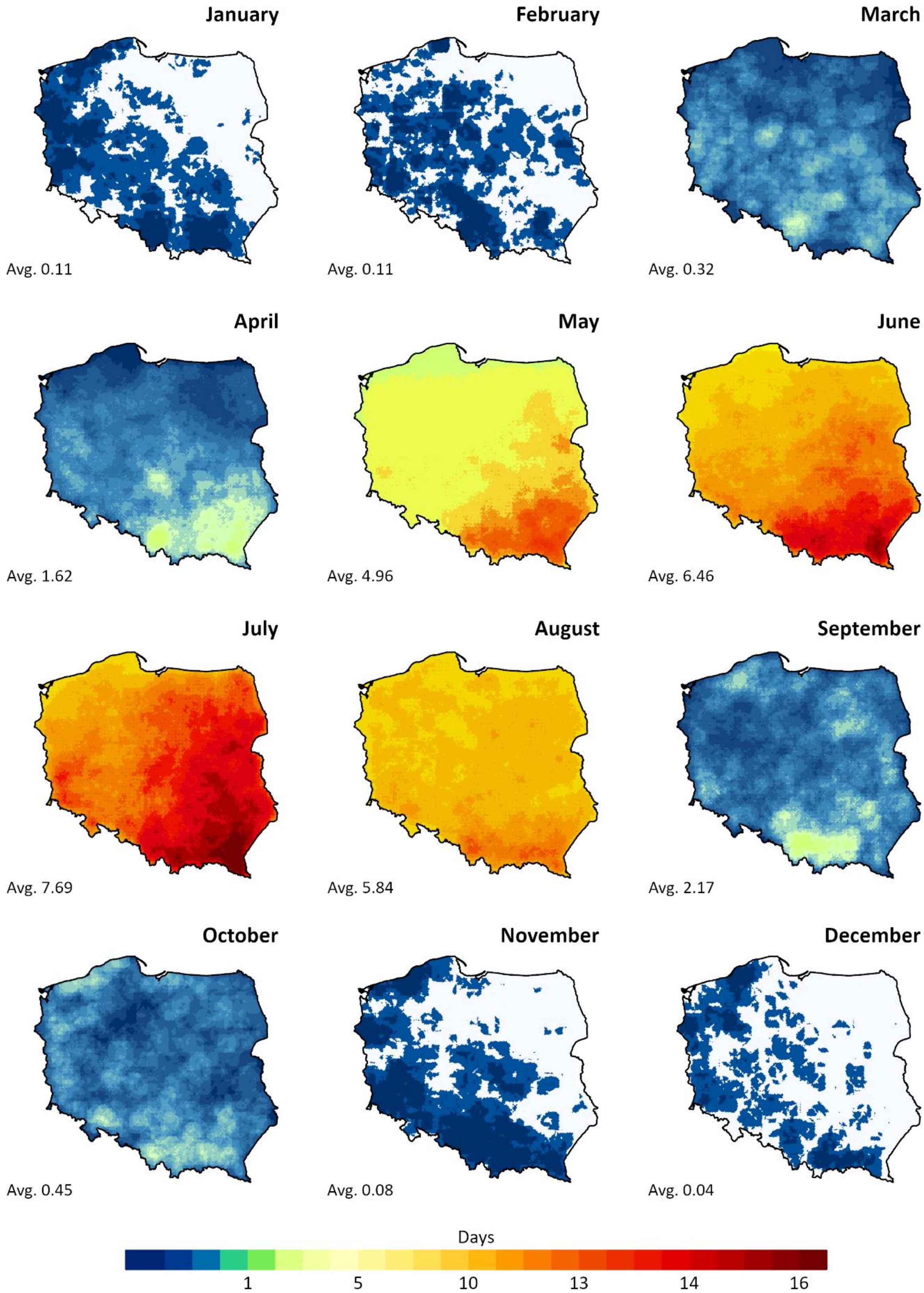
Przebieg roczny wyładowań CG i liczby dni z burzą

W przebiegu rocznym największa ilość wyładowań CG występuje wraz z początkiem cieplejszej połowy roku. W analizowanym okresie sezon burzowy w Polsce rozpoczynał się w maju i trwał do końca sierpnia. Przez pojęcie głównego sezonu burzowego można rozumieć wystąpienie średnio ok. 5 (i więcej) dni z burzą w danym miesiącu. W niektórych latach zdarzają się przypadki podwyższonej aktywności elektrycznej również we wrześniu. Pod względem potencjału do generowania wyładowań, najkorzystniejsze warunki występują w lipcu (ponad 17 wyładowań/km^2)[P3], natomiast w okresie jesienno-zimowym wyładowania CG występują sporadycznie (ryc. 10).



Rycina 5. *Średnia miesięczna liczba wyładowań CG przypadająca na kilometr kwadratowy. Obliczona w siatce grid o wymiarach 10 x 10 km dla lat 2002-2020. Opracowano na podstawie danych PERUN.*

Burze w Polsce występują o każdej porze roku. Na podstawie analizy liczby dni z burzą (dane SYNOP i PERUN) potwierdzono, że w latach 2002-2020 główny sezon burzowy rozpoczyna się już w maju (średnio 5 dni z burzą) i trwa zazwyczaj do końca sierpnia/początku września (ryc. 11). Najwięcej dni z burzą występuje w lipcu, średnio 7.9 dni [P4]. W okresie jesienno-zimowym burze występują sporadycznie i są związane zazwyczaj z frontami atmosferycznymi lub adwekcją powietrza arktycznego/polarno-morskiego o znacznej chwiejności. Jako główny kierunek napływu powietrza można wskazać sektor zachodni (typ cyrkulacji SEo, SWo, SWc i NWc) oraz południowo-zachodni (typ cyrkulacji Nc, Wc, NWc)(Kolendowicz, 1996).



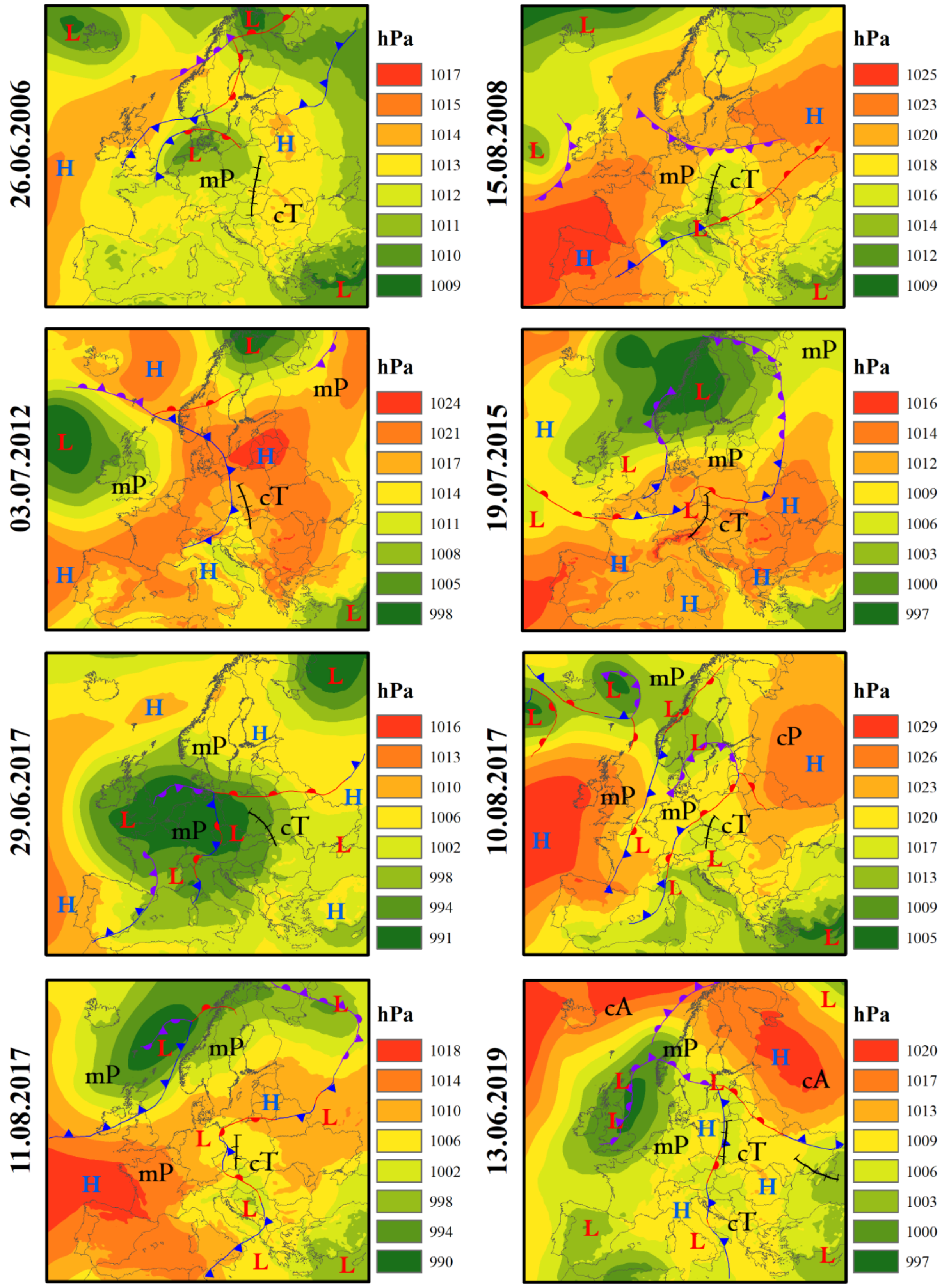
Rycina 6. *Średnia miesięczna liczba dni z burzą obliczona na podstawie danych z systemu PERUN w latach 2002-2020.*

Dni o szczególnej aktywności elektrycznej komórek burzowych

Powstawanie burz i zjawisk im towarzyszących jest związane z wieloma czynnikami. Jak wykazały badania Bielec (1998) i Kolendowicza (2006) istotne znaczenie ma położenie ośrodków barycznych oraz sterowana nimi cyrkulacja atmosferyczna. Stwierdzono zwiększoną częstość burz przy cyrkulacji północno-zachodniej oraz antycyklonalnej. W niniejszej rozprawie przeanalizowano warunki panujące w atmosferze dla 8 dni z wysoko aktywnymi elektrycznie burzami, o sumie dobowej wyładowań CG powyżej 60 tysięcy [P1]. Stwierdzono, że:

- Rozkład przestrzenny wyładowań CG w czasie burz o dużym potencjalne generowania wyładowań na obszarze Polski nie jest stały, występowały one w różnych regionach kraju;
- Najczęściej takie wysoko energetyczne burze występowały od czerwca po sierpień;
- Wysoko aktywne elektrycznie burze mogą powstawać w ciągu zarówno dnia, jak i w nocy, nie ma uprzywilejowanej pory doby;
- Burze te były inicjowane głównie przez chłodny front atmosferyczny w układzie niskiego ciśnienia;
- Wszystkie analizowane przypadki burz przemieszczały się z południowego-zachodu na północny-wschód;
- Przed bezpośrednim wystąpieniem burz występował znaczny gradient termiczny, zarówno na wysokości 2 m, jak i na poziomie 850 hPa;
- Wysoko aktywne elektrycznie formy burzowe mogą rozwijać się z środowisku umiarkowanych wartości CAPE i ścinania wiatru.
- Roczna liczba dni z burzą na obszarze Polski nie odzwierciedla intensywności zjawisk elektrycznych w pojedynczych dniach.

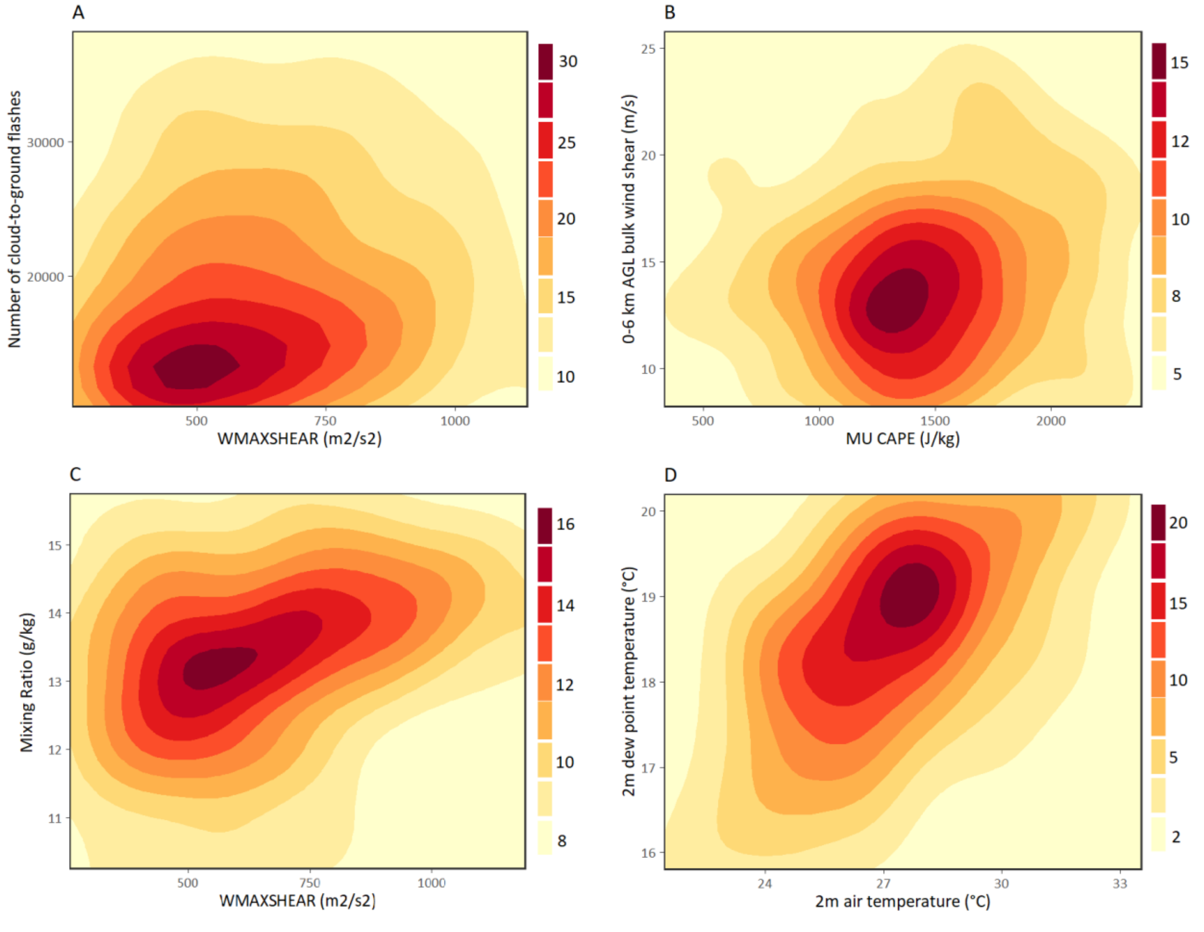
Analizowane formacje silnie rozbudowanych układów burzowych związane były z ośrodkami niskiego ciśnienia w rejonie Morza Północnego oraz przemieszczającą się ostrą zatoką niskiego ciśnienia nad Polską (ryc. 12). Dominował przy tym napływ ciepłego i zarazem wilgotnego powietrza z południa i południowego-zachodu. Jak zauważył Kolendowicz (1996), za sprzyjające warunki powstawania burz latem można uznać wszystkie typy cyrkulacji należących do kierunków S i SW. W atmosferze wystąpiły zwiększone wartości ścinania wiatru w warstwie 0-6 km z jednoczesnym wzrostem wyładowań w tej strefie. Ścinanie wiatru w profilu pionowym 0-3 km o wartościach 15 $m \cdot s^{-1}$ również stwarzało bardzo korzystne warunki dla tworzenia się mezoskalowych układów konwekcyjnych, nawet przy niezbyt wysokich wartościach CAPE. Istotną rolę odgrywają również warunki wilgotnościowe, stwierdzono podwyższone wartości pary wodnej (PW > 40 mm) oraz stosunek jej zmieszania na poziomie 14 $g \cdot kg^{-1}$.



Rycina 7. *Mapy synoptyczne wykonane na potrzeby analizy wystąpienia konkretnych przypadków silnych burz dla godziny 0000 UTC. Wartości ciśnienia atmosferycznego oparto o dane ERA5.*

Warunki kinematyczno-termodynamiczne tworzenia chmur burzowych

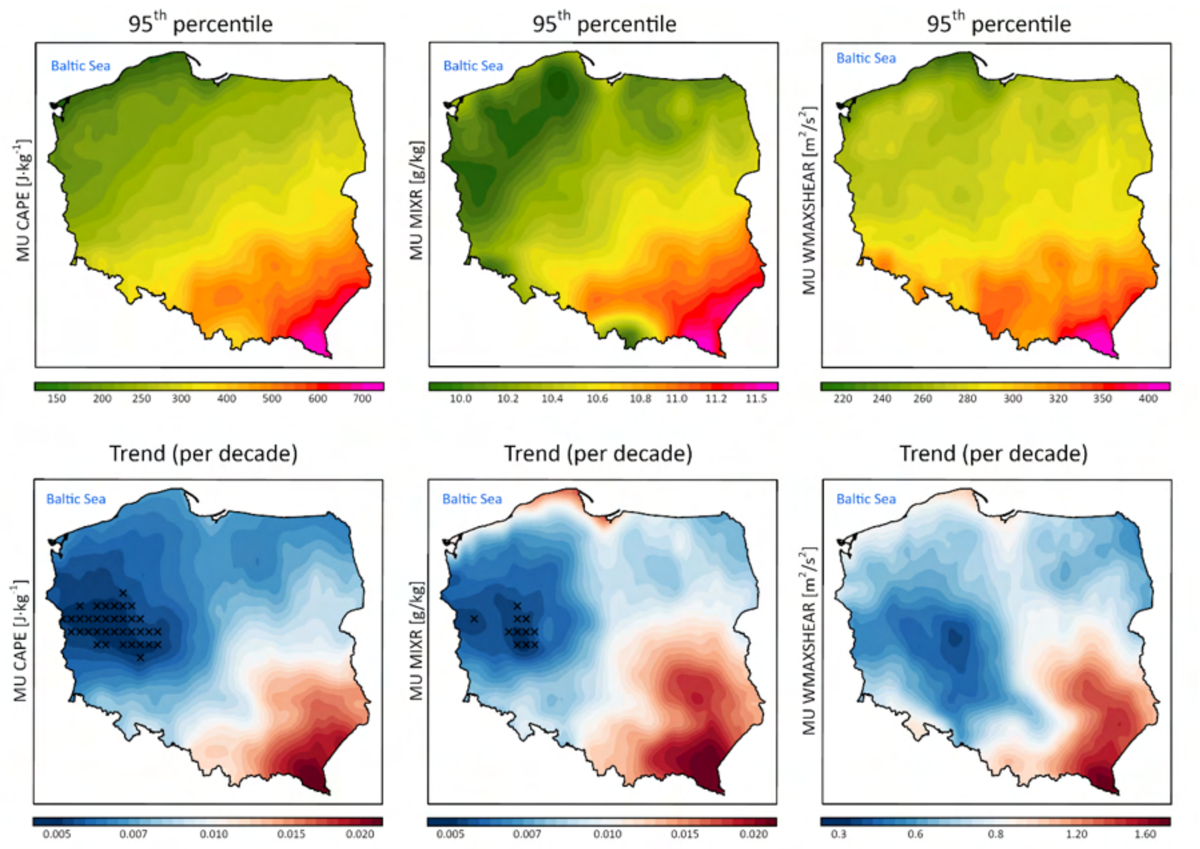
Inicjacja konwekcji jest czynnikiem niezbędnym do stworzenia zalążka chmury burzowej [P5]. W procesie dynamicznej rozbudowy komórki burzowej istotnym parametrem jest energia konwekcji, prędkość ścinania wiatru oraz stosunek zmieszania pary wodnej zawartej w powietrzu. W warunkach klimatu umiarkowanego ciepłego optymalne warunki do generowania przez chmury burzowe wyładowań doziemnych występują, gdy parametr WMAXSHEAR wynosi ok. 500 m^2/s^2 (ryc. 13A). Zbyt silny przepływ powietrza w rdzeniu komórki burzowej może doprowadzić do rozpadu jej struktury, dlatego też idealne warunki dla występowania wyładowań doziemnych dla DLS wynoszą ok. 15 $m \cdot s^{-1}$ oraz dla CAPE 1300 $J \cdot kg^{-1}$ (ryc. 13B). Równocześnie zachowane muszą zostać proporcje pomiędzy stosunkiem zmieszania na poziomie ok. 13 $g \cdot kg^{-1}$, przy temperaturze powietrza około 28-29°C oraz temperaturze punktu rosy przekraczającej 18°C.



Rycina 8. A – Relacja pomiędzy wyładowaniami doziemnymi i parametrem WMAXSHEAR. B – Relacja pomiędzy ścinaniem wiatru i energią konwekcyjną. C – Relacja pomiędzy stosunkiem zmieszania pary wodnej, a wskaźnikiem WMAXSHEAR. D – Relacja pomiędzy temperaturą powietrza, a temperaturą punktu rosy na 2m. Opracowano na podstawie danych PERUN i ERA5 dla okresu 2002-2020.

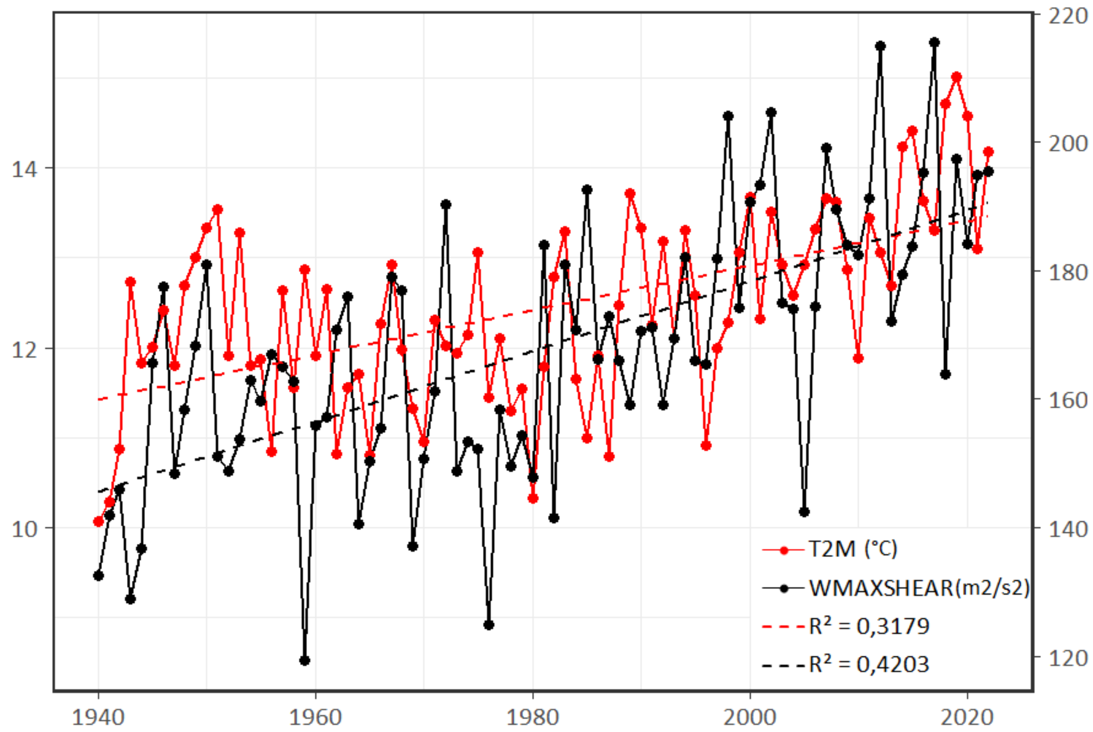
Zmienność i trend wyładowań w latach 2002-2020

Określenie warunków konwekcyjnych sprzyjających powstawaniu chmur Cumulonimbus jest kluczowe dla zrozumienia procesów zachodzących w troposferze. Nie mniej ważne jest określenie zmian przestrzennych i czasowych zachodzących w ostatnich dekadach. Najnowszy raport klimatyczny Międzyrządowego Zespołu ds. Zmian Klimatu (IPCC 2023) potwierdził statystycznie rosnący trend temperatury powietrza na kuli ziemskiej mierzonej na standardowej wysokości 2 metrów nad poziomem gruntu. Co więcej, największe zmiany temperatury występują na kontynentach. Wzrost temperatury powietrza jest pośrednio związany ze zmianami środowiska konwekcyjnego w wyższych partiach troposfery, co może wpływać na rozwój niebezpiecznych burz (Brooks i in., 2003; Taszarek i in., 2017; Taszarek i in., 2020). Na obszarze Polski parametry związane z konwekcją na przestrzeni lat korespondują z liczbą burz [P5]. Jedynie w przypadku Mixing Ratio w rejonie Tatr można zaobserwować niższe wartości, niż ma to miejsce w górzystym obszarze południowo-wschodniej Polski (ryc. 14). W wyższych partiach górskich zachodzi większa stabilność sucha, co może prowadzić do większych pionowych gradientów temperatury powietrza.



__Rycina 9.__ 82-letni przebieg klimatologiczny 95 percentyla MU CAPE, MU Mixing Ratio i MU WMAXSHEAR. Trendy pochodzą z rocznych wartości o rozdzielczości godzinowej. Opracowano na podstawie danych ERA5.

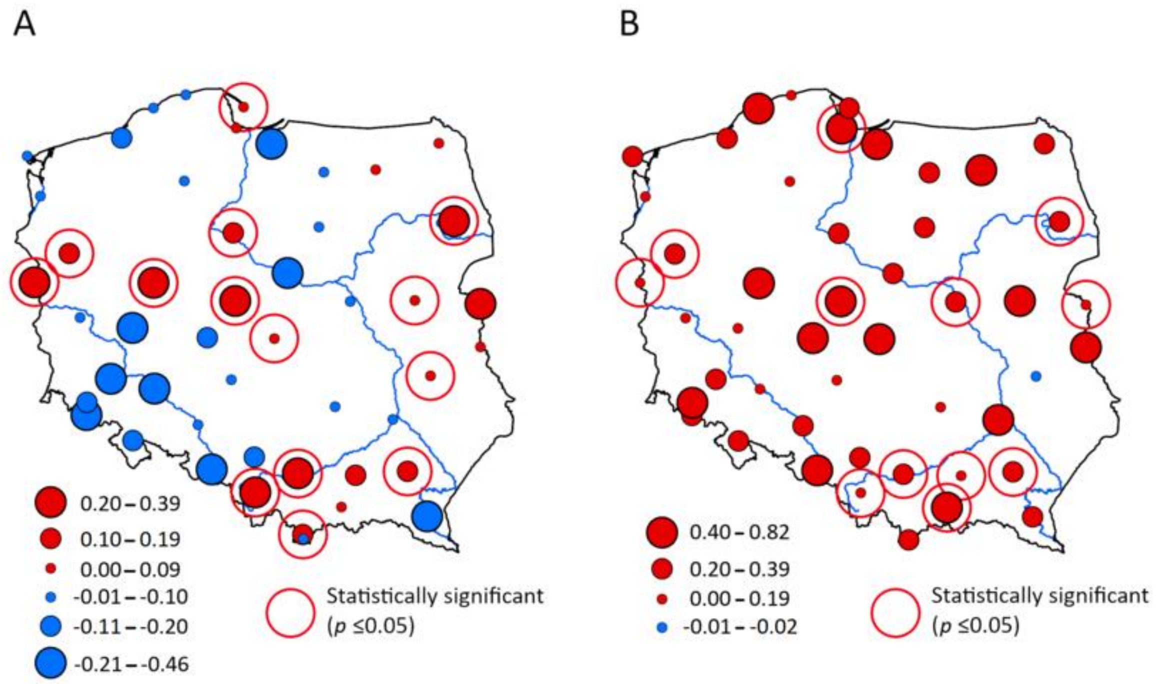
Niezwykle istotnym wskaźnikiem niezbędnym do skutecznego prognozowania zjawisk konwekcyjnych jest parametr określający stosunek dostępnej energii w relacji z wartościami ścinania wiatru. DLS (ang. Deep Layer Shear) jest kluczowy jeśli chodzi o formowanie się zorganizowanych form burzowych jak i zdolności do generowania opadów dużego gradu. W przypadku wystąpienia niskich wartości DLS, burze będą miały ograniczone warunki rozwoju. Bez ścinania wiatru na danym terenie, lecz z relatywnie umiarkowanym/wysokim CAPE, zainicjowane burze będą miały charakter komórek generujących podwyższone ilości opadów atmosferycznych zwłaszcza w przypadku nagromadzenia znacznej ilości pary wodnej - PW (ang. Precipitable water ok. < 30 mm). Jest to domena głównie burz występujących na terenach o klimacie tropikalnym. Na obszarze Polski w latach 1940-2020 odnotowuje się ciągły wzrost parametru WMAXSHEAR (Ryc. 15). Jak wykazano w badaniu Taszarek i in. (2020), wzrost tego wskaźnika jest również widoczny w północno-zachodniej Europie, co może być przyczyną przesunięcia prądu strumieniowego z powodu osłabienia gradientu termicznego między średnimi szerokościami geograficznymi, a Arktyką (Pena-Ortiz i in., 2013; Coumou i in., 2015). Ponadto klimatologia współczynnika WMAXSHEAR dla Europy wyraźnie wskazuje, że silne burze najczęściej występują latem w korytarzu z północno-wschodniej Hiszpanii przez części Europy Środkowej, Włoch lub Półwyspu Bałkańskiego (Taszarek i in., 2020). Z kolei wiosną pozytywne trendy odnotowano dla większości Europy (w tym Polski), co potwierdza, że korzystne warunki dla głębokiej konwekcji są coraz częstsze również wiosną. Zmiany te mogą wynikać głównie ze wzrostu energii potencjalnej, wilgoci przy stałych wartościach DLS.



Rycina 10. *Przebieg czasowy rozkładu temperatury powietrza (T2M) oraz wartości ścinania wiatru w profilu pionowym 0-6 km wraz z parametrem CAPE (WMAXSHEAR) w latach 1940-2022 na obszarze Polski. Opracowano na podstawie danych ERA5.*

Systematyczny wzrost parametru WMAXSHEAR oraz jednocześnie postępujące ocieplenie atmosfery skutkuje wzrostem liczby dni z burzą, co potwierdzają badania zawarte w opracowaniach [P4] oraz [P5]. Wzrastająca liczba dni z burzą określona na podstawie danych PERUN jednoznacznie prezentuje wzrost liczby tego procesu (ryc. 16B). Jednocześnie wartym odnotowania jest fakt, iż burze w cieplejszym klimacie są coraz częstsze, ale mogą być również mniej intensywne ze względu na wspomniane wcześniej osłabienie aktywności prądu strumieniowego, który inicjuje rozwój silnych układów burzowych. Nie mniej, burze o charakterze pojedynczych komórek, nadal będą stanowiły poważne zagrożenie, zwłaszcza na terenie silnie przekształconym przez człowieka ze względu na możliwość generowania nawalnych opadów deszczu o charakterze stacjonarnym. Efektem tego będą lokalne powodzie i podtopienia. Należy więc przystąpić do działań adaptacyjnych i przebudowy miejskich systemów odwadniania.

Analiza danych synoptycznych z lat 2002-2020 wykazała istotnie statystyczny trend (na poziomie p ≤ 0,05) wzrostu liczby dni z burzą w Polsce w 14 stacjach (Artykuł P4). W pozostałych stacjach trend nie jest jednoznaczny, co potwierdza wcześniejsze badania Bielec-Bąkowskiej (2002, 2003, 2013, 2021). Dane z systemu PERUN są bardziej obiektywne i wykazały wzrost liczby dni z burzą w Polsce, ale tylko w części stacji jest on istotny statystycznie (ryc. 16).



Rycina 11. *Zmiany w postaci liczby dni z burzą w Polsce (na dekadę) w przedziale lat 2002-2020 na podstawie danych A – SYNOP i B – PERUN. Miejsca istotne statystyczne (p≤0.05) zaznaczono symbolem okręgu.*

Podsumowanie i wnioski

Każdego roku na terenie całej Polsce odnotowuje się około 160 dni z burzami. Jednocześnie komórki burzowe generują różne ilości wyładowań atmosferycznych, a ich liczba i rozkład przestrzenny jest nieco inny każdego roku (Sulik, 2022). W badanym okresie 2002-2020 system PERUN wykrył i zlokalizował ponad 8 milionów wyładowań doziemnych (CG), które zostały przeanalizowane w niniejszym opracowaniu. Podstawowym problemem było określenie parametrów środowiska konwekcyjnego inicjującego powstanie chmur burzowych oraz wyładowań atmosferycznych. Do tego zadania wykorzystano dane z reanaliz ERA5.

W wyniku przeprowadzonej analizy można sformułować następujące wnioski:

1. Średnia roczna liczba dni z burzą na podstawie analizy wyładowań CG w systemie PERUN wynosi około 30 dni. Najmniej dni z burzą występuje na północnym zachodzie (10-15 dni), a najwięcej na południowym wschodzie (35-40 dni),
2. Każdego roku występuje średnio około 480 000 wyładowań doziemnych, 96% wszystkich wykrytych wyładowań doziemnych posiada ładunek ujemny,
3. Największa aktywność elektryczna (liczba wyładowań) występuje w centralnej Polsce oraz na Lubelszczyźnie i Górnym Śląsku,
4. Największa liczba dni burzowych i aktywność elektryczna przypada na lipiec, a sezon burzowy trwa od maja po sierpień. Wyładowania atmosferyczne występują również w innych miesiącach, nawet zimą,
5. W okresie 2002-2020 wystąpiło 8 dni z burzami, podczas których suma dobowa wyładowań CG przekroczyła 60.000,
6. Wyładowania doziemne występują najczęściej w środowisku WMAXSHEAR wynoszącym około 500 m^2/s^2,
7. Parametr WMAXSHEAR pozytywnie koreluje ze współczynnikiem zmieszania w zakresie 12-14 $g \cdot kg^{-1}$,
8. Dane o wyładowaniach doziemnych pochodzących z systemu PERUN można z powodzeniem wykorzystać w procedurze wyznaczania liczby dni z burzą, należy przy tym zastosować bufor 15 km,
9. WMAXSHEAR bardzo dobrze koreluje z indeksem wielkości gradu, co świadczy o intensywności procesów w chmurze *Cb* i liczbę generowanych wyładowań CG, zwiększona liczba wyładowań CG związana jest z superkomórkami burzowymi charakteryzującymi się silną prędkością prądu wstępującego, rotacją i potencjałem do generowania dużych opadów gradu,
10. Wartości MU CAPE w zakresie od 1.000 do 1.500 $J \cdot kg^{-1}$, w połączeniu z DLS około 13 $m \cdot s^{-1}$, posiadają znaczny potencjał generowania wyładowań,
11. Prawdopodobieństwo zwiększonej aktywności elektrycznej wzrasta przy temperaturze powietrza sięgającej około 28°C i temperaturze punktu rosy przekraczającej 18°C,
12. Na terenie Polski w latach 2002-2020 zaznacza się wzrost liczby wyładowań atmosferycznych oraz liczby dni z burzą, wynika to ze wzrostu temperatury powietrza oraz parametru WMAXSHEAR.

Przedstawione na wstępie hipotezy badawcze zostały zweryfikowane:

H1: na terenie Polski występuje zróżnicowanie przestrzenne wyładowań doziemnych uwarunkowane czynnikami geograficznymi.

POTWIERDZONA – stwierdzono znaczne zróżnicowanie przestrzenne wyładowań atmosferycznych w Polsce uwarunkowane orografią, odległością od Morza Bałtyckiego, cyrkulacją atmosferyczną – rosnącym w kierunku wschodnim kontynentalizmem klimatu.

H2: rozkład przestrzenny wyładowań atmosferycznych CG w Polsce pozytywnie koreluje z rodzajami pokrycia terenu.

CZĘŚCIOWO POTWIERDZONA – na obszarach miejskich województwa kujawsko-pomorskiego wyładowania CG koncentrują się w okolicach najwyżej położonych punktów. Wraz ze zwiększaniem odległości od rzeki Wisły, liczba wyładowań wzrasta.

H3: liczba wyładowań atmosferycznych wykazuje zmienność w ciągu roku.

POTWIERDZONA – wyładowania atmosferyczne stwierdzono we wszystkich porach roku, jednak zaznacza się wyraźny sezon burzowy, trwający od maja po sierpień (w niektórych latach po wrzesień).

H4: wzrost temperatury powietrza wpływa na liczbę wyładowań doziemnych oraz liczbę dni z burzą w Polsce.

CZĘŚCIOWO POTWIERDZONA – w latach 2002-2020 z roku na rok występuje znaczna zmienność burz. Jednakże odnotowuje się wzrost liczby wyładowań na obszarze całego kraju. Widoczny jest również wzrost liczby dni z burzą, natomiast istotnie statystyczny trend zaznacza się tylko w części stacji w Polsce.

H5: silne układy burzowe generujące podwyższone wartości wyładowań doziemnych mogą tworzyć się w środowisku umiarkowanego wskaźnika CAPE i relatywnie niskiego ścinania wiatru w warstwie 0-6 km AGL – Deep Layer Shear.

NIEJEDNOZNACZNIE POTWIERDZONA – jest to możliwe, aczkolwiek za najkorzystniejsze warunki można uznać CAPE ok. 1300 $J \cdot kg^{-1}$ (co w klimacie Polski jest wartością podwyższoną) oraz obecność ścinania wiatru powyżej 13 $m \cdot s^{-1}$.

H6: obecność opadu gradu o średnicy do 2 cm świadczy o intensywności komórek burzowych i jest pozytywnie powiązana z ilością generowanych wyładowań doziemnych.

POTWIERDZONA – proces ten szczególnie towarzyszy burzom superkomórkowym generującym opad gradu o średnicy 2 cm i wykazującym przy tym podwyższoną aktywność elektryczną.

Uzyskane wyniki i prawidłowości dla obszaru Polski pokazują regionalne uwarunkowania formowania się chmur burzowych *Cb* i wyładowań relacji chmura-ziemia CG. Pozwolą one precyzyjniej prognozować niebezpieczne zjawiska pogodowe, jakimi są burze z wyładowaniami doziemnymi, z silnymi porywami wiatru, ulewnymi opadami, czy też opadami dużego gradu. Wraz ze stopniowo ocieplającym się klimatem, następuje również zmiana środowiska tworzenia się komórek burzowych. Jednak na przestrzeni lat wystąpiły epizody niszczycielskich burz przerywane latami o słabszej aktywności elektrycznej. Nie mniej liczba dni z burzą wzrasta wraz z generowanymi wyładowaniami CG. Parametry termodynamiczne i kinematyczne atmosfery jednoznacznie świadczą o warunkach sprzyjających formowaniu się chmur *Cb* i wzrostu liczby dni z burzą oraz ich intensywności elektrycznej w przyszłości. Burze w kolejnych latach mogą być częstsze, a ich aktywność może objawiać się zwiększonymi sumami opadów atmosferycznych, co stanowi zagrożenie zwłaszcza na terenach miejskich. Pomimo ciągłego rozwoju metod oraz technologii badawczych zjawiska konwekcyjne nadal powodują znaczne straty materialne, a nawet ofiary śmiertelne, o czym świadczą dane z bazy danych ESWD. Poszerzenie wiedzy związanej ze środowiskiem, w którym powstają wyładowania atmosferyczne pozwoli na precyzyjne określenie obszaru zagrożonego i ochronę ludności.

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Formation factors of the most electrically active thunderstorm days over Poland (2002–2020)

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ABSTRACT

This research documents atmospheric conditions and development of high electrically active thunderstorm days that occurred over Poland in period 2002–2020. The 8 days with the highest number of detected cloud-to-ground flashes during one storm cell life cycle were analyzed. The study used data from the PERUN lightning detection and location system, ERA5-reanalysis, vertical atmospheric soundings, and synoptic maps as well. As a result of the analysis, it can be concluded that the development of thunderstorms is positively influenced by the low-pressure area above the North Sea and the atmospheric fronts with zone of wind convergence in the lower troposphere. The analyzed storm systems on the analyzed days were created in the atmosphere of a high vertical wind shear (from 10 to 18 m s^{-1}), lifted index (from +0.04 to –8.22), thermodynamic instability (CAPE 1000–3700 J kg^{-1}), rich boundary layer moisture (mixing ratio: 12–14 g kg^{-1}), and high tropospheric moisture (total column water vapour >50 kg m^{-2}). Very moist air masses ahead of the storm systems provided consistent access to large amounts of latent heat released into the clouds and intensified upward mass fluxes and development of intense lightning activity from Cumulonimbus cloud.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Weather and Climate Extremes.

Conception and design of study: **Sławomir Sulik.** Acquision of data: **Sławomir Sulik.** Analysis and interpretation of data: **Sławomir Sulik.** Drafting the manuscript: **Sławomir Sulik.** Approval of the version of the manuscript to be published: **Sławomir Sulik**.

1. Introduction

Thunderstorm is a dangerous phenomenon that often poses a threat to property, health and life of people. It manifests itself in strong gusts of wind, hail, torrential rainfall which in turn causes flash floods in cities (Dotzek et al., 2009). However, the main attribute of the thunderstorm is necessarily lightning, which is mainly equated with the thunderstorm. Thunderstorm is defined as one or more atmospheric electricity discharges (lightning, thunder) associated with the occurrence of Cumulonimbus clouds, Niedźwiedź (2003).

In Poland, with the oncoming of the flood of the millennium in 1997, the danger arising from the force of nature began to be noticed and the problem began to be examined more closely. Probably since then, the dangerous weather conditions have attracted media attention and continues to this day. The awareness of the possible occurrence of dangerous phenomena led to the creation of the POLRAD Doppler radar system in Poland in 2000 (Jurczyk et al., 2008) and that of the PERUN lightning detection system in 2002, Bodzak (2006). The introduction of the new system in Poland creates new opportunities to conduct specific research on the spatial distribution of lightning. From time to time, dangerous weather phenomena are noted such as extremely severe thunderstorms that occurred, among others, on August 10 and 11, 2017 (Taszarek et al., 2019; Sulik and Kejna, 2020).

The progressing climate change in the world is most often manifested by an increase in air temperature. In Poland, an increase in the average air temperature of0.33 °C/10 years is observed. The greatest warming was recorded in the west of the country and in the area of the Baltic Sea (>0.4 °C/10 years). Importantly, the greatest temperature increases take place in the summer in July, Kejna and Rudzki (2021). Importantly, the peak of the storm season in Poland falls around June, July and

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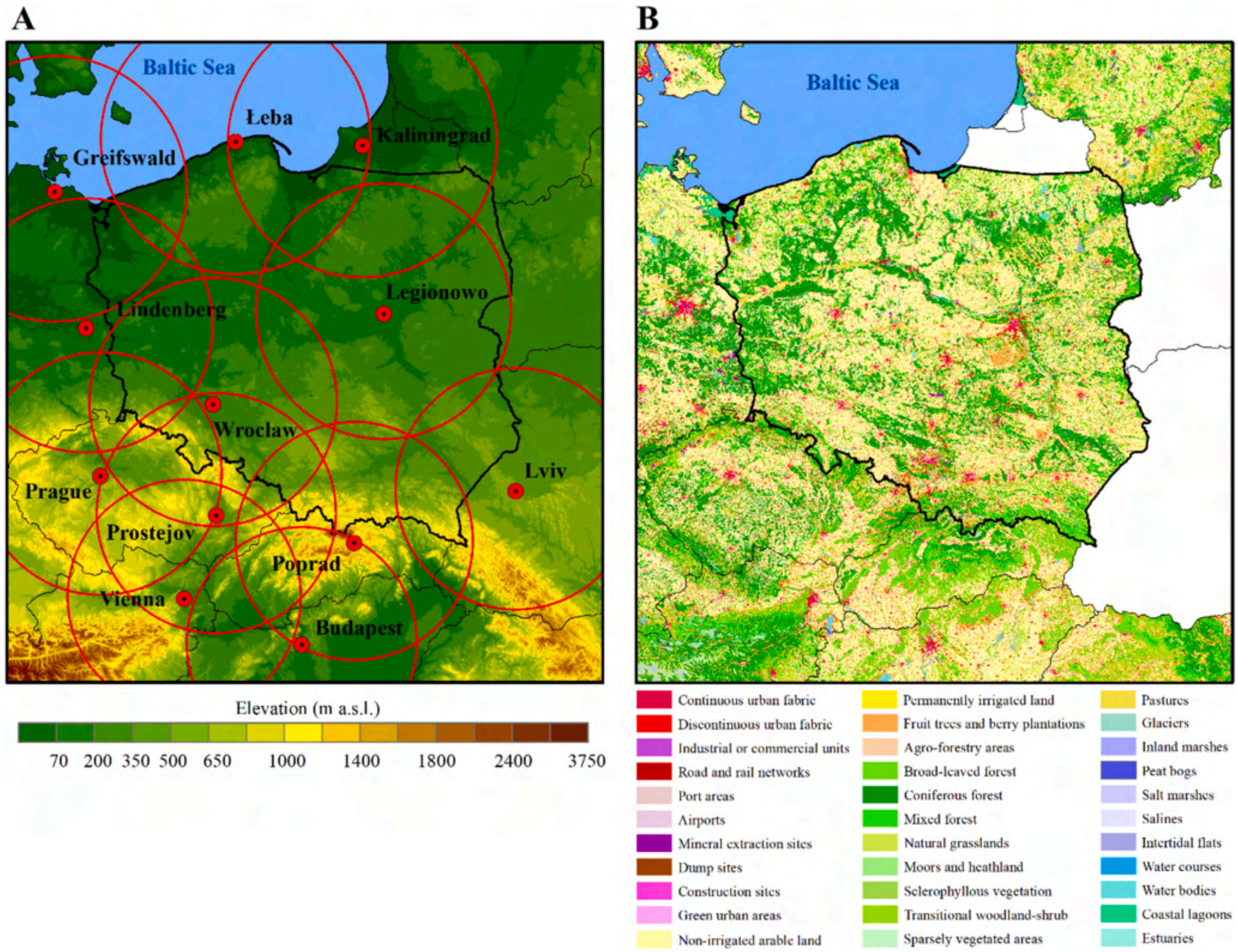

Fig. 1. A – Hypsometric map of Poland on the Shuttle Radar Topography Mission Global Coverage (SRTM3) with location of rawinsonde stations used in this study with 125-km buffer zones (source: NASA, 2021). B – Land use map of Poland and neighboring countries based on the Corine Land Cover (2018) data (source: NASA, 2021).

August, with July being the month with the highest storm activity (Taszarek et al., 2015). According to the research, supercell storms (MCS – Mesoscale Convective System) origin in Poland are not rare. In the period 2008–2017, there were 77 MCS systems and 49 days with MCS. These systems are most often formed between 12:00 and 14:00 UTC and disappear around 20:00 UTC (Surowiecki and Taszarek 2020).

Perhaps the increase in air temperature in the world will contribute to the formation of increasingly stronger thunderstorms systems also in Europe, including Poland (Taszarek et al., 2021). In Poland, an average of 10 bow echoes are reported each year (Taszarek et al., 2018; Celiński-Mysław and Matuszko 2014; Celiński-Mysław and Palarz 2017). Bow echo storms are mainly associated with wind storms that cause significant damage due to strong wind gusts generated by the MCS. However, not always, strong wind storms can also show high electrical activity. According to research on the electrical activity of the atmosphere over Europe, the high storm season falls on the period from May to August with the peak of storm activity in July. Of course, storms can also occur in other periods, but they are not as strong as in the strict summer months (Wapler 2013; Anderson and Klugmann 2014; Taszarek et al., 2015).

The main objective of this research is to determine the weather conditions on days characterized by high electrical activity of storms that occurred in Poland in the years 2002–2020.

2. Area of interest, dataset and methodology

The study area covers the territory of Poland and the neighboring countries. Poland is located in Central Europe, right on the shores of the Baltic Sea. It is mostly a lowland country and in the south there are also upland areas and mountain ranges (Carpathian mountains). The height of the terrain decreasesfrom the south to the west, but the height does not decrease gradually due to the alternating lower and higher elevated lands. According to land cover analyzes, over 60% of Poland's territory is occupied by agricultural land, followed by forests and semi-natural ecosystems (Fig. 1) CORINE Land Cover (2018).

A cloud-to-ground lightning flashes data was derived from PERUN lightning detection system located in Poland combined into nine stations. To distinguish between type of flashes, low-frequency electromagnetic waves was used. Due to this, system detects lightning flashes categorised into (CC) cloud-to-cloud, (IC) intra-cloud and (CG) cloud-to-ground and it's capable to detect up to 100 strikes per second. Importantly, in the case of CG flashes with a negative charge, these types of discharges tend to "strike" several times during one discharge in one and the same place (multistrokes). Therefore, when processing data, only the first discharge that took place was taken into account. Lightning flash density was computed into a resolution of 10x10-km grid cells. The discharges are geographically located in decimal units (WGS84 – World

Table 1
Overview and comparison of detected CG flashes with associated factors.

Date	All CG flashes	Average number of CG flashes per km^{-2}	Highest number of CG flashes in one 10 x 10 km^{-1} grid cell	Equilibrum level (hPa)	Lifted index (°C)
June 26, 2006	73.504	0.23	651	231.65	- 2.66
August 15, 2008	63.399	0.20	354	437.81	- 0.25
July 02/03, 2012	80.416	0.25	882	450.01	- 0.11
July 19, 2015	72.030	0.23	325	486.79	- 0.21
June 26, 2017	69.769	0.22	653	275.78	- 1.93
August 10, 2017	154.524	0.50	845	301.81	+0.04
August 11, 2017	56.510	0.18	482	190.38	- 8.22
June 13, 2019	86.124	0.27	407	202.56	- 4.45

Geodetic System '84). Due to the local reference system, it was necessary to convert the coordinates from WGS84 to the Polish metric PUWG (European Petroleum Survey Group: 2180) system. The methods are similar as employed in Sulik and Kejna (2020).

The analysis time covers 8 days with the highest value of cloud-to-ground flashes that occurred in 2002–2020 over Poland. These days were selected on the basis of a total of more than 60.000 CG flashes in one day. Days such as June 26, 2006; August 15, 2008; July 03, 2012; July 19, 2015; June 29, 2017; August 10, 2017; August 11, 2017; June 13, 2019 were chosen. Similar thunderstorms systems are often associated with the United States, and this study documents the days when such storms occurred over territories over which they are unlikely to be documented.

The main data resource was ERA5 data obtained for the previously discussed research area. ERA5 data is distributed by ECMWF – European Center for Medium-Range Weather Forecasts and includes various atmospheric parameters (Hersbach et al., 2018a). Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. This principle, called data assimilation, is based on the method used by numerical weather prediction centers, where every so many hours (12 h at ECMWF) a previous forecast is combined with newly available observations in an optimal way to produce a new best estimate of the state of the atmosphere, called analysis, from which an updated, improved forecast is issued. Data has been regridded to a regular lat-lon grid of 0.25° for the reanalysis and 0.5° for the uncertainty estimate. There are four main sub sets: hourly and monthly products, both on pressure levels (upper air fields) and single levels (atmospheric, ocean-wave and land surface quantities) (Hersbach et al., 2018b). From the ERA5 resources, values such as atmospheric pressure, air temperature and dew point at various heights, geopotential, convective available potential energy, total cloud cover or wind direction and speed were obtained. For this research, among others, data obtained from vertical atmospheric surveys were used, therefore, for better results, there was a need to use data also from outside Poland borders.

Vertical atmospheric soundings are performed in several dozen locations in Europe, including 3 stations in Poland (Łeba, Legionowo, Wrocław). Soundings take place twice a day, at 1200 and 0000 UTC, and in some stations also at 1800 UTC. The data was obtained from archives collected by the University of Wyoming. The data from the rawinsonde was served mainly as a reference to the ERA5 data. This treatment was chosen deliberately due to the possible underestimation of some parameters, such as CAPE. In some latitudes, values from reanalysis differ with rawinsonde. For example, in the great plains of the USA, ERA5 underestimate CAPE values compared to vertical atmospheric surveys. In contrast, reanalysis best represents temperature, moisture variables, mid-tropospheric lapse rates and mean wind (Taszarek et al., 2021).

The analyzed hours 1200 and 0000 UTC of individual atmospheric factors were adjusted to the similar occurrence of storms on a given day so that all data was homogeneous.

The synoptic maps used to determine the synoptic conditions on individual days were made independently, based on the standardization of various European synoptic maps. Designations of the types of air masses have been used as in Mishra (2017). However, ERA5 data was used to determine the spatial distribution of atmospheric pressure. Spatial analysis in the form of maps in this study were computed in the ESRI ArcMap 10.8.1 computer software.

3. Results

3.1. Cloud-to-ground lightning flash density

In Poland, the intensity and occurrence of thunderstorm increases from the north-west (from the Baltic Sea) to the south-east (to the Carpathian mountains). The greatest number of lightning strikes occurred in the south-eastern part of central Poland (from the Kraków-Częstochowa upland through Mazovia to Masuria) (Taszarek et al., 2015).

On the analyzed days, a total of 656.280 CG flashes was detected over Poland (Table 1). The vast majority of the discharges were concentrated in the previously discussed zone of storm passage in Poland and fell within the limits of the storm alley that occurs in Poland in the central part of the country. The exception was August 11, 2017, when the storm passed in the western part of the country. The highest electrical activity was shown on August 10, 2017, when 154.524 CG flashes occurred during one day, of which 18% had a positive charge. Undoubtedly, strongly electrically active storms affect the spatial distribution of lightning flashes. The time of day (day or night) does not matter when it comes to thunderstorm electrical activity because high electrically active thunderstorm may occur in daylight (June 13, 2019 with 86.124 CG flashes) and also at night (August 10, 2017 with 154.524 CG flashes or July 3, 2012 with 80.416 CG flashes) (Fig. 2). On all days, the storms traveling through Poland lasted several hours. On all analyzed days, it can be notice the north or north-east direction of storm movement. The main direction of movement of the storm centers was determined by the direction of movement of the atmospheric front. Such a situation can be observed, for example, on August 11, 2017, when the cool atmospheric front entered Poland from the west, encountering the previously heated air separated by a zone of convergence. As a result, lightning strikes occurred only in the western part of the country.

3.2. Thunderstorms development factors

In the climate of Central Europe, including Poland, the occurrence of thunderstorms is influenced by many factors. Undoubtedly, one of them is the location of the baric systems. Earlier studies for Poland showed that the most favorable conditions for the formation of storms occur during the north-west cyclonal and north-eastern anticyclonal situation (Bielec 1998, 2000; Kolendowicz 2006).

On all analyzed days with electrically active storms, it was possible to observe the convergence line in the vicinity or on the territory of Poland. This zone separates two different masses of air, in this case the most common type of separated masses are tropical and maritime polar air mass. All analyzed days were associated with the atmospheric fronts and severe thunderstorms occurred on either the warm or cold front (Fig. 3).

The formation of dangerous storms is also due to the location of baric centers above Poland or in its close vicinity. The given examples show

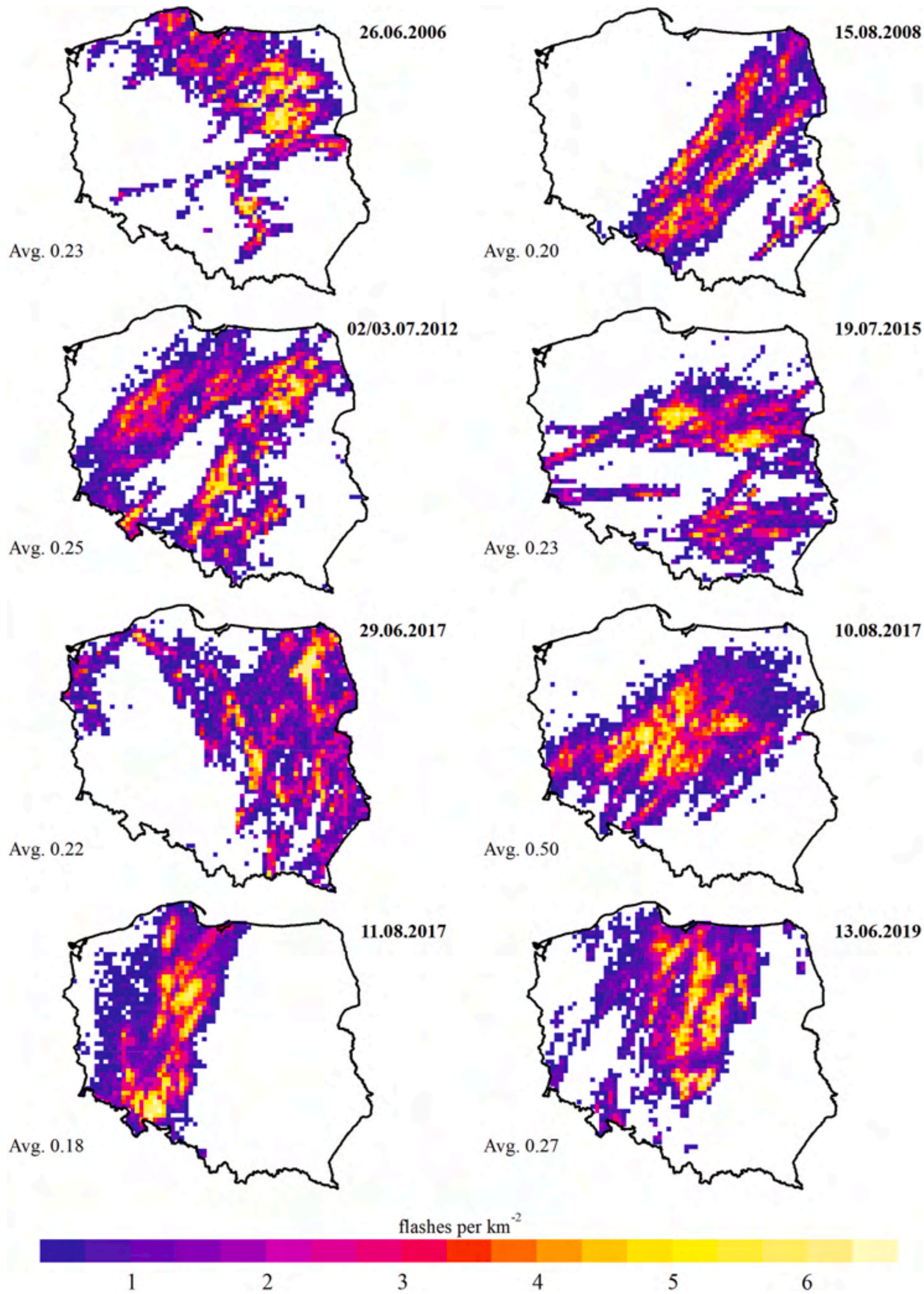

Fig. 2. Number of cloud-to-ground lightning flashes in Poland on individual days. Lightning densities are computed in 10 × 10 km grid cells. Based on lightning data derived from the PERUN network.

that the high pressure center located in the eastern part of Europe and the low baric center by the North Sea are of great importance for the development of thunderstorms above Poland.

The cloud cover or the direction of air inflow are also related to the baric centers. Very moist air masses ahead of the storm systems provided consistent access to large amounts of latent heat released into the clouds and intensified upward mass fluxes (Fig. 4). On the analyzed days, it was possible to observe the influx of hot and humid air over the territory of Poland. Taking into account the current state of knowledge, it can be concluded that large amount of moisture in the clouds is related to the high electrical activity.

The described baric situations and the presence of hot air masses are not uncommon in Poland. Sometimes there is a situation when heat waves last several dozen days in Poland, Wibig (2017). Heat waves occurring in the season of the highest intensity of storms have a positive effect on their development. This happens as a result of the influx of a cool mass of air at some time moving behind the atmospheric front over the areas where still hot and often moist air mass remains. In the case of the analyzed days, the air temperature at a height of 2 m often reached above 35 °C already at 1200 UTC with 21.5 °C dew point temperature (Fig. 5). During the days when heavy thunderstorms occur during the night hours, tropical nights can be observed. In addition a high thermal contrast can be observed at the height of 850 hPa, where the thermal gradient sometimes reached over 10 °C. The large temperature

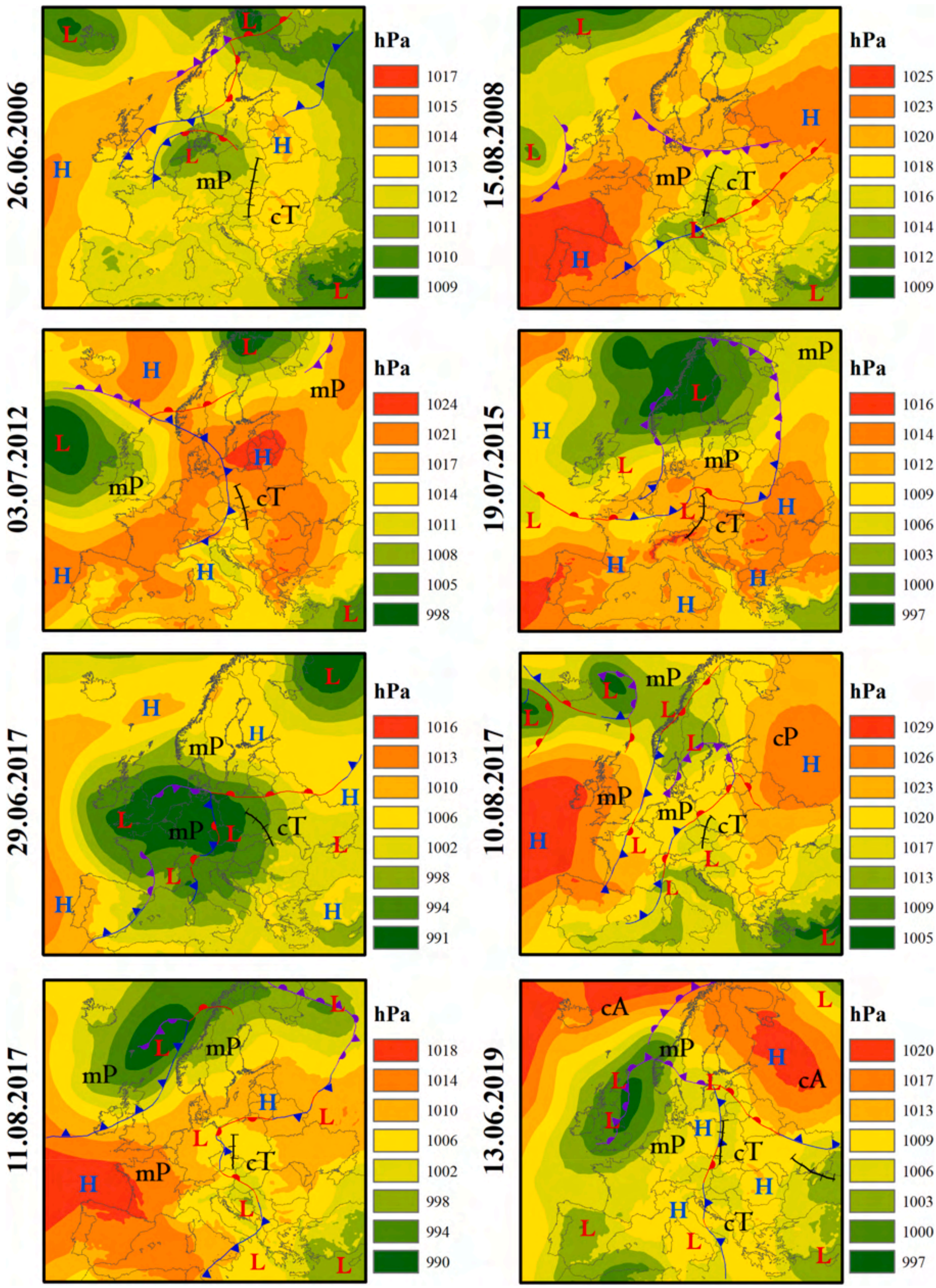

Fig. 3. Synoptic maps on individual days at 0000 UTC; H – high pressure, L – low pressure, cT – continental tropical air mass, mP maritime polar air mass, cP – continental polar air mass, cA – continental arctic air mass, warm front – red line, cold front – blue line, occluded front – purple line. Atmospheric pressure values are based on ERA5 data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

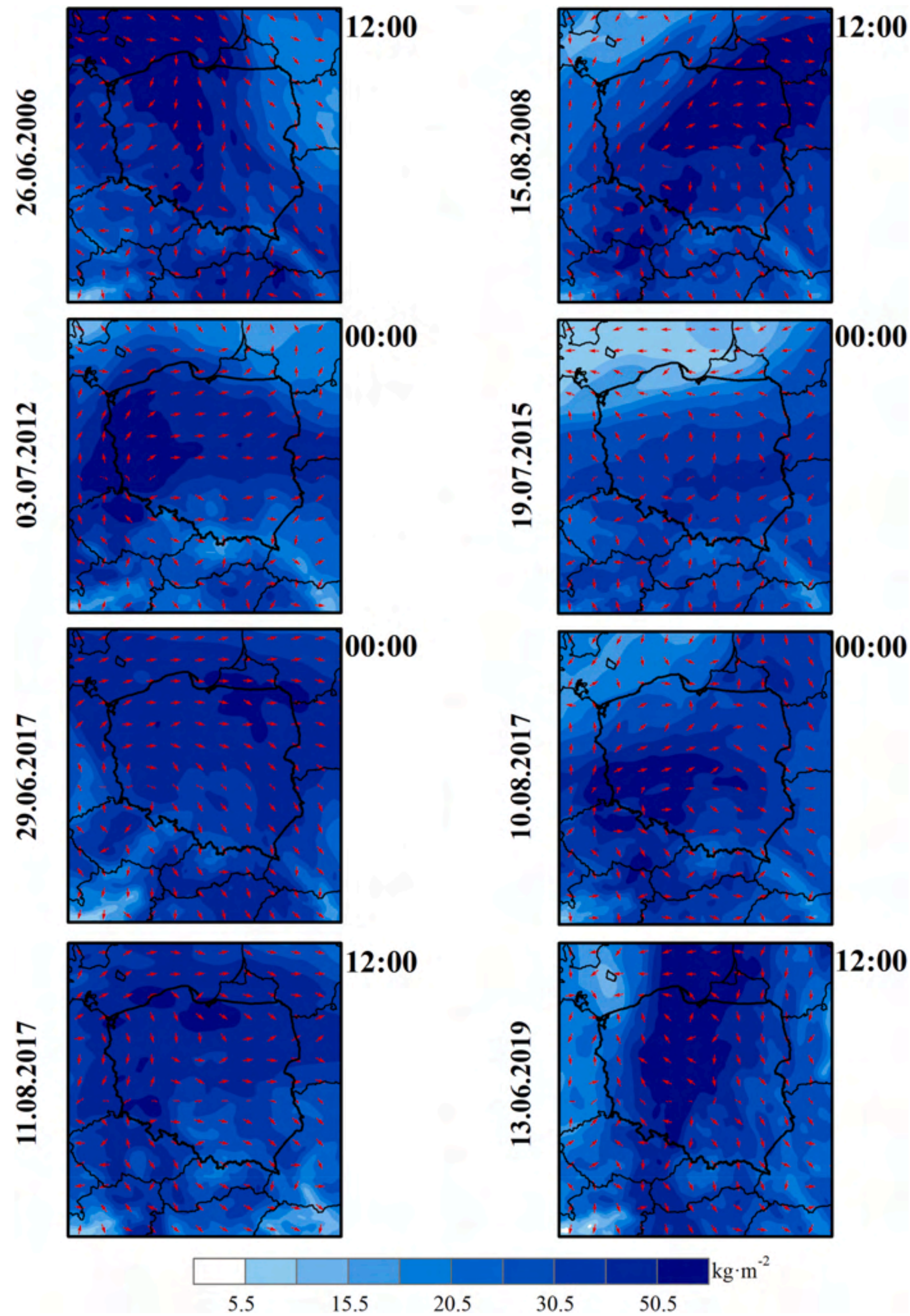

Fig. 4. Total column integrated water vapour at individual days and hours with wind direction at 850 hPa (arrows) in Poland. Based on ERA5 data.

differences at this altitude are also reflected near the ground and vice versa. Thermal gradients show well the course and direction of the cold front which is equivalent to and coincides with the occurrence of lightning flashes (Fig. 6). The most common factors for a well-organized MCS are sufficient amounts of moisture in the boundary layer, steep low and midlevel temperature lapse rates.

The occurrence of thunderstorms, and hence lightning, is mainly defined by the convective available potential energy (CAPE). This parameter is determined by two main factors, namely the boundary layer moisture and temperature lapse rates aloft. CAPE energy exists in an unstable layer of the troposphere (the so-called free convection layer) when the temperature of the rising air particle is higher than the ambient temperature. Warmer air is lighter, so this condition guarantees rising. Any CAPE value greater than 0 indicates instability and the possibility of dangerous phenomena. CAPE is calculated by integrating the local air displacement in the free convection layer (i.e. at heights from the level of free convection (LFC) to the equilibrium level (EL)). However, the lightning probability is based on values of the CAPE and EL (equilibrium level). If the temperature drops to −10 °C, the chance of heavy discharges increases. This situation with individual parameters is shown on Skew-T charts (Fig. 7). A skew-T log-P diagram is the plotting of rawinsonde soundings which give a vertical profile of the temperature and dew point temperature throughout the troposphere and lower stratosphere. Atmospheric values are measured by a weather balloon (rawinsonde) and sent to the station where a graph is created from the obtained data. Whole diagram is embedded in a moist and dry adiabatic mesh. High lightning probability is associated with state of the atmosphere, where steep lapse rates frequently compensating for poor low-

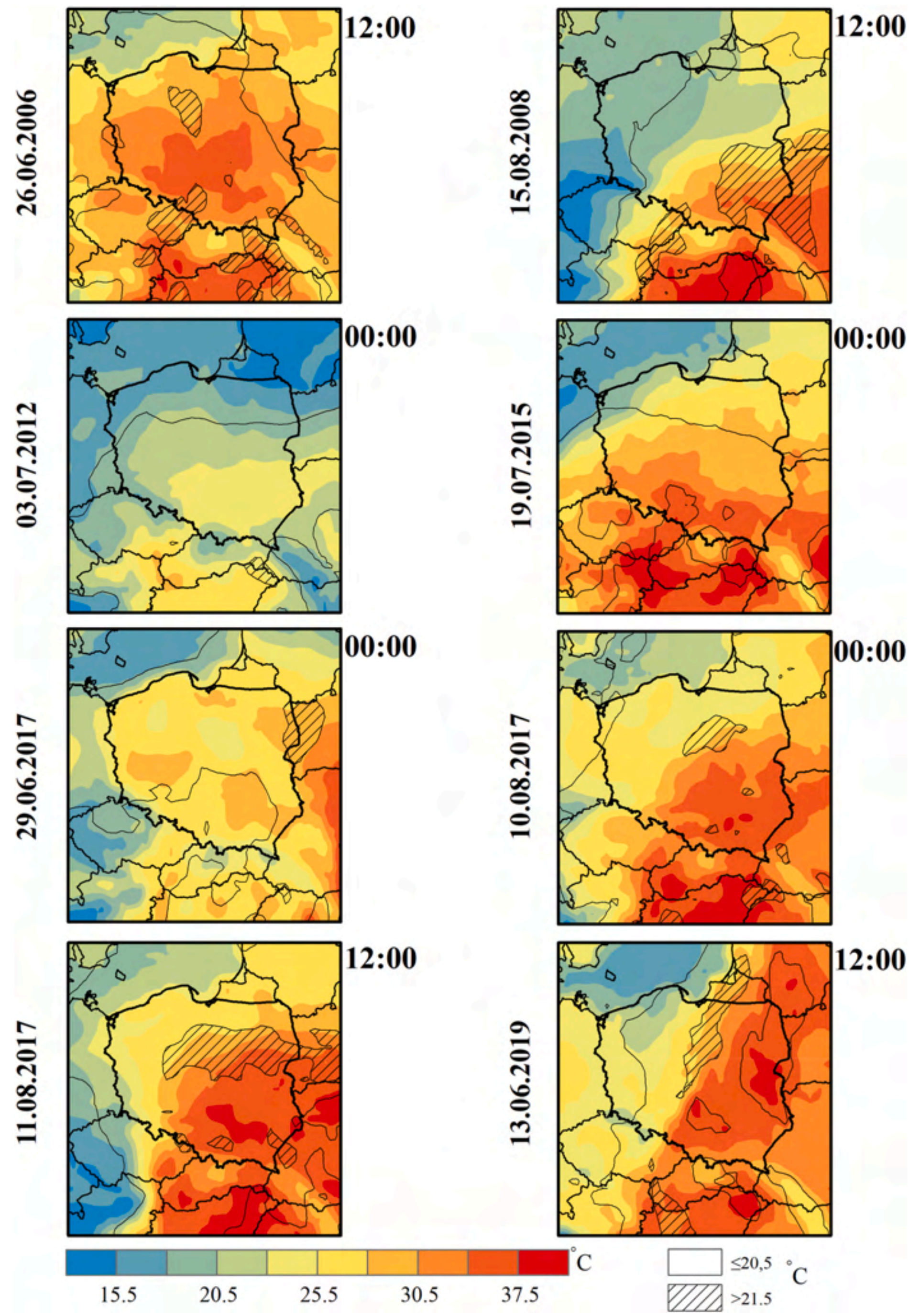

Fig. 5. 2-m air temperature (shaded) with 2-m dew point temperature (contours) in Poland on individual days and hours. Based on ERA5 data.

level moisture and vice versa. The highest values of CAPE on the examined days were 3770 J kg^{-1} (August 11, 2017) however, increased values of discharges appeared in areas with increased wind shear (WS). The parameters of increased CAPE, WS and EL must coincide fairly evenly to increase the chance of intense discharges. Low CAPE values do not mean there is no risk of a severe thunderstorm. Such examples are the days of July 19, 2015 and June 29, 2017, when despite the CAPE value at the level of around 1500 J kg^{-1} and lower, there were storms generating about 70 thousand CG flashes (Fig. 8). A wind shear with a magnitude of approximately 15 m s^{-1} in a 0–3 km layer is also considered conductive for a long-lived linear MCS capable of producing widespread wind damage (Taszarek et al., 2019a). An equally important indicator is Total Totals (TT) index. The difference in air temperatures at 850 hPa and 500 hPa is called the Vertical Totals Index, while the difference in dew points at 850 hPa and 500 hPa is called the Cross Totals Index. In the case of the Total-Totals index with values above 55, the risk of severe storms is significant, while when the index values are less than 50, the risk of storms development decreases. For the analyzed days, there were no storms in regions with TT values less than 38 °C (Fig. 9).

3.3. Factors overview and data comparison

As mentioned at the beginning of the study, mainly ERA5 data was used for the research. The data from reanalysisis has the record (x, y, z, t) and is collected in the grid values calculated from various sources. This is especially important for parameters that are sensitive to the small spatial and temporal variations in atmospheric profile, such CAPE

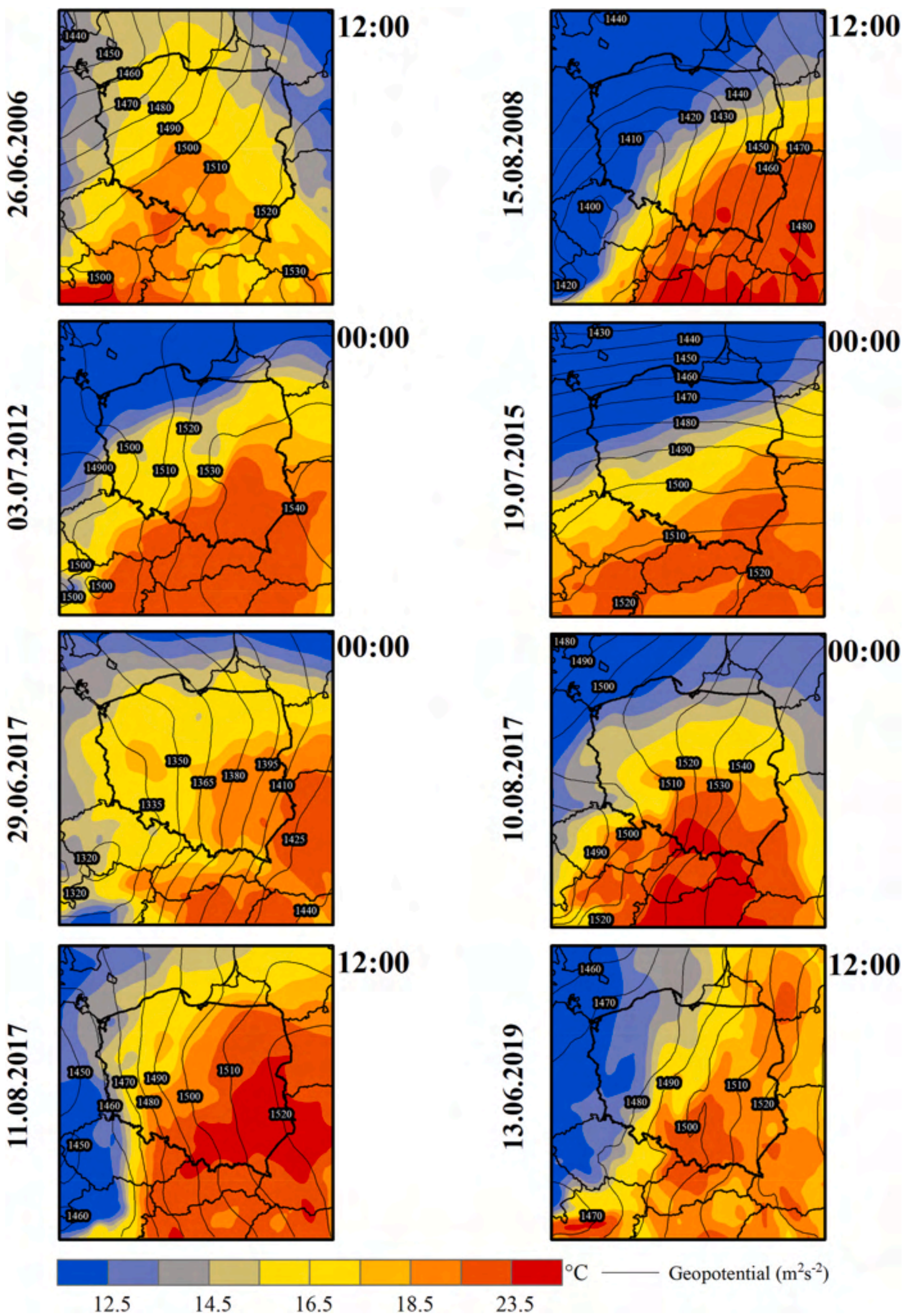

Fig. 6. Air temperature (shaded) and geopotential (contour) at 850 hPa in Poland on individual days and hours. Based on ERA5 data.

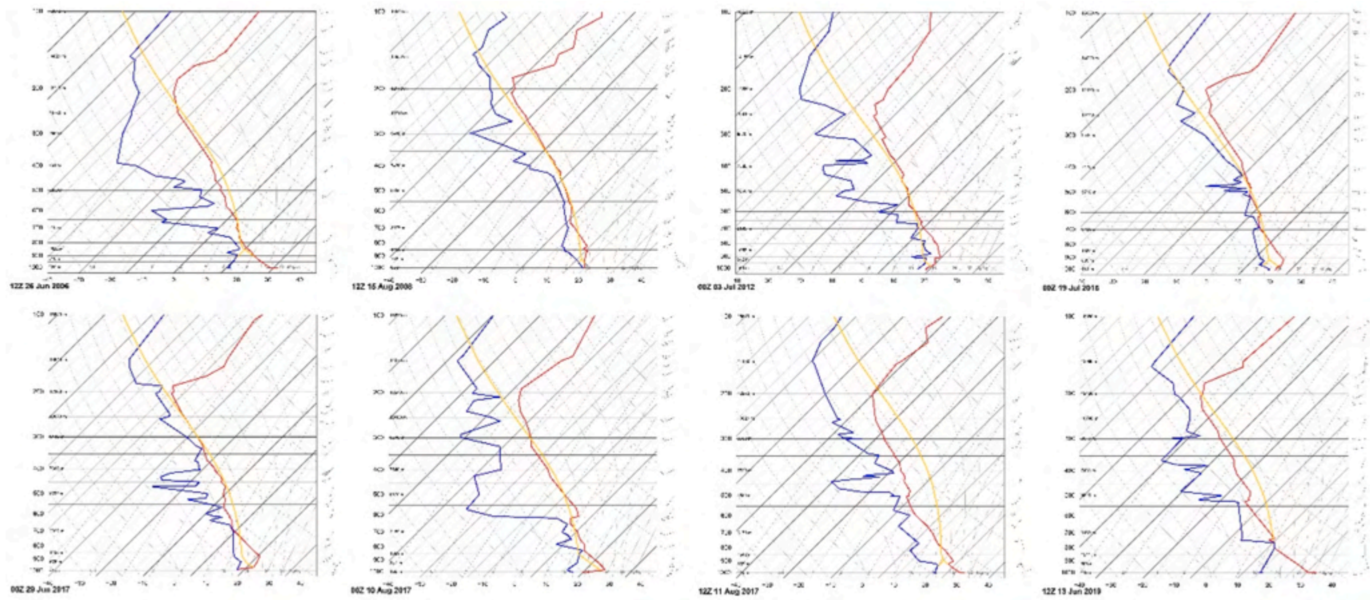

Fig. 7. Vertical profiles of air temperature (red line), dew point temperature (blue line) for individual days and hours measured in Legionowo (52°24', 20°56′). Orange line denotes most-unstable parcel. Source: University of Wyoming. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Potvin et al., 2010). During the 8 analyzed days, the mean CAPE values from the ERA5 data ranged from 250 J kg^{-1} to over 1880 J kg^{-1}. The lowest values of this factor occurred in the west of the country and in the regions of the Baltic Sea. As for the K-index, this index determines the probability of storms in compartments (less than 20 to more than 35). The index harnesses measurements such as vertical temperature lapse rate, moisture content of the lower atmosphere, and the vertical extent of the moist layer. This parameter is a measure of the potential for a thunderstorm to develop, calculated from the temperature and dew point temperature in the lower part of the atmosphere. The calculation uses the temperature at 850, 700 and 500 hPa and dewpoint temperature at 850 and 700 hPa. Higher values of K-index indicate a higher potential for the development of thunderstorms. Both the highest CAPE and K-index values occurred in places with the highest electrical activity of thunderstorms. The CAPE values measured by the rawinsonde differ from the data from ERA5. It should also be mentioned that for some places where measurements are take place, data was not available (Kaliningrad, Vienna, Lviv). However, in the case of K-index measurements, the data from the rawinsonde coincide almost identically with the data from ERA5 (Fig. 10). Summing up the total number of CG discharges that occurred, the day with the highest intensity of lightning undoubtedly was August 10, 2017, despite the positive Lifted index. However, the number of CG flashes located in a grid with an area of 100 km^{-2} was also similar on the night of July 2 to 3, 2012 (Table 1).

4. Summary and concluding remarks

In the climate of Central Europe, including Poland, the occurrence of thunderstorms is influenced by many factors such as location of the baric systems, direction of inflow and type of air mass or even direction and velocity of the jet stream wind. Earlier studies for Poland showed that the most favorable conditions for the formation of storms occur during the north-west cyclonal and north-eastern anticyclonal situation (Bielec 1998, 2000; Kolendowicz 2006). In Poland, the intensity and occurrence of thunderstorms days increases from the north-west (from the Baltic Sea – 15 t days per year) to the south-east (to the Carpathian mountains – 35 t days per year) (Taszarek et al., 2015). This research documents the atmospheric conditions and development of a severe weather outbreaks that occurred in the period 2002–2020 in Poland. The days on which the electrical activity of the storms exceeded 60.000 CG flashes were analyzed. Undoubtedly, the documented storms were the strongest storms since the measurements carried out by the PERUN discharge detection system in Poland. Taking into account the common features of all thunderstorms, it can be stated:

- The spatial distribution of CG flashes is not even,
- Highly electrically active storms can form both during the day and at night (the number of discharges is similar and does not depend on the time of day),
- Highly electrically active storms occur over Poland during the separation of two different air masses in the period June–August,
- Thunderstorms were initiated by the activity of the atmospheric fronts. They were most often created on the cold atmospheric front,
- The development of storms is positively influenced by the low baric center displacing hot tropical air,
- All analyzed storm cases has north and north-east direction,
- Before the occurrence of the storms, a large thermal gradient of 2 m AGL and 850 hPa is visible,
- Highly electrically active thunderstorms can also form at low CAPE with moderate wind shear,
- Annual number of thunderstorm days in Poland does not represent the intensity and electrical activity (intensity independent of the regions with highest numbers of t. days).

The analyzed storm systems were created in the environment of a high vertical wind shear (from 10 to 18 m s^{-1}), lifted index (from +0.04 to – 8.22), moderate thermodynamic instability (CAPE 1000–3700 J kg^{-1}), rich boundary layer moisture (mixing ratio: 12–14 g kg^{-1}), and high tropospheric moisture (precipitable water: 40–48 mm). However moisture and instability variables were not surprising for this time of a year given the climatology of central Europe (Taszarek et al., 2018). The days of August 10 and 11, 2017, when two extremely strong storms occurred one after the another, deserve special attention. August 10 will remain the day with the highest electric intensity in Poland since the measurements began, although August 11 will be the strongest wind storm in the history, Sulik and Kejna (2020). A better understanding of the storm's formation environment will allow it to be better monitored and forecasted in the future.

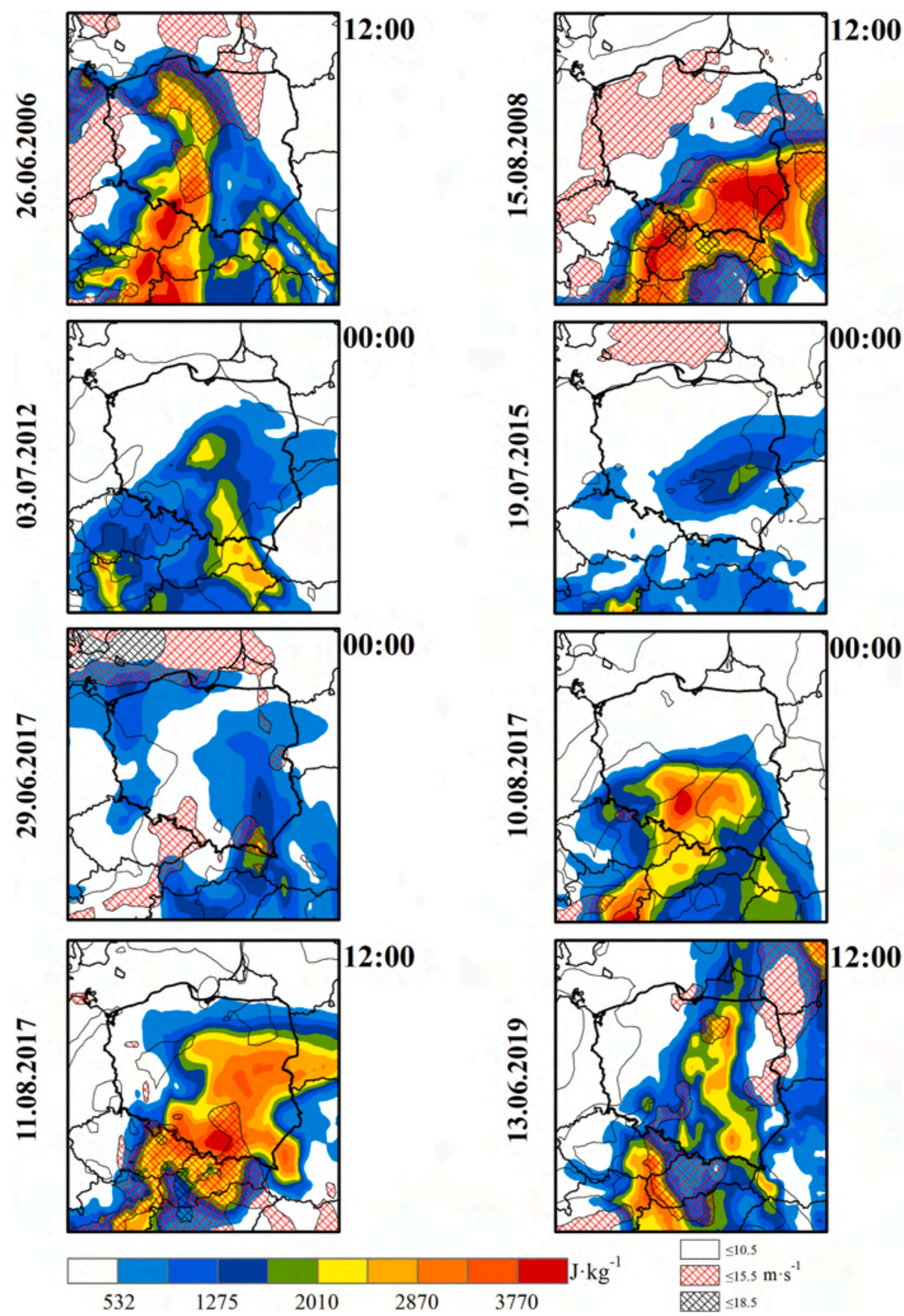

Fig. 8. Convective Available Potential Energy (shaded) and wind shear (contour) in Poland on individual days and hours. Based on ERA5 data.

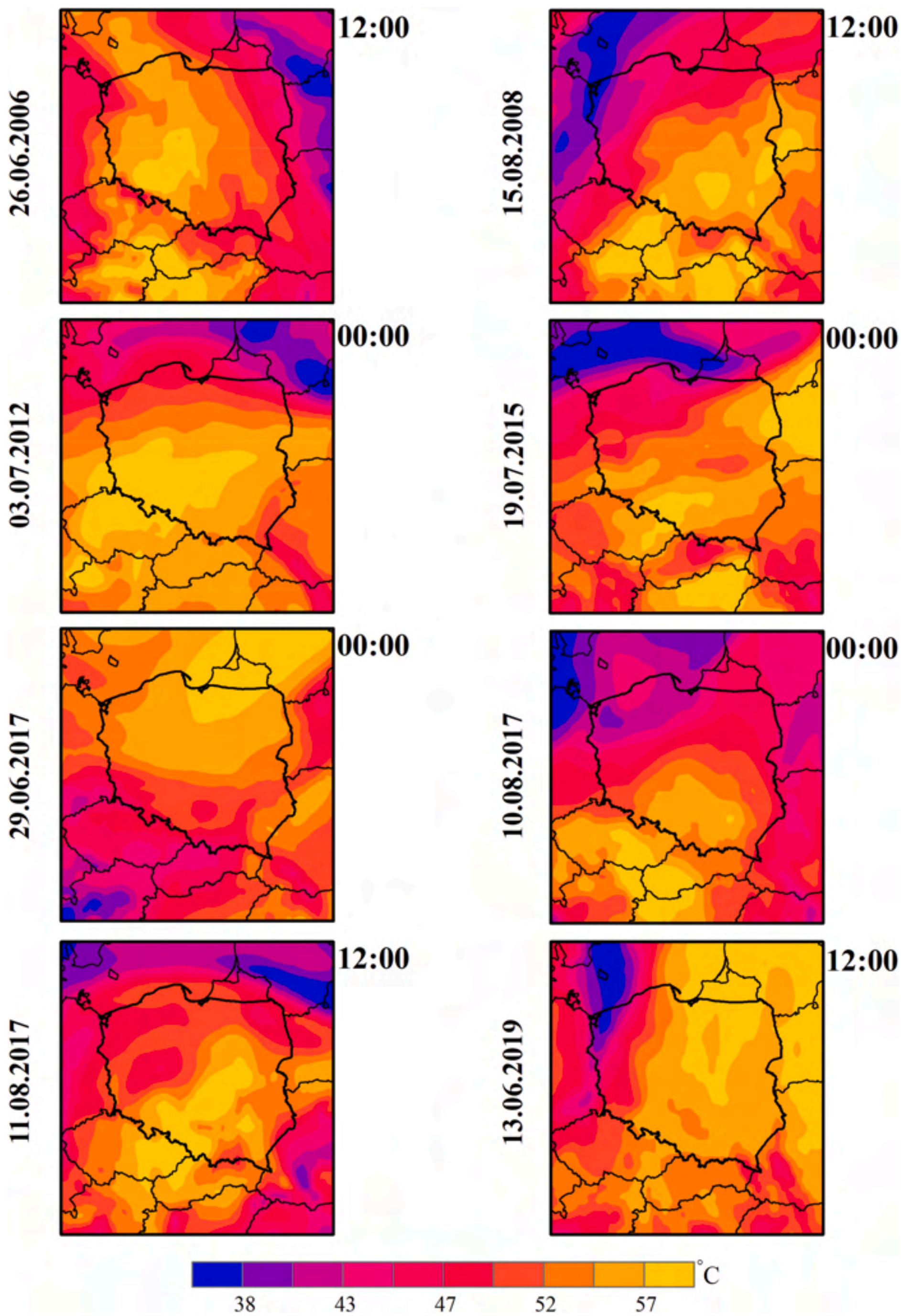

Fig. 9. Total Totals index for individual days and hours based on ERA5 data.

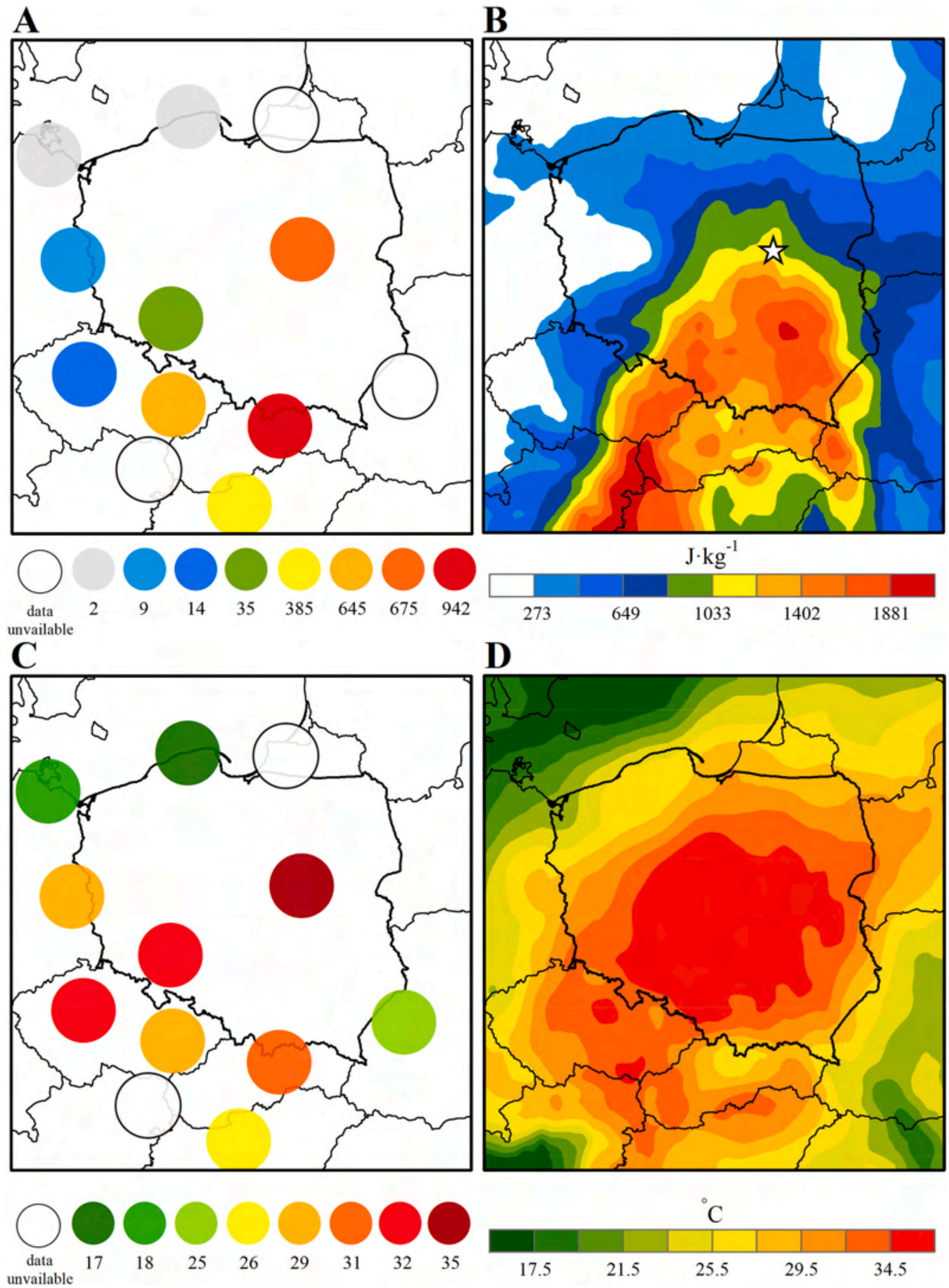

Fig. 10. A – Average CAPE values measured at rawinsonde locations during individuals days and hours. B – Average CAPE values in Poland based on ERA5 data during individuals days and hours (star symbol denotes location of Legionowo rawinsonde station for model soundings presented in Fig. 7). C – Average K-index values measured at rawinsonde locations during individuals days and hours. D – Average K-index values in Poland based on ERA5 data during individuals days and hours.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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SPATIAL DIVERSITY OF CLOUD-TO-GROUND LIGHTNING FLASHES IN THE KUJAWSKO-POMORSKIE VOIVODESHIP (POLAND), 2002-2019

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Abstract

This research focuses on the spatial diversity of cloud-to-ground (CG) flashes in the Kujawsko-Pomorskie voivodeship (Poland) based on data from the PERUN lightning detection system, 2002-2019. The storm season usually lasts from May to September, with July having the highest number of thunderstorms days and flashes. Thunderstorms most often occur in the afternoon. A generated grid of 5×5-km cells was used to characterise the variables related to CG flashes. In the analysed period 432,925 CG flashes were detected in the voivodeship (24,051 flashes year^{-1}). The highest electrical activity was found in the south-eastern part of the province. In grids with a large water surface, the number of CG flashes was small and increased with distance from the Vistula River. The distribution of atmospheric discharges in major cities of the region (Bydgoszcz, Toruń, Włocławek and Grudziądz) was random. Years with greater electrical storm activity (27,614 discharges in 2017) are interspersed with calmer years (5000-7000 discharges). There were found an upward trend in lightning discharges (of 1681 discharges year^{-1}) during period 2002-2019. To develop maps specifying the number of thunderstorm days, a 1×1-km grid cell was used with a 15-km radius buffer from the bin centre. The annual number of thunderstorm days in the voivodeship fluctuates from 27 to 41 days and increases from north-west to south-east. Consecutive days with a thunderstorm, the most common runs are of three days in a row with a storm. The number of thunderstorm days shows an increasing trend (0.82 days year^{-1}). This trend is related to the increase in air temperature in the storm season (Apr-Sep) reaching (0.04°C year^{-1}).

Key words

cloud-to-ground lightning • thunderstorm days • climate change • Kujawsko-Pomorskie voivodeship • Poland

Introduction

Thunderstorms pose a threat to human life, health and property. The danger is generated not only by severe wind, heavy rainfall and hail but also by cloud-to-ground (CG) lightning flashes. According to reports of Statistics Poland (GUS, 2020), on average 16 people die in Poland every year as a result of lightning. According to the European Severe Weather Database, in the period 2012-2014 in Poland there were over 100 storm cell transitions with high electrical activity, which killed 17 people (Taszarek et al., 2015).

Previous studies on lightning climatologies have been made very difficult by the lack of an appropriate system that would allow detection of lightning. Thunderstorm days were defined as the occurrence of an atmospheric discharge spotted by an observer, most often at a synoptic station. The results of years of observation made it possible to carry out climatological studies of storm phenomena, e.g. research by Bielec-Bąkowska (2013) in Poland. However, these observations did not allow the spatial differentiation of lightning discharges to be determined. The currently used detection methods enable detection of discharges and their division by type and charge. This makes it possible to calculate the number of discharges on a given day, with exact locations.

A number of studies have been published concerning various European countries. Based on data from the Austrian detection system, alternative to the Polish equivalent, Schulz et al. (2005) made a study covering 1992-2001 that proved that storms occur most often in the period from May to August, reaching the highest frequency in the southern part of Austria, where meteorological and topographic conditions are optimal for creating storms. In the study, the authors adopted a 1×1-km grid as the primary field. They found that on average there are 4 CG flashes $km^{-2}·yr^{-1}$. The same grid cell was also used in research for Germany and the surrounding area, but Wapler (2013) received as many as 30 discharges per square kilometre. Similar studies were conducted in the Czech Republic using 20×20-km grids, this time with average discharge values in the range of 1-3 flashes $km^{-2}·yr^{-1}$ (Novák & Kyznarová, 2011).

Research in Portugal has shown the occurrence of a storm season from May to September with a peak period from 16 to 18 UTC (Santos et al., 2012). In Spain, Soriano et al. (2005) analysed ground discharges for fields with dimensions of 0.2×0.2°. The team showed a relationship between lightning and local topography and atmospheric circulation with a maximum of occurrence in the Pyrenees and a minimum around the coast of Catalonia (2 discharges yr^{-1}). In Italy, using fields with dimensions 0.1×0.1° Biron (2009) decided to use a 10×10-km grid field using the Italian detection system (LAMPINET). The highest frequencies of discharges in the period 2005–2007 were recorded in the area of Lake Como, Sardinia, the bay of Trieste and the central Apennines.

In northern Europe, in Sweden, research was conducted for the years 2002-11 for fields with dimensions identical to those of Spain, and the existence of a storm season usually lasting from June to August was confirmed. Work on Finland was combined with research for the United States and was carried out by the team of Mäkelä et al. (2011) with a 20×20-km field, while Enno (2011) performed a study on Estonia for the period 2005-09 with a 10×10-km grid field.

The latest research, from 2019, covering the area of Europe (including Poland) has shown and confirmed the peak of storm activity in July and August. There was also an increase in thunderstorm days, especially in the Alps, and in central, south-eastern and eastern Europe (Taszarek et al., 2019). To explain the conditions of storm formation and discharges, the authors of that publication used meteorological data obtained from vertical atmosphere surveys, observations from synoptic stations, data on discharges from ZEUS and EUCLID and reports on weather hazards. The study describes annual storm cycles with days with a thunderstorm and their spatial extent.

In Poland, atmospheric discharge studies were made possible by the 2002 introduction and continuous development of the detection system called PERUN. This made it possible to refer to previous synoptic observations regarding, among others, the development of the number of days with a storm for Poland by various authors: Kolendowicz (1996, 2006); Bielec (2000) and Bielec-Bąkowska (2013). Values of thunderstorm days obtained on the basis of visual observations ranged from 15 days in the Baltic Sea region to 33 days in the Carpathian region (Lorenc, 2005; Bielec-Bąkowska, 2013). In 2015, a study was developed by authors from the Adam Mickiewicz University in Poznań, where Taszarek et al. (2015) analysed data obtained from the PERUN detection system for Poland for the period 2002-13. To create this analysis, the authors used ground discharges in a 10×10-km reference field. To determine the days with the storm based on the discharges, a 1×1-km field grid was used and a buffer of 17.5 km was derived from the centre of each field. During a day with a thunderstorm, they reported only on situations in which at least two CG flashes were recorded in the area. The authors found as many as 4,328,892 discharges throughout the entire period studied, with an average of 151 days of storm each year throughout the country. The increase in the number of thunderstorm days from the Baltic Sea towards the south-east was also confirmed. The storm season usually lasts from May to August, with July as the month with the highest frequency of storms. Most of the recorded storms occur during the day, with a maximum around 14:00 and a minimum around 07:00. Importantly, almost 97% of all discharges had a negative charge and only 3% positive. By contrast, discharges with a positive charge occurred more often in winter than in summer.

The aim of this article is to provide a spatial analysis of the days with a storm and CG flashes in a smaller area – the Kujawsko-Pomorskie voivodeship. This Polish province is characterised by slight differences in hypsometry, but a significant diversification in land use (Fig. 1B). There are agricultural areas and extensive forest complexes here. The largest river in Poland, the Vistula River, flows through the voivodeship, which may affect the movement of storms. The analysis examined the variability of lightning throughout the year and day, as well as the variability and trend of the number of days with storms and CG flashes in the analysed period (2002-2019).

Dataset and methodology

By courtesy of the Instytut Meteorologii i Gospodarki Wodnej (PIB), we were able to build a database of lightning strikes detected by the PERUN network. This network is part of a European lightning detection system SAFIR (Surveillance et d'Alerte Foundre par Interferometrie Radioelectrique). Polish part was launched in 2002 and since that, the system has been nicknamed as PERUN, in reference to the god of thunder and lightning in Slavic mythology (Bodzak, 2006; Czernecki et al., 2016).

The whole lightning measuring network is combined into nine stations located in different regions of Poland: Gorzów Wielkopolski, Częstochowa, Kalisz, Toruń, Sandomierz, Warsaw, Olsztyn, Białystok and Włodawa (Fig. 1A). To distinguish between type of flashes, low-frequency electromagnetic waves was used. Due to this, system detects lightning flashes categorised into (CC) cloud-to-cloud, (IC) intra-cloud and (CG) cloud-to-ground and it's capable to detect up to 100 strikes per second. The introduction of the new system in Poland creates new opportunities to conduct specific research on the spatial distribution of lightning. The locations of lightning strikes are saved in a lightning listing, along with other parameters such as current charge time, numbers for recognising type of lightning. However, detailed discharge data such as polarity, peak current estimate (kA)

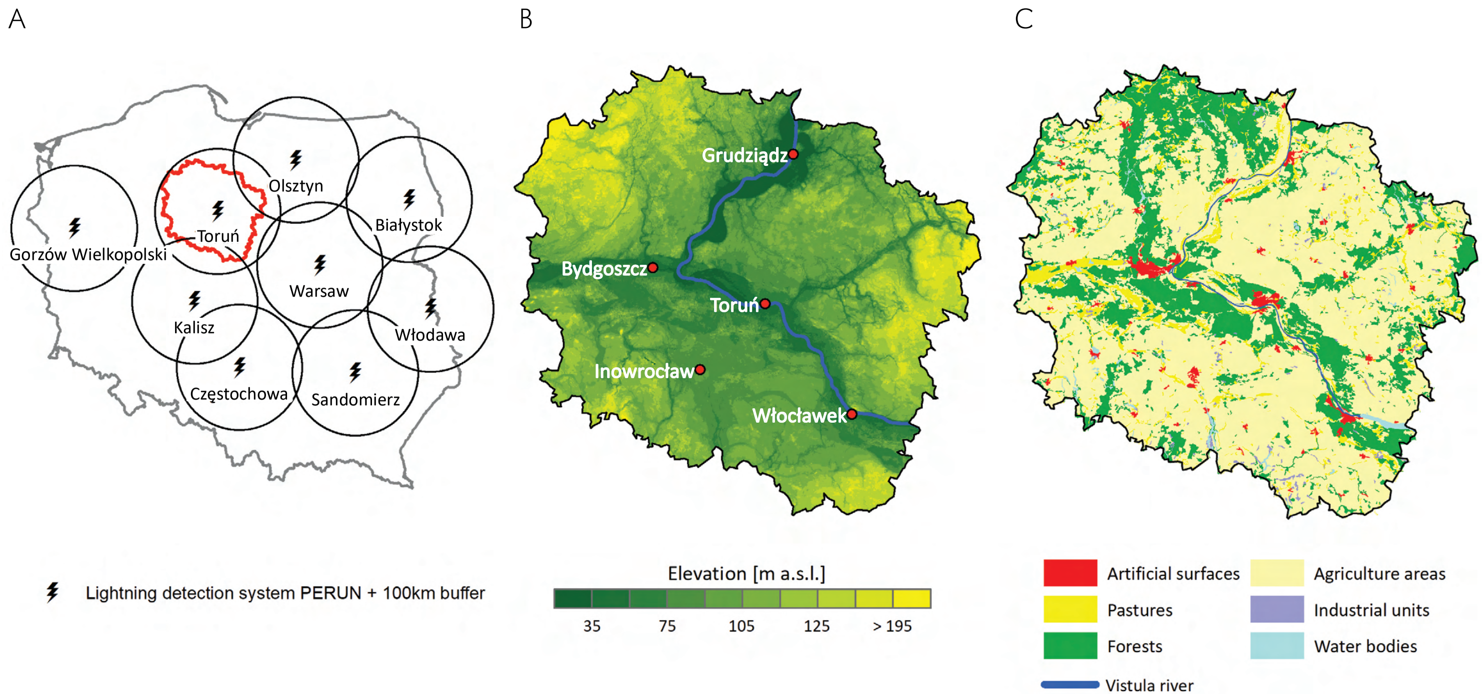

Figure 1. A – Locations of SAFIR3000 lightning sensors in the PERUN network with 100-km buffer zones (black circles) and administrative borders of study area (red line) – (Sulik & Kejna, 2020). B – Hypsometric map of Kujawsko-Pomorskie voivodeship based on the Shuttle Radar Topography Mission Global Coverage (SRTM3) – based on Land Copernicus (2018). C – Kujawsko-Pomorskie land use map based on CORINE Land Cover (2018)

and multiplicity is available only for CG flashes. Due to location errors in detection of CC flashes, only CG flashes were used. Importantly, in the case of ground discharges with a negative charge, these types of discharges tend to "strike" several times during one discharge in one and the same place (multistrokes). Therefore, when processing data, only the first discharge that took place was taken into account.

Taking in account previous studies, it was shown that a reliable accuracy for flash density can be achieved when an average of more than 80 flashes occurs in each grid cell (Diendorfer, 2008). In case of that, we used a 5×5-km grid cell, and we believe it's optimal unit. The calculated data were separated for the administrative area of the Kujawsko-Pomorskie voivodeship. The discharges are geographically located in decimal units (WGS84). Due to the local reference system, it was necessary to convert the coordinates from WGS84 to the Polish metric PUWG (EPSG: 2180) system. The methods are similar as employed in Sulik & Kejna (2020).

In this study we use a resolution of 5×5-km grid, and we believe that this is the most appropriate for our database and research area. In the area of the Vistula River and cities, we use a 0.5×0.5-km cell grid for smoother analysis. For this purpose, the ESRI ArcMap program generated a grid for the Kujawsko-Pomorskie voivodeship. The average number of CG flashes and their maximum daily values were calculated for each grid annually, providing their number per km^2. The same procedure was used to analyse the course of annual discharges for each of the 18 years. As the system locates discharges over time, this type of data was used to plot the course of the daily discharges and these were compiled on charts.

A thunderstorm is a local phenomenon, but an observer can see it from many kilometres away. Often, storm phenomena such as lightning are visible, but they are not experienced in the immediate vicinity of the station. In the climatological literature concerning the area of Poland, it is possible to distinguish various directions of research on storms. It was sometimes difficult to distinguish thunderstorm days based on meteorological observations, due to the horizon being covered or light pollution of the sky, which often occurs at meteorological stations located in cities. Detection systems have overcome these obstacles to determine the number of days with a storm for a selected area, especially for areas where there are no weather stations.

It should be noted that a lightning discharge is visible and audible even from a distance of about 15 kilometres, (Wu et al., 2016) and in an open area, without trees or other elements obscuring visibility, it is visible even from a distance of about 30 km. To refer to earlier standards and guidelines for calculating the occurrence of a storm on a given day, a 1×1-km grid cell was used, from which a buffer was derived in the form of a circle with a radius of 15 km. Similarly, a thunderstorm day was counted when at least one lightning strike (in this case CG) occurred inside this circle. For the statistics on the number of lightning discharges and spatial diversity, only discharges that occurred only within the voivodeship's borders were taken into account.

Results

Thunderstorm days

In Poland, there is quite a significant variation in the number of thunderstorm days. Their smallest turnout is recorded in the north of the country within the Baltic Sea coast (15 days), and their number increases to the south-east (33 days in the Tatra Mountains – Bielec-Bąkowska, 2013). Therefore, the highest discharge activity occurs in central Poland. This is also the area of conditions most favourable to the formation of tornadoes, as documented in another study by Taszarek et al. (2015).

Taking into account the lightning strikes within 15 km, 737 days with a storm were found in the Kujawsko-Pomorskie voivodeship in the years 2002-2019. The average number of days with thunderstorms shows quite a wide variation from 27 to 41 days year^{-1} (Fig. 2). The most days with thunderstorm occurred in the eastern part of the province. However, there were clearly fewer days with a storm in the in large forest complexes (Bory Tucholskie – north-west, and in the Bydgoszcz-Toruń Basin – central part of a map).

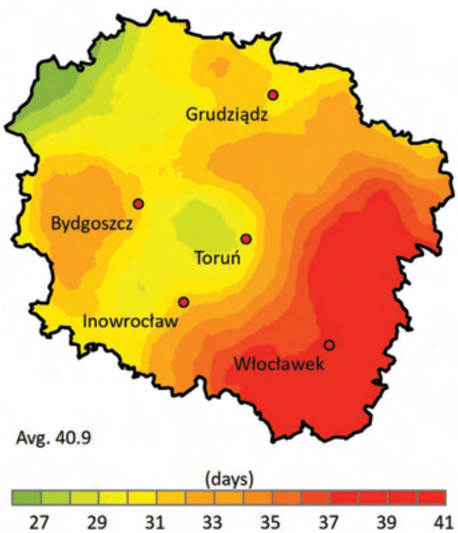

Figure 2. Average number of thunderstorm days in the Kujawsko-Pomorskie voivodeship during the period 2002-2019, based on lightning data from the PERUN network

The results obtained from the remote-sensing method differ from previous studies based only on meteorological stations, which for the area of the Kujawsko-Pomorskie voivodeship showed an average of 23 days with a thunderstorm (Bielec-Bąkowska, 2013). These differences may be related to significant distances between stations, e.g. only two synoptic stations, in Toruń and Bydgoszcz, operate in the province. Hence, for many regions, the number of days with a storm was interpolated and extrapolated. Remote-sensing data is therefore more reliable.

Analysing individual years it can be seen that, in each of the years there are areas in different parts of the province that have a higher occurrence of storms (Fig. 3). The south-eastern part of the province dominates as the area where the most thunderstorms occur. This area was also marked in the study of Taszarek et al. (2015) and it is also a small fragment of the extensive storm trail occurring from Mazovia to the regions of the Great Masurian Lakes.

Annual CG lightning flash density

In the whole period under study (2002-2019), the PERUN lightning detection system detected over the Kujawsko-Pomorskie voivodeship 432,926 CG discharges, so each year there were on average 24,051 CG lightning flashes. The most atmospheric discharges occurred in the eastern part of voivodeship (Fig. 4A). This area belongs to the storm trail crossing Poland (Taszarek et al., 2015). Furthermore, based on the development of data from the ATD system for the period 2008-2013 (Anderson & Klugmann, 2014) and from the EUCLID system for 2011 (Pohjola & Mäkelä, 2013) this area was determined to be characterised by an increased occurrence of CG flashes. The computed map shows an area with a much lower frequency of discharges in the north-western part of the voivodeship, and in the Lower Vistula Valley (the Bydgoszcz-Toruń Basin). However, analysing the spatial distribution of storms in the voivodeship, one can also see that weak storm cells expanding over areas such as arable land (low albedo) that are directed by pressure gradients over the Vistula riverbed area often disintegrate due to streams carried by river-cooled air that limits convection. Also, areas located close to the river such as forests or smaller trees have a lower air temperature. Therefore, individual storm cells also often move along the Vistula, without going to the other side, while also strengthening.

The maximum daily discharges amounted to 13.5 flashes km^{-2} (Fig. 4B). Also, a lot of CG flashes (13 flashes km^{-2}) occurred in the north-central area. This means that some storm cells are able to generate more discharges in a given area one day than they

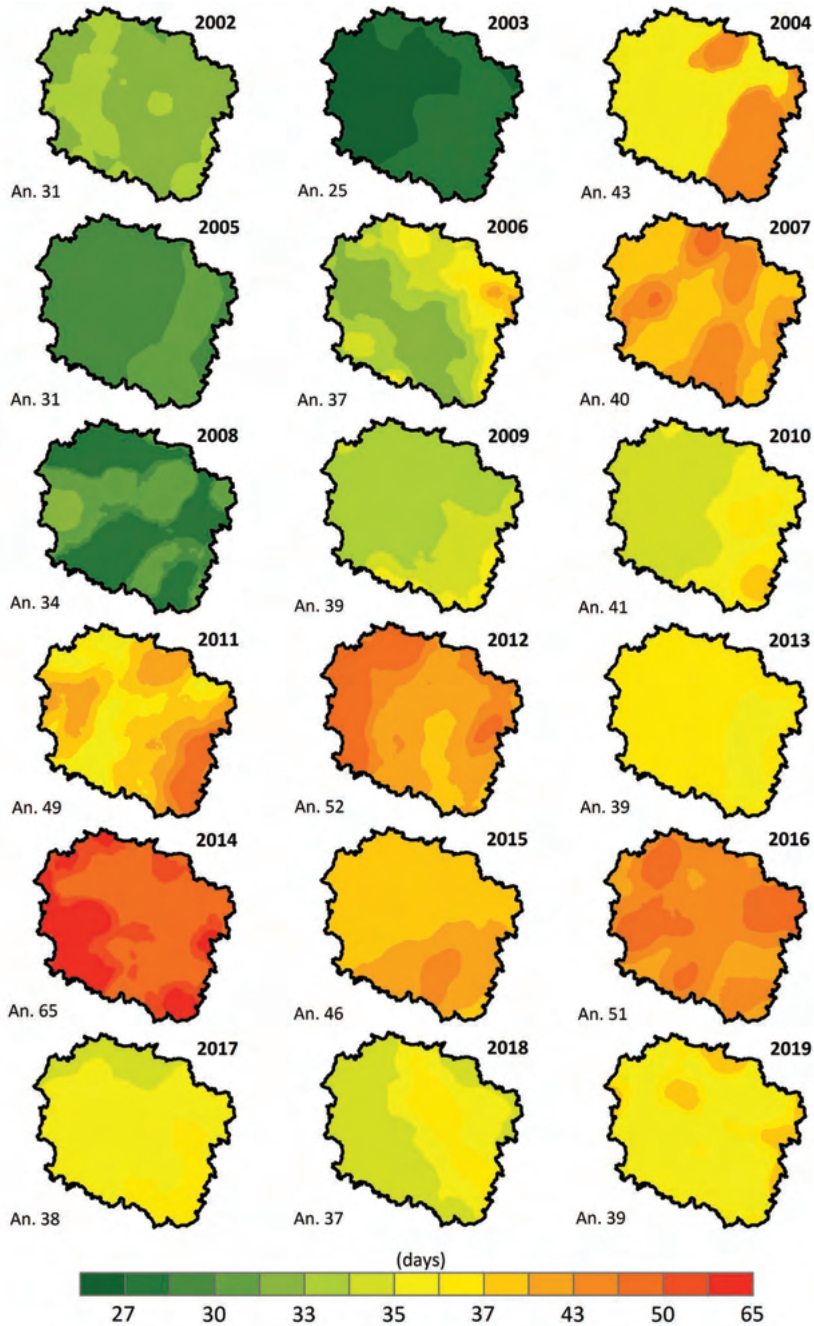

Figure 3. Annual number of thunderstorm days in the Kujawsko-Pomorskie voivodeship during the period 2002-2019, based on lightning data from the PERUN network

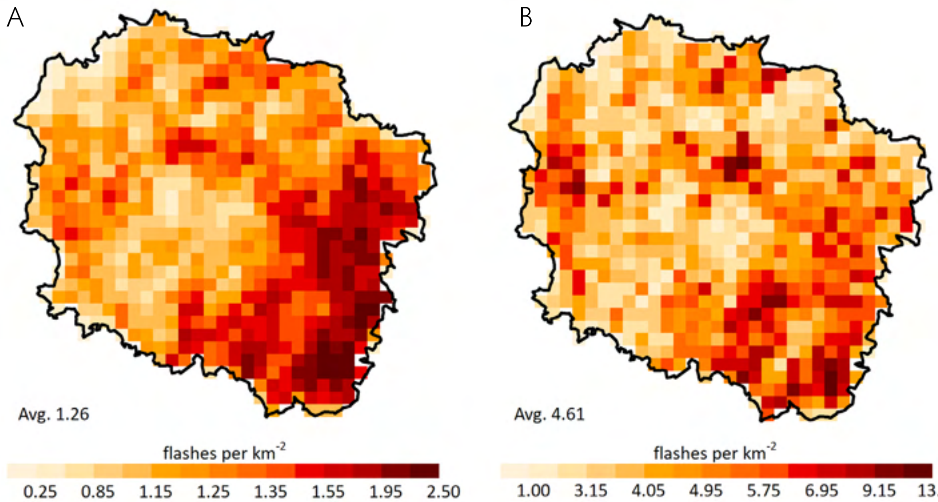

Figure 4. Number of CG flashes km^{-2} in the Kujawsko-Pomorskie voivodeship during the period 2002-2019. A – the annual average, B – the daily maximum. Lightning densities are computed for 5×5-km grid cells, based on lightning data from the PERUN network

do throughout the year in other areas. This type of storm is referred to as a "mesoscale convective system" (MCS) (Houze, 2004), which is characterised by high electrical activity due to the strong development of storm cells. Thunderstorms of this type do not occur in Poland very often, but their occurrence determines the spatial distribution of CG flashes. This was the case on, for example August 10 and 11, 2017 (Sulik & Kejna, 2020).

In each case of the analysed years of this period, a slightly different spatial distribution of discharges is noted in the voivodeship. However, there are clearly more discharges in the east of the voivodeship. The lowest values were recorded in the central part of the study area and in the north-west (a region of forest land). In the spatial distribution for the period 2002-2019 (Fig. 5) it is hard to clearly determine the impact of land cover or its influence on the occurrence of increased discharges. However, the dominant direction of movement of storm cells from south-west to north-east is clearly noticeable. This corresponds to the typical movement of air masses in moderate climatic zones (inflow of polar-sea air from the west and tropical air from the south). The prevailing wind direction in Poland is westerly, so in central Poland there are sometimes conditions favourable to the formation of storms and movement to the north-east, often taking well-developed (mature stage) forms of Cumulonimbus cloud already in the province. In this case, various forms of spatial differentiation in terms of storm activity are visible. The occurrence of far calmer years is associated with a much cooler summer in months characterised as months in which severe weather phenomena occur. The marked eastern corridor of passing storms in the Kujawsko-Pomorskie voivodeship seems to be disappearing or even inactive in 2013. Most of the storms in that year were concentrated in the central part of the analysed area. Undoubtedly, the strongest storm incident occurred over two special days in August 2017 when, during one day, a storm supercell generated a significant number of discharges exceeding the total number of recorded discharges for one year. Therefore, August 2017 was the year with the largest number of atmospheric discharges recorded in the Kujawsko-Pomorskie voivodeship since the beginning

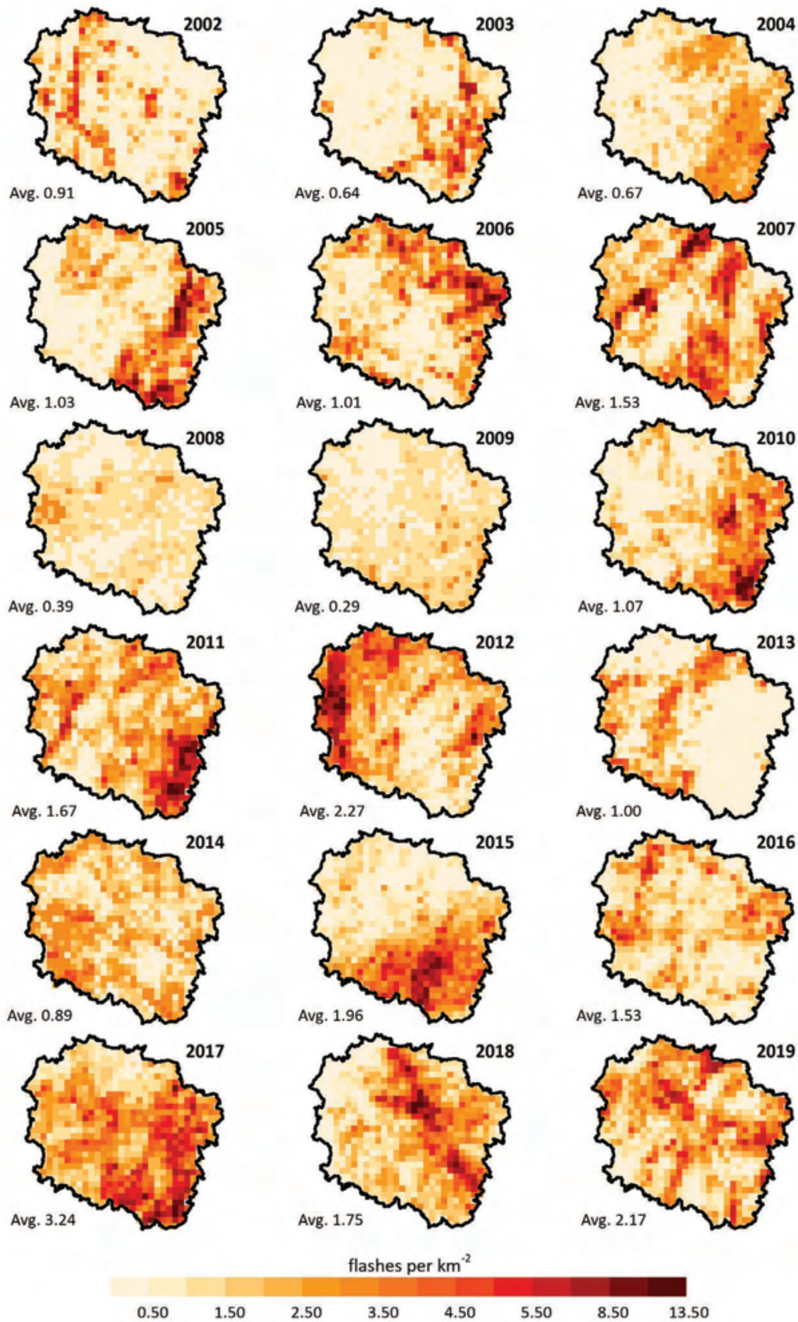

Figure 5. Annual number of CG flashes km^{-2} in the Kujawsko-Pomorskie voivodeship during the period 2002-2019, based on lightning data from the PERUN network

of the PERUN detection system. There were 58,288 discharges detected at that time, of which 44,823 were on August 10 and 11 (Sulik & Kejna, 2020).

The impact of rivers and cities on lightning flash density

Local topographic conditions can significantly affect the movement of storm cells and the spatial distribution of lightning. Storm activity is much more diverse in mountain areas than at the seaside (Bielec-Bąkowska, 2013; Taszarek et al., 2015). In the lowlands, therefore, high-temperature land surfaces and much cooler areas of forests or vast rivers and lakes have a great impact on the formation of storm clouds.

The main axis of the Kujawsko-Pomorskie voivodeship is the Poland's largest river, namely the Vistula. In the studied area, the river flows for a distance of about 300 km. On this section, the Vistula riverbed is 0.3-1.0 km wide. An artificial reservoir on the Vistula in the vicinity of Włocławek is the only larger open water body (average 1.5 km wide). To determine how the occurrence of lightning depends on the Vistula River in the voivodeship, a strip (buffer) was designated at a distance of 10 km from the river, containing 10 separate sub-buffers of about 1 km wide. The entire 18 years of PERUN system measurements were calculated in grids of 0.5×0.5 km so as to render and present the spatial differentiation of discharges as precisely as possible.

The general spatial distribution of CG discharges in the Vistula region is quite diverse. In the whole 10 km buffer area, about 95,165 CG flashes were detected (Fig. 6). A significantly smaller number of CG flashes were found in the grids through which the river flows (2758 flashes), while in the belt 1-2 km from the river there were 9017. When analysing the values in the remaining buffers further from the Vistula River, a slight increase in discharges can be observed, sustained in the range above 9000 flashes. Therefore, it is confirmed that the river's influence on the number of CG flashes is only marked in its immediate vicinity. The cooler water in the summer season has a lower convective potential for the development of storm clouds.

The general spatial distribution of discharges is also confirmed for urban areas (Fig. 6). Urban areas are characterised by a diversified structure of land use. There is dense development and there are anthropogenically transformed areas. In urbanised areas, an urban heat island is created (e.g. in Toruń it reaches 1°C – Przybylak et al., 2017). Atmospheric instability increases above the hot areas, which favours the development of convection clouds. The discharges generated from the Cumulonimbus cloud are initiated by high objects located in cities. The average values of annual CG discharges increase in a south-eastwards direction with the values of 7.2 discharges in Grudziądz to 12.5 in Włocławek. However, when analysing the distribution of the CG discharges, no regularity was found (Fig. 6).

Annual course of CG lightning flash density

The previously mentioned climatological studies on the electrical activity of storms in Poland were examined by Taszarek et al. (2015). Those authors said that the most storm activity was in the warm half of the year, with a maximum in July.

The analysis carried out in this study proves that the storm season in the voivodeship begins in April, especially in its second half, and lasts until September. July is the month with the most electrical storm activity. The months from May to the end of August are characterised by a significant number of hot or very hot days. In summer, thunderstorms often occur on the atmospheric fronts, when cooler polar-sea air displaces hot tropical air. In June, storm trails are visible in the central-western part of the region (Fig. 7). In July and August, the maximum electrical activity of storms occurred in the eastern part of the province.

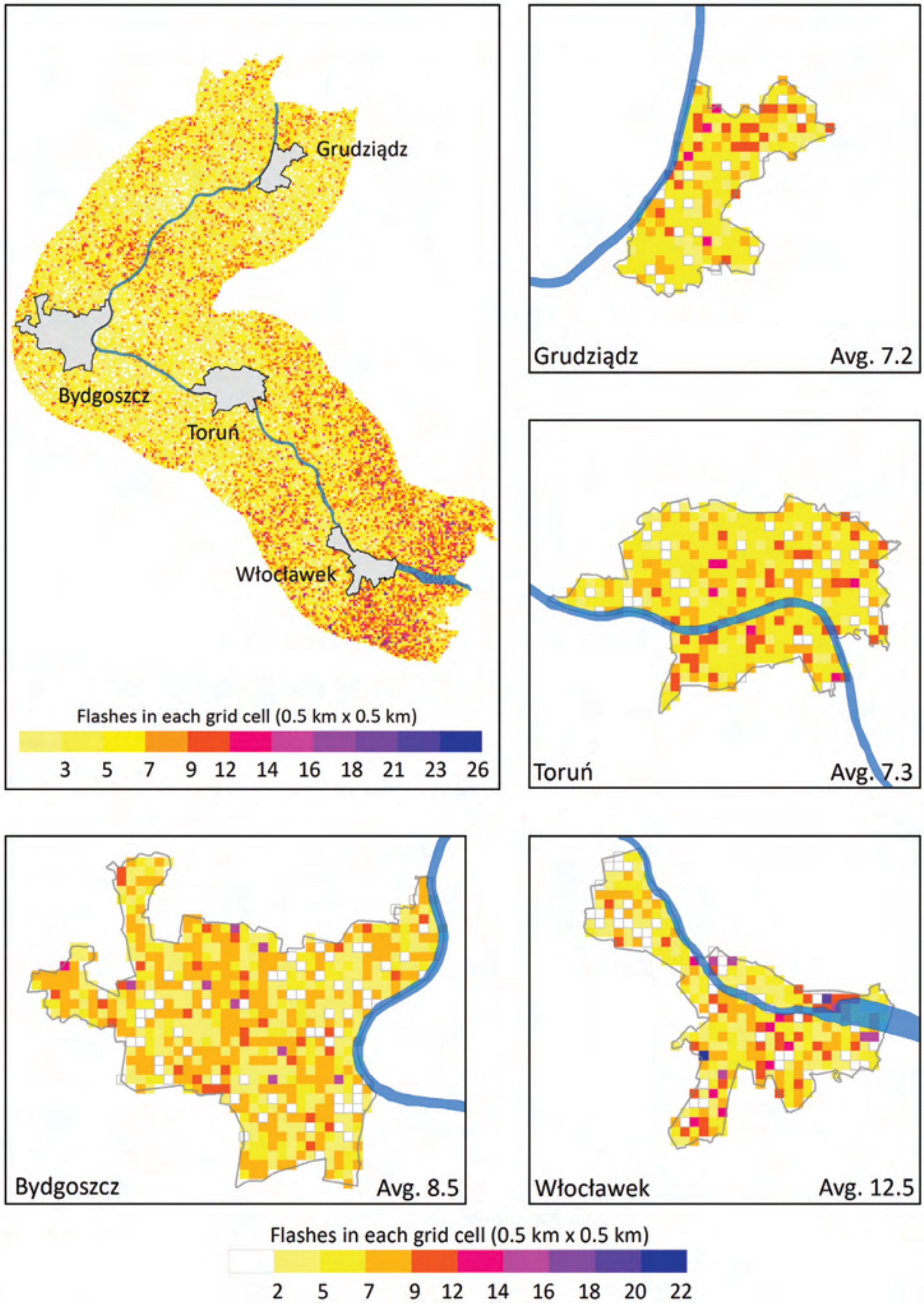

Figure 6. Annual number of CG lightning flashes computed in 0.5×0.5-km grid cells, 2002-2019. Spatial diversity computed in 0.5×0.5-km grid cells for Vistula riverbed with 18-km buffer. Based on lightning data derived from the PERUN network

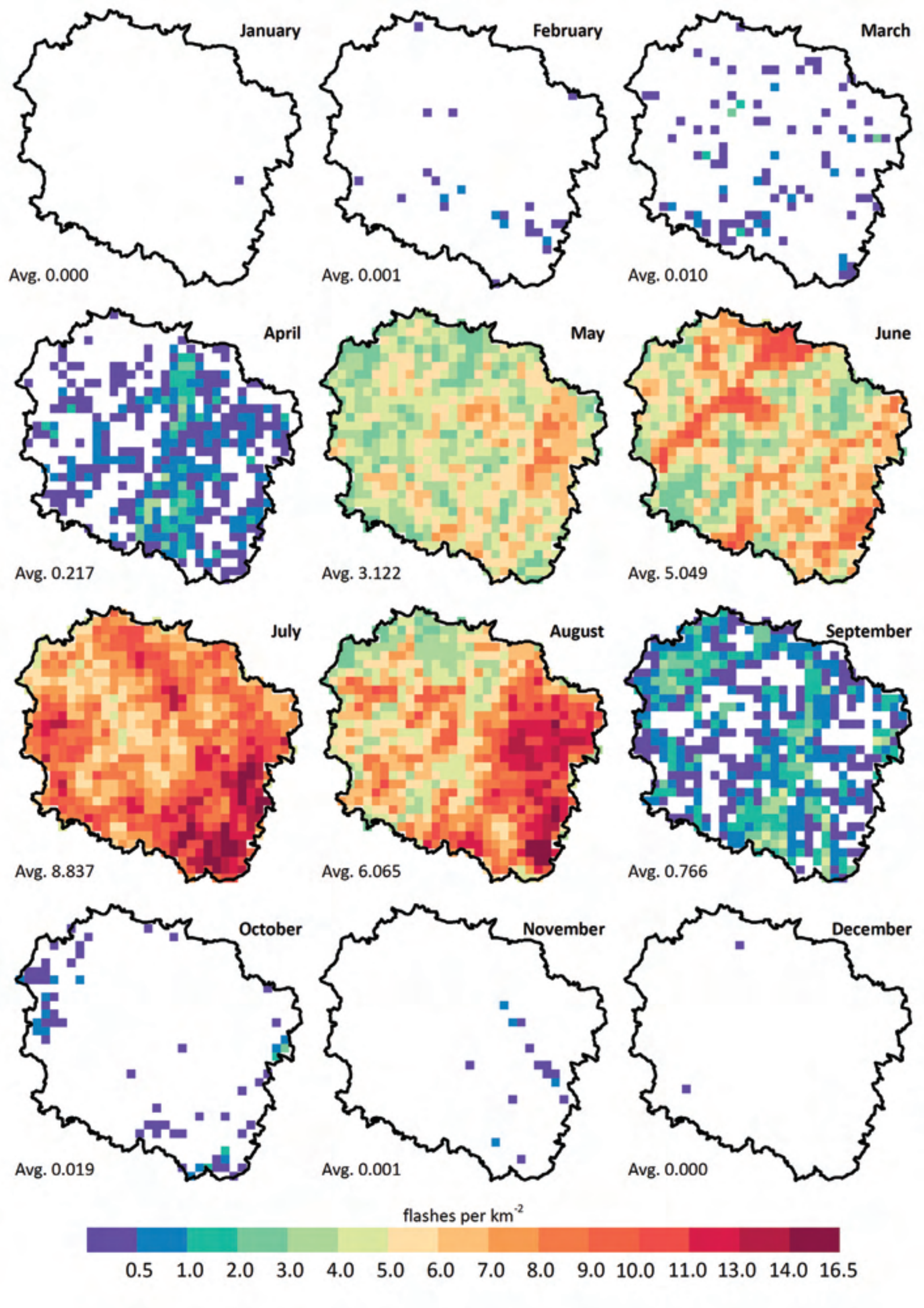

Figure 7. Average monthly number of CG flashes km^{-2} in the Kujawsko-Pomorskie voivodeship during the period 2002-2019, based on lightning data from the PERUN network

In some years, there were months with increased electrical storm activity. The aforementioned case of the formation of a supercell storm is not the only one in the history of measurements in the province, though it is the most extreme. Equally strong storm incidents in one month are evidenced by data from July 2012, where the detection system detected 31,699 discharges. Similarly, on August 10, 2017, the powerful MCS system generated more than 20,000 ground discharges in one hour in the abovementioned area (Sulik & Kejna, 2020).

Daily course of CG lightning flashes

Time of day is also important in forming storms and electrical phenomena. In many regions of the world there is a tendency for them to increase in frequency in the afternoon, when daily air temperatures are the highest (Kotroni & Lagouvardos, 2016). This research analyses the daily course of storm incidence and atmospheric discharges in individual months (Fig. 8). In the period 2002-19, storms occurred most often between 14:00 and 18:00. However, thunderstorms are possible at other times of the day. They are most often associated with storms of frontal genesis.

In January and February, due to the lack of conditions favourable to the formation of storms, discharges practically do not occur, and if they are recorded by the detection system, this usually happens between 11:00 and 18:00. March is a month in which storms are also few and the number of discharges is negligible, reaching a maximum of 3.8 discharges from 12:00 to 13:00. The storm season in Poland begins in April, and especially in its second, much warmer half. In the surveyed period, in April, on average, there were even 50 discharges recorded in the warmest period of the day from 13:00 to 16:00. Intensive influx of solar radiation, ground heating and much higher temperatures during the day determine the significant activity of storms in the afternoon. In May, the peak of electrical activity occurs from 16:00 to 18:00. In June, apart from the intensification of discharges in the afternoon, there was a second maximum in the morning. This is related to atmospheric fronts, on which complex multicellular clusters are often created that generate an increased number of lightning discharges, hence recorded average values exceeding 300 discharges. In July and August there is the largest number of storms and the lightning strikes they generate. According to research by Bielec (2000), storms can occur at any time during this period, but as in the case of other months, their peak falls between 11:00 and 18:00. The tendency for maximum storm activity in the afternoon is confirmed during this period (Fig. 8C). The autumn months are the period during which storm activity gradually disappears. However, not infrequently, especially in the years 2017-19, in the early days of October, residual air of tropical origin increases the formation of Cumulonimbus clouds generating single lightning strikes. Such a process is also determined by the advancement of air masses from the west and the movement of fronts on which storms form. On average, at the peak time of 13:00 to 14:00 there were only 7 discharges in October, which means that the storm season is over. Storm activity is negligible in November and December (Fig. 8D) and, in the daily course, the maximum number of storms and lightning occurs in the afternoon.

Trends and patterns

It can be assumed that progressive climate change will contribute to extending the duration of the storm season and, consequently, storm activity (Taszarek et al., 2015). In the Kujawsko-Pomorskie voivodeship there is a significant variation in the number of days with a storm in individual years. There is a clearly visible upward trend in the number of days (0.82 days year^{-1}) (Fig. 9B). According to the adopted methodology, the fewest storm days occurred in 2003 (25 storm days). The highest number of thunderstorm days was in 2014 (65 days).

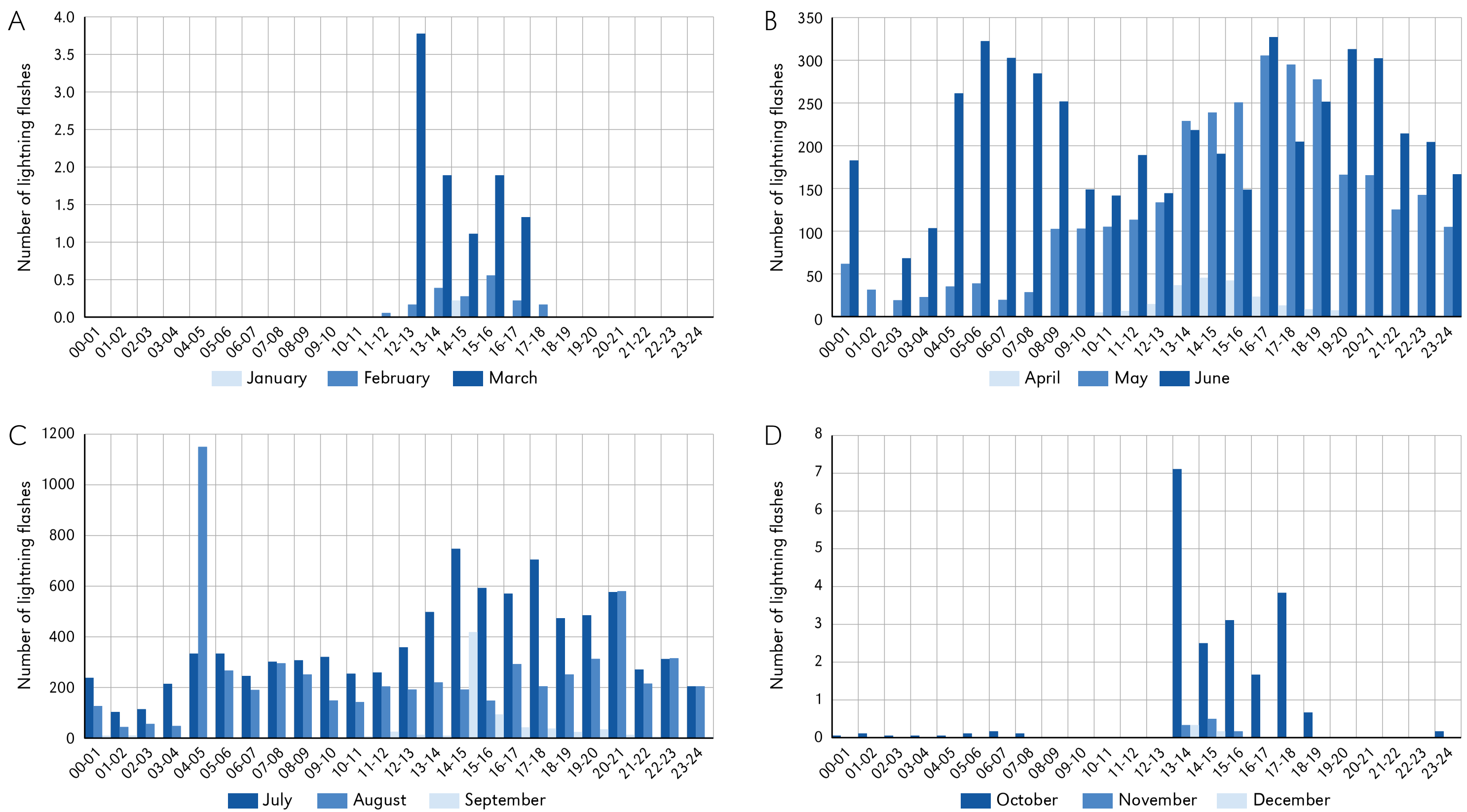

Figure 8. Hourly distribution of CG lightning flashes in the Kujawsko-Pomorskie voivodeship, 2002-2019. A – January to March. B – April to June. C – July to September. D – October to December. Based on lightning data derived from the PERUN network

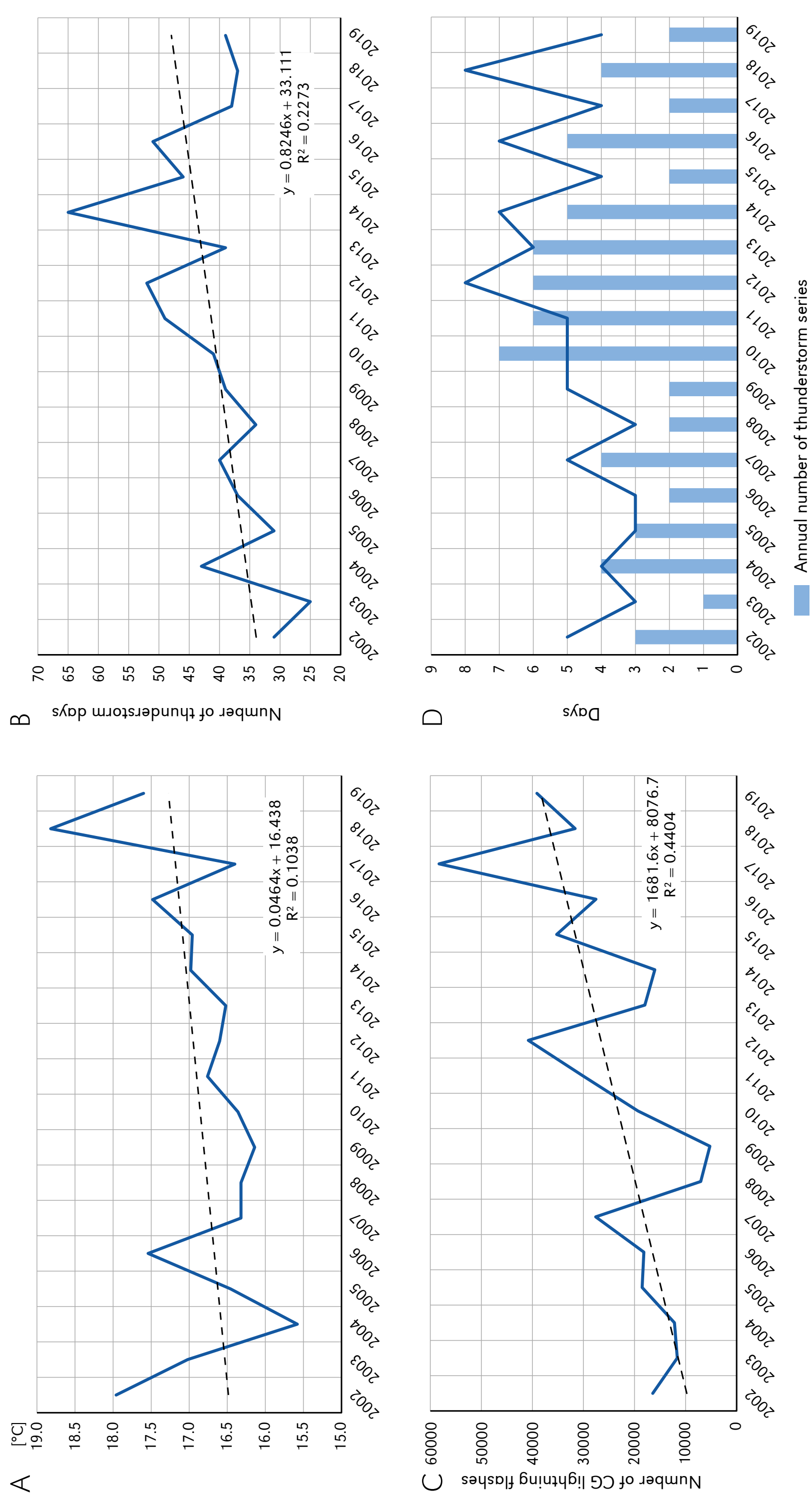

Figure 9. A – Average air temperature measured in May–Sept at synoptic station in Toruń (Wrzosy). B – Annual number of thunderstorm days. C – Annual number of CG lightning flashes and D – Sequences of thunderstorm days in the Kujawsko-Pomorskie voivodeship, 2002-2019. Based on lightning data derived from the PERUN network and IMGW

Throughout the period considered, years with great storm activity are separated by calmer years. The number of three-day storm series is also increasing. In the analysed period, two strings of eight days in a row with a storm were found (Fig. 9D).

In the voivodeship in the analysed period frequency of discharges is clearly growing, by 1681 discharges year^{-1} (Fig. 9C). This trend is disturbed for years with increased storm activity, which appear every few years, separated by calmer years. Their annual total increased from approx. 15,000 up to 27,614 discharges detected in 2007. In the years 2008-09 there was a clear decrease in storm activity: these were the years with the lowest discharge values during the 18 years of research. Since 2009, the number of discharges has increased, up to 40,795 in 2012. In subsequent years there were fluctuations in the number of discharges from the maximum in 2017 (58,228 discharges). However, it should be noted that this large number of discharges was affected especially by two days (10 and 11 August). In these days there were very intense MCS systems (Taszarek et al., 2019; Sulik & Kejna, 2020). The increasing number of lightning discharges indicates the growing potential energy of the atmosphere. Record values occurred in 2007, 2012 and 2017, when storm systems in the form of MCS and training storms occurred.

There has been an upward trend in the number of discharges in individual months. It was also found that the storm season begins sooner than in previous years and lasts longer. In recent years, storms have the potential to create dangerous phenomena, such as the example of August 11, 2017.

Summary and final remarks

The main purpose of the study was to examine the spatial diversity of cloud-to-ground (CG) lightning flashes in the Kujawsko-Pomorskie voivodeship (Poland) in the years 2002-2019, to determine the daily, monthly and annual course, and to calculate the number of thunderstorm days along with trends. To carry out this study, data on CG flashes from the Polish lightning detection system PERUN were used.

Based on the analysis of CG discharges, it has been shown that in the Kujawsko-Pomorskie voivodeship the number of days with a storm ranges from 27 to 41. These are higher values than those given in previous studies, in which approx. 23 days with a storm were given annually in the voivodeship (Lorenc, 2005; Bielec-Bąkowska, 2013). This difference results from the fact that observations made by observers at meteorological stations do not take into account all discharges. Some discharges were not noticed by observers.

In the years 2002-2019 in the Kujawsko-Pomorskie voivodeship 432,926 CG flashes were detected, which gives an average annual value of about 24,051 discharges. On average, 2.5 lightning strikes km^{-2}·yr^{-1} occurred in areas of maximum discharge. This is comparable to the results obtained by Taszarek et al. (2015), who stated that in the years 2002-13 the maximum in Poland occurred in Mazovia (2.7 flashes km^{-2}·yr^{-1}). These values are much lower than in southern Europe, e.g. in Italy 5 CG flashes km^{-2}·yr^{-1} (Taszarek et al., 2019). In terms of spatial differentiation of ground discharges, each year was slightly different, but the south-eastern part of the voivodeship is clearly marked by an increased number and frequency of discharges. This area has also been designated by Taszarek et al. (2015) as part of the main storm trail in Poland. In that study, the authors found as many as 4,328,892 discharges throughout the entire period (2002-13), with an average of 151 days of storm each year throughout the country. The number of days with a storm was also confirmed to increase in a south-eastwards direction from the Baltic Sea, which would agree with the distribution of days with the storm in the Kujawsko-Pomorskie voivodeship. Areas with fewer discharges include, among others, the north-western or central part of the research area, where there are extensive forest complexes. The analysis showed the influence of the Vistula River on the distribution of atmospheric discharges. Their number are small in the grids through which the Vistula flows and grows with distance from the river. In the largest cities, the distribution of discharges is random.

The work also analysed the variability of storms and lightning in the seasonal cycle. In Poland, the storm season usually lasts from May to August, with July being the month with the highest frequency of storms. This was also confirmed for the area of the voivodeship: in July each year, there are an average of 8830 discharges in the region, whereas in winter months (Dec-Feb) CG flashes average five per year. Thunderstorms during this period are rare, but they cannot be completely ruled out, especially since increasingly often there is no cold winter in the Polish climate, which leads to an increase in air instability also in the winter months. Over the course of the day, most of the recorded storms occur in the daytime, with a maximum around 14:00 to 18:00, and with average values of about 1500 discharges, and a minimum around 07:00, when air instability is at a minimum.

In recent years we have been observing disturbing changes taking place in nature: prolonged drought, rising air temperature, intensification of extreme weather phenomena. Rising air temperature, which causes the surface of the seas and oceans to heat up, also affects the activity of storms, which is confirmed by Kotroni and Lagouvardos (2016) in their study using data from the ZEUS system. Under conditions of rising global air temperature, which also pertain to Poland (Wibig, 2017) it has been hypothesised extreme weather phenomena are increasing in frequency and intensity. The temperature during the storm season, which in Poland falls from May to September, is of particular importance. This paper analyses the variability and trend of days with storm and lightning discharges in the Kujawsko-Pomorskie voivodeship in the years 2002-19. The number of thunderstorm days also shows an increasing trend (0.82 days $year^{-1}$). Older climatological studies on the subject of storms in Poland proved that for many years the increase in the number of days with a storm could not be confirmed based on synoptic observations (Bielec, 1998). The number of CG flashes was found to increase at a rate of 1681 discharges per year. This trend is related to the increase in air temperature in the storm season (Apr–Sept) reaching (0.04°C $year^{-1}$). Sequences of days with a storm occur more frequently.

The latest research confirms the increase in dangerous atmospheric phenomena in Europe. However, there are places where a downward trend can be noted. The changes are fastest in northern Europe and slowest in southern areas (Taszarek et al., 2020). In the area of central Europe, there is an increase in storm activity in July and August. As for the increase in the number of days with a storm, such changes took place in the area of the Alps, central and south-eastern Europe, in the form of 5–10 days with a storm per year. The probability of severe thunderstorm days also increases from year to year (Taszarek et al., 2019). Further research into this topic is necessary, especially concerning the atmospheric conditions during the days with the most intense thunderstorms.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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A cloud-to-ground lightning density due to progressing climate change in Poland

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ABSTRACT

This research focuses on the climatology of cloud-to-ground (CG) lightning flashes based on PERUN lightning detection network managed by IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute) during period 2002 to 2020. To present statistical data converted from raw lightning data, a grid cell with dimensions of 10 km × 10 km was used in order to standardize the results and refer to research conducted in other countries. As a result of the research, it can be concluded that the PERUN system detected 8,626,200 CG flashes during the 18-year period under study. Lightning data were used to determine the spatial distribution of CG flashes, number of thunderstorm days, the annual distribution or the hours of lightning occurrence. The average annual value of CG flashes varies from 0,5 to 3,5 flashes $km^{-2} \cdot yr^{-1}$. The highest electrical activity occurs in central Poland (Mazovian Lowland) and the lowest in the Pomeranian Lake District. As a result of the research, it is possible to identify a storm trail that begins near Kraków-Częstochowa Upland and ends at the Masurian Lake District. The month with the highest electrical activity in Poland is July, while the highest electrical activity of thunderstorms occurred in 2017. Positive current flashes accounted for 4% of all detected CG flashes, with the greatest activity in June but since 2015, there has been visible increasing activity of thunderstorms carrying CG's with positive current. As a result of the analysis, it was also possible to identify a growing tendency of CG flashes in the area of whole country.

1. Introduction

Thunderstorms have fascinated mankind for centuries. Initially, people explained the phenomenon of the thunderstorm as the anger of the gods or identified lightning as their attribute of power. Nowadays, no one pays attention to old beliefs or rituals to ward off the thunderstorm anymore. With the advancement of technology in the subject of thunderstorms, there has also been progress, but still not everything is known. Thunderstorm is a local phenomenon and is mainly associated with torrential rainfall, sometimes with hail, combined with strong gusts of wind and lightning. According to the thematic dictionary of terms, expressions and phrases of the Institute of Meteorology and Water Management, a thunderstorm is "one or more atmospheric discharges (lightning, thunder) associated with the occurrence of Cumulonimbus clouds: often associated with a sharp increase in speed and change of wind direction and showers of rain or hail" (Niedźwiedź, 2003). All over the world, we can consider the thunderstorm taking into account similar aspects of its operation. According to AMS *Glossary of Meteorology*, the thunderstorm is defined as "a local storm, invariably produced by a cumulonimbus cloud and always accompanied by lightning and thunder, usually with strong gusts of wind, heavy rain, and sometimes with hail" (Byers and Braham, 1949).

Initially, the observation of the thunderstorms was made by an observer at the synoptic station. The observations made were recorded at individual stations and the thunderstorm days was counted when the observer noticed at least one lightning discharge. This methodology is used to this day at stations in Poland, which is an area of this research (Fig. 1). The results of these observations made it possible to carry out climatological studies on thunderstorms, mainly thunderstorms in Poland (Bielec, 1998, 2000; Bielec-Bąkowska, 2013; Kolendowicz 1996, 2006). However, this study did not allow to determine, for example, the spatial distribution of lightning discharges in Poland due to the lack of an appropriate lightning detection network. The currently used detection methods enable detection of discharges and their division by type and charge. This makes it possible to calculate the number of flashes on a given day, with exact locations.

Until now, several dozen of research have been carried out for the area of Europe with the use of lightning detection and location systems. The authors of various studies decided on different ranges of years or the dimensions of the base field needed for statistical calculations and the determination of the spatial distribution of the discharges. A number of studies on lightning climatology have been prepared for the area of Europe. The most frequently chosen primary field was a grid of 10 km × 10 km, 20 km × 20 km, 0.1° × 0.1° (approximately

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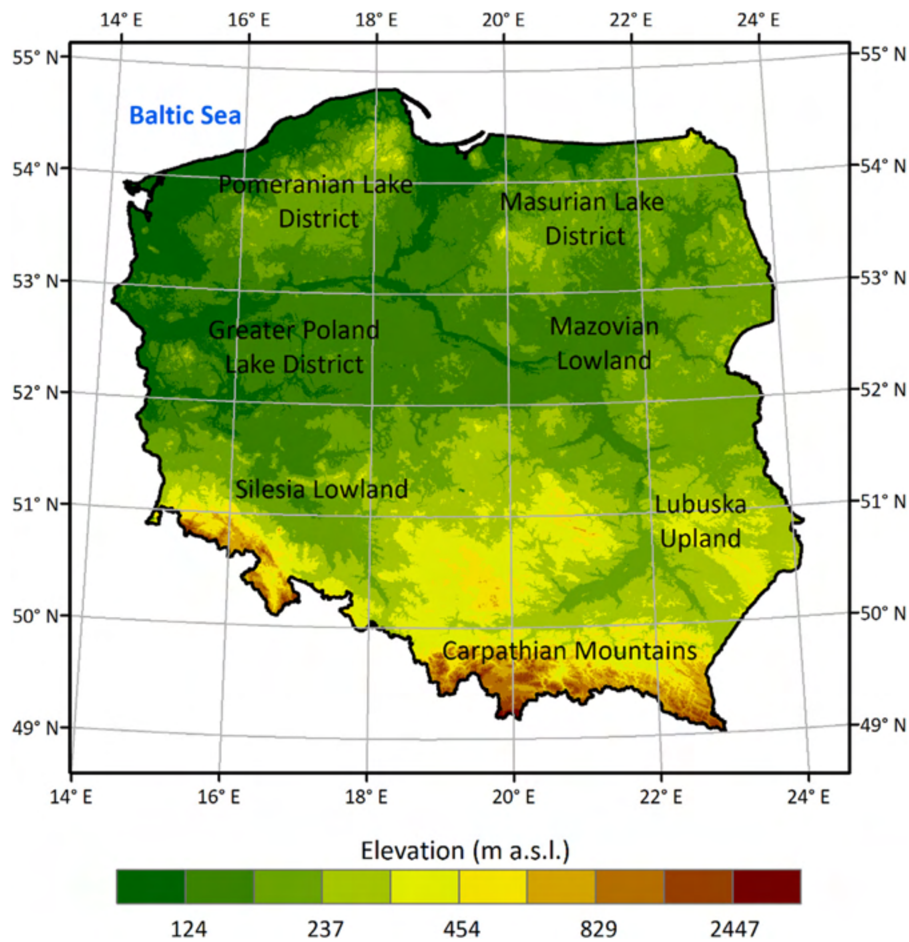

Fig. 1. Hypsometric map of Poland based on the Shuttle Radar Topography Mission Global Coverage (SRTM3) (source: National Aeronautics and Space Act (NASA) (2022)).

10 km × 10 km), 0.2° × 0.2° (approximately 20 km × 20 km) and 5 km × 5 km (eg., Biron et al., 2009, Betz et al. 2009, Enno 2011, Wapler 2013, Feudale et al. 2013, Kotroni and Lagouvardos 2016, Mäkelä et al. 2011, Novák and Kyznarová 2011, Pohjola and Mäkelä 2013, Santos et al. 2012, Schulz et al. 2005, Soriano et al. 2005, Taszarek et al. 2015, Sulik and Kejna 2022). In the United States of America, Koehler (2020) used a grid resolution of 926 m × 926 m and all counts were summed over subsets to yield counts on a coarser grid with 3704 m × 3704 m resolution. As a result, the maximum CG flash values were found over Tampa, Florida. What important, several locations in California, had no lightning flashes during the 26-yr period.

2. Area of interest, dataset and methodology

The research area is Poland, which is located in Europe in the vicinity of countries such as Germany (from the west) or the Czech Republic (from the south). Poland has access to the Baltic Sea from the north and the Carpathian Mountains chain begins in the south. The area of Poland consists mainly of lowlands (Fig. 1). The territory of Poland slopes from the south to the north-west. However, the height does not decrease gradually, but by leaps and bounds, i.e. the lower and higher lands alternate in stripes stretching from west to east. Starting from the south, the following belts are distinguished: mountains, valleys, highlands, central Poland lowlands, lake districts and coasts. The diverse land cover in Poland is dominated by agricultural land, which constitutes 60%, followed by forest land with a total area of 9,6 million ha (CORINE Land Cover, 2018) (Fig. 2).

Courtesy of the Polish Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB), it can be obtained lightning data from the PERUN system. This system detects lightning flashes divided into intra-cloud (IC) and cloud-to-ground (CG). Distinguishing the type of discharge is possible due to the use of low-frequency electromagnetic waves. As mentioned earlier, the SAFIR (Surveil-lance et d'Alerte Foundre par Interferometric Radioelectrique) system was launched in Poland in 2002 and since then, has been nicknamed PERUN, after the god of thunder and lightning in Slavic mythology. The system mainly applies the technique of detecting the direction of arrival of the DF (Direction Finding) signal (Bodzak, 2006). The entire system is integrated by means of 9 stations located more or less throughout Poland. The system includes masts located at synoptic and meteorological stations such as: Gorzów Wielkopolski, Częstochowa, Kalisz, Toruń, Sandomierz, Warszawa, Olsztyn, Białystok and Włodawa. According to Gajda (2021) in recent years, 3 more stations: Legnica, Chojnice and Kozienice, have been launched into use (Fig. 3A). Location of detection masts in various regions of the country ensures location precision up to 1 km and detector coverage of 95% of the territory of Poland, which results in strikes detection up to 100 km from the detector. When analyzing the data collected in entire database, it can be concluded that about 88% of Poland has a precision of less than 1 km and 12% more than 1 km (Fig. 3B). It is certainly related to the location of detection stations in the map of Poland. The improvement of the efficiency of lightning detection would be ensured by the creation of further masts of the PERUN system at stations managed by the Institute of Meteorology and Water Management - National Research Institute. According to the system administrator (IMGW-PIB), in 2012 the sensors in the entire

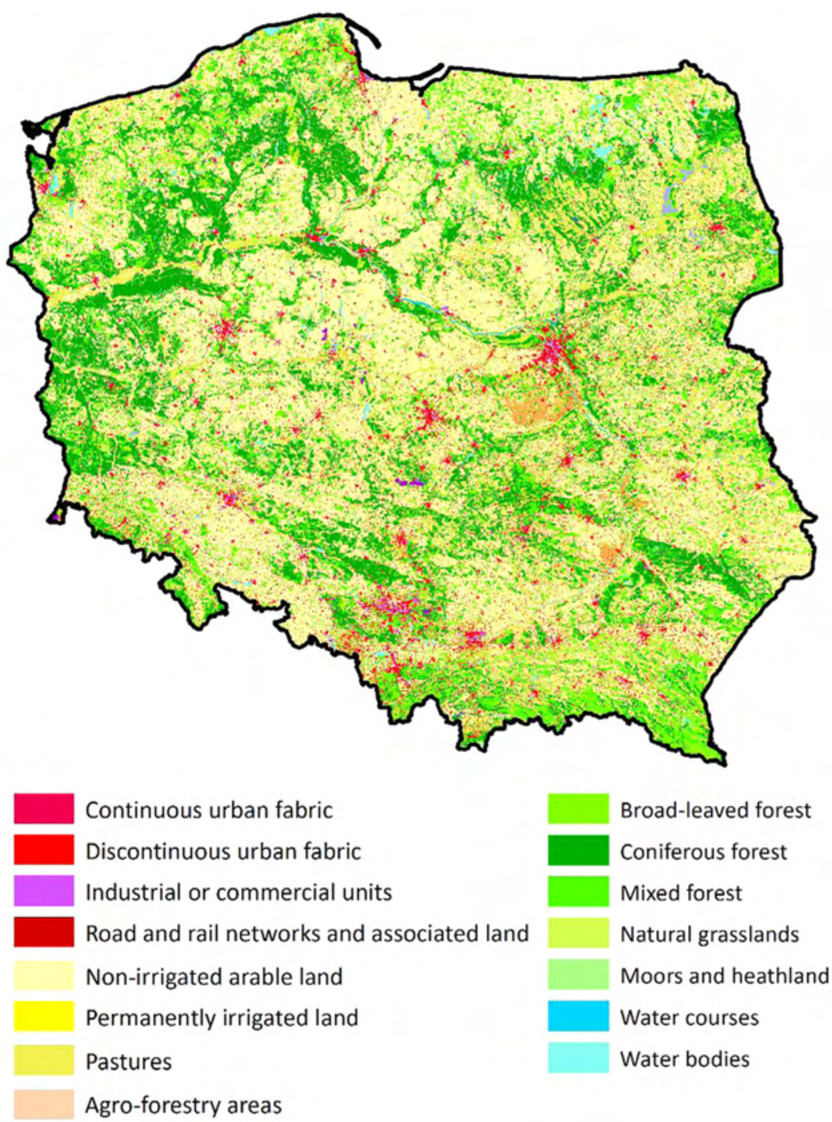

Fig. 2. Land use map of Poland and based on the Corine Land Cover 2018 data (source: Land Copernicus 2019).

network were renovated, which was to improve the quality of detection. For 2022, the launch of another part of network in Lesko station is planned. Also in recent years most stations have replaced the sensors of the SAFIR3000 system, operating since 2002, with Vaisala TLS200. In the future, IMGW plans to equip all stations with TLS200 receivers. The care treatments of the PERUN system, along with the inclusion of three new stations into the network, improved the accuracy of the location of lightning flashes in the center of the country from the previous 2 to 0.5 km. Therefore, the data from the PERUN system is becoming more and more reliable.

In this study, a 10 km × 10 km grid (100 km^2 area) was chosen following the study of precision in relation to the surface area in which the flashes occurred (Diendorfer, 2008). Turning to the methodology, only CG flashes were used in this research. IC flashes were deliberately omitted in the calculations because they were incorrectly detected by the detection system. The errors consisted in generating an artificial circle with a diameter of 16 km, the center of which was above the station with the detector and such an image of the thing would certainly have a negative impact on the obtained results by falsifying them. It's associated with use of long radio waves with a frequency of 30–300 kHz and a length of 10–1 km (Bodzak, 2006). These errors were first noticed by Sulik and Kejna (2022) in detailed study for the Kujawsko-Pomorskie voivodeship. As shown by studies by Cummins et al. (1998) some CG flashes with a charge below 10 kA can be detected by sensors as IC, so also such flashes were also removed from database. Importantly, in the case of CG flashes with a negative current, these types of flashes tend to "strike" several times during one flash at the same place (multistrokes). Therefore, when processing data, only the first stroke that took place was taken into account. From the occurred strokes at the same location and time, only one that occurred first was selected to final database.

After detecting a lightning flash, the detection system sends the necessary information to the central server located at the IMGW-PIB headquarters in Warsaw. Detected flashes are located and saved in the Global Positioning System (GPS), which imparts them coordinates. Location of lightning strikes is saved in a lightning listing with other parameters, such as current charge time, numbers for detected type of lightning (IC intra-cloud, or CG cloud-to-ground), polarity, peak current estimate (kA) and multiplicity. Originally, the system records the lightning location information in the WGS84 (World Geodetic System) latitude and longitude in decimal degrees. Due to the local coordinate system for Poland, it was necessary to convert the coordinates from the WGS84 to the CS92 (EPSG: 2180) metric system. The R software (R. Core Team, 2014) was used to organize the raw dataset from the PERUN network and after this, all maps were made in ESRI ArcGIS PRO 2.8.3. software.

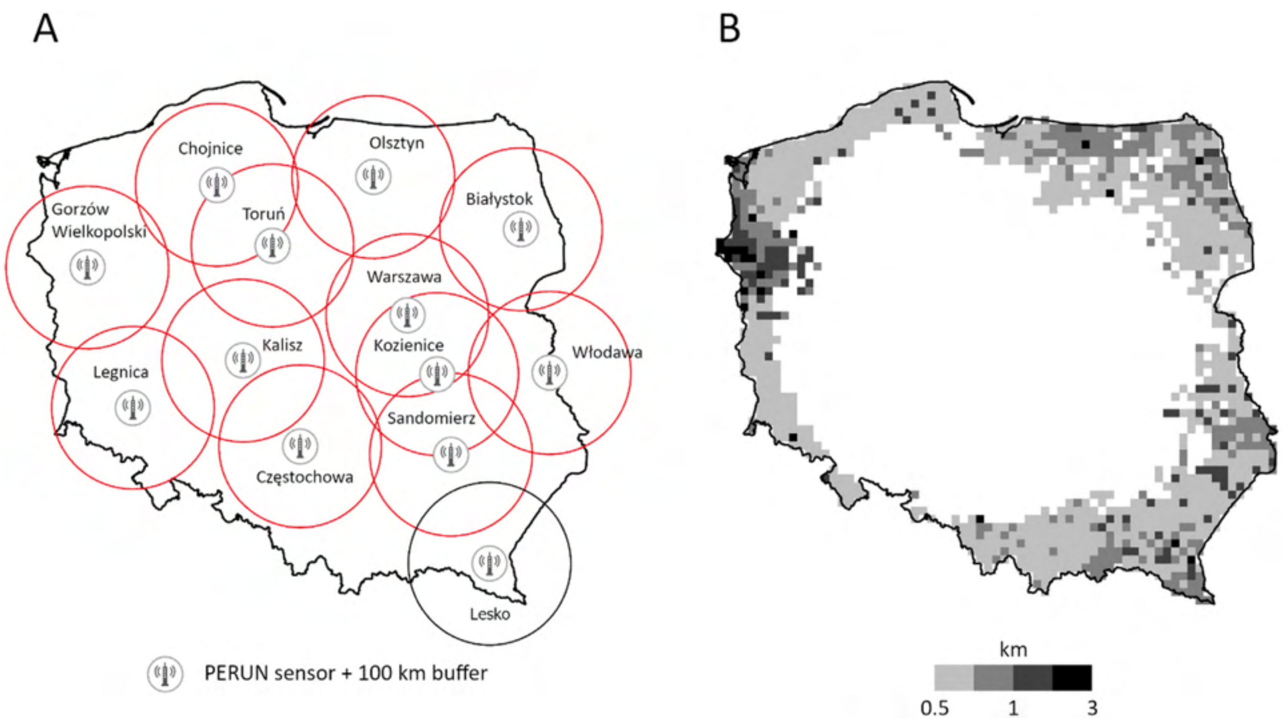

Fig. 3. A – Locations of SAFIR3000 lightning sensors in the PERUN network with 100 km buffer zones. The launch of the station in Lesko is planned for 2022. B – Average CG lightning flash location accuracy (km) derived from the PERUN database during 2002–2020. Computed in 10 km × 10 km grid cells.

3. Results

3.1. Average annual number of thunderstorm days

A 1 km × 1 km grid was used to calculate the number of thunderstorm days. From the center of each grid, a buffer with a radius of 15 km was led out. This length of the radius correlates best with human perception and the ability to observe the storm by an observer at a synoptic station. Thunderstorm day was counted when at least one lightning was inside the buffered circle. As a result of the adopted methodology, it can be concluded that the number of thunderstorm days increases from the Baltic Sea region (10–15 days) towards south-eastern Poland (35–40 days) and the average number of thunderstorm days is approx. 30 days (Fig. 4). Such a spatial distribution of this phenomenon is confirmed by previous studies based on data from observations made in Poland since 1885 (Bielec-Bąkowska, 2003). However, as Czernecki et al. (2016), SYNOP reports are unfortunately not homogeneous and error-free. The

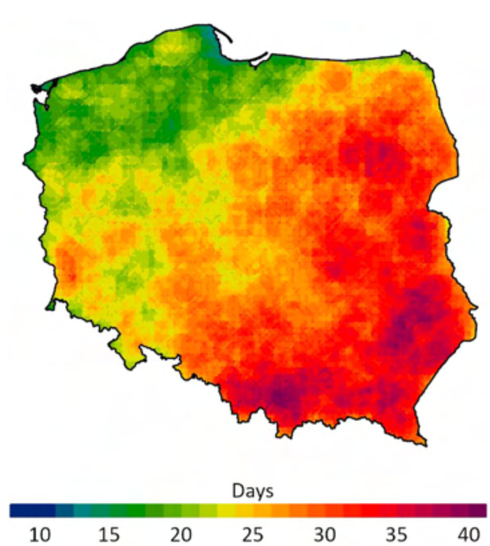

Fig. 4. The average annual number of thunderstorm days during 2002–2020. Computed for 1 km × 1 km grid cells within a radius of 15 km from the bin center based on lightning data derived from the PERUN network.

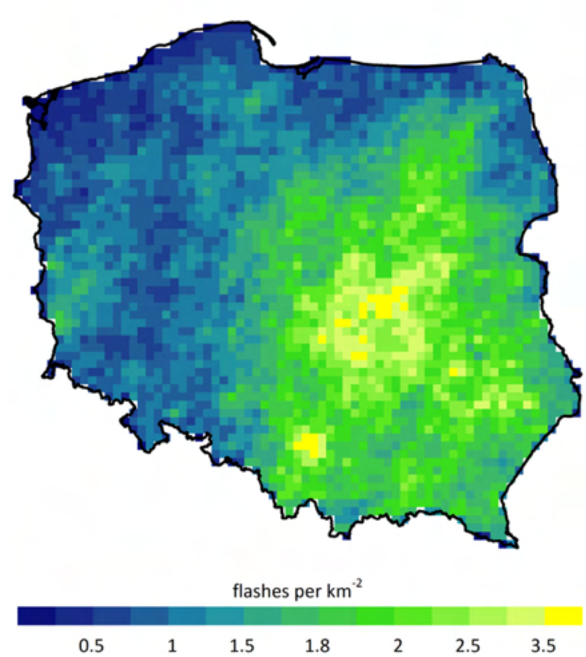

Fig. 5. The average annual number of CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during 2002–2020. Based on lightning data derived from the PERUN network.

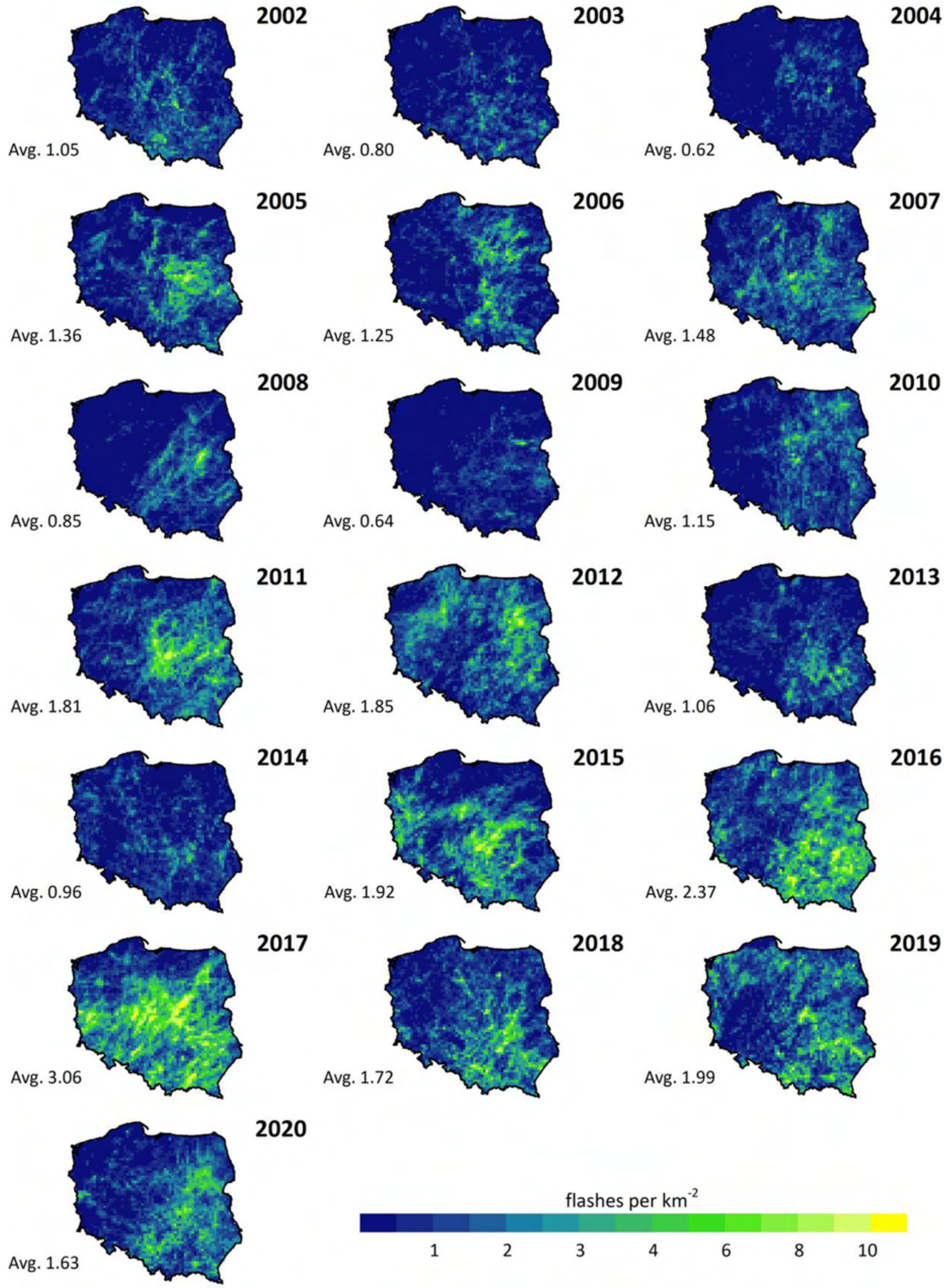

Fig. 6. Annual number of CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during 2002–2020. Based on lightning data derived from the PERUN network.

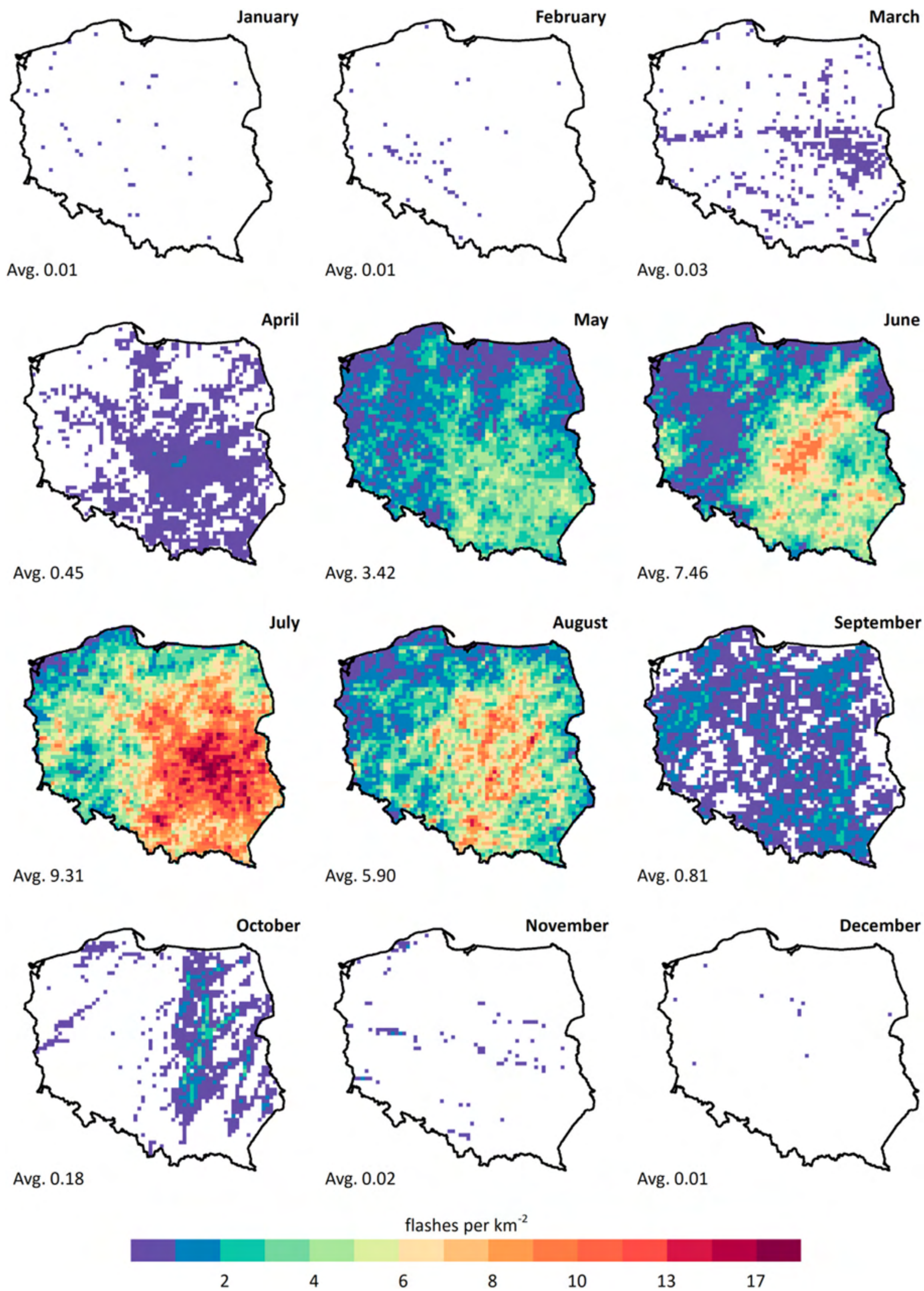

Fig. 7. Average monthly number of CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during 2002–2020. Based on lightning data derived from the PERUN network.

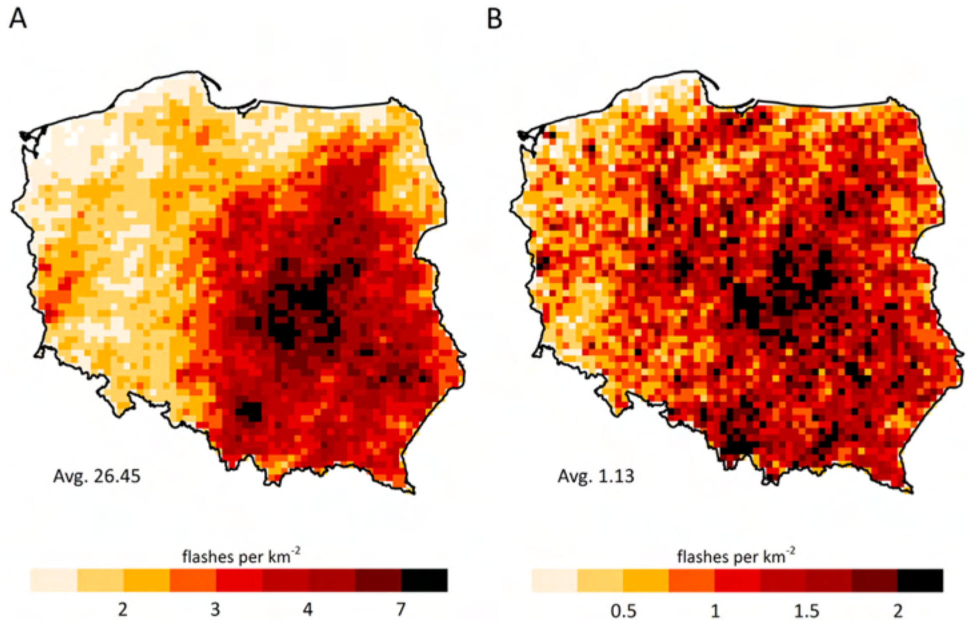

Fig. 8. A – The average annual number of negative peak current CG lightning flashes km^{-2}. B – The average annual number of positive peak current CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during the years 2002–2020. Based on lightning data derived from the PERUN network.

real number of thunderstorm days calculated from the remote sensing data is therefore more accurate and reliable.

3.2. Average annual CG lightning flash density

In the period 2002–2020, in the annual course, an average of less than 0,5 to more than 3,5 CG flashes km^{-2} was recorded (Fig. 5). The largest concentration of lightning discharges was observed in Masovia, Lublin and Upper Silesia. The lowest values were recorded in north-western Poland. In the course of the year in the analyzed period, an increase in the annual sum of the flashes in the period 2015–2020 was observed, with the maximum in 2017 (Fig. 6). During this period, the air temperature was significantly higher, and in the summer seasons there were heat waves (Jędruszkiewicz and Wibig, 2019). In the same year, Poland was affected by the "thunderstorm of the century" described, among others, by Taszarek et al. (2019) or Sulik and Kejna (2020).

3.3. Annual course of CG lightning flash density

In the annual course, the highest sums of flashes occur, not surprisingly, in the summer months (7,56), with the maximum in July - an average of 9,31 flashes (Fig. 7). This month has the highest number of CG flashes throughout the year. In June and August, storm routes running from the south-west to the north-east were clearly marked in the spatial distribution. There are definitely more discharges in May compared to September. The lowest sums occur in winter – 0,01 flashes year^{-1}. In the area of south-eastern and central Poland, storms in the period from May to August inclusive are more frequent due to the strong heating of the substrate overlapping with the boundary layer's high moisture content often results in high convective available potential Energy (CAPE) (Riemann-Campe et al., 2009; Sulik, 2021).

3.4. Average annual positive lightning flash density

Cumulonimbus clouds have the ability to separate pools of positive and negative charges in and around them. In that case, creating a powerful electric fields. Lightning is "born" between two oppositely charged regions as a network of electrically conductive channels called leaders (Rakov and Uman, 2003). Then materialize and begin to tunnel a path through the poor conductive air in between. The most common CG is negative charged. In this type of CG's a negatively charged step leader approaches the ground. Electric field between the step leader and the ground strengthens to the point that an oppositely charged leader begins reaching up bridging the gap between the two (Rakov and Uman, 2003). More than one upward leader may initiate an attempt to connect with the downward leader. However the first to reach a downward propagating step leader will suddenly complete a channel path through the resisting air for the flow of powerful electrical current between the earth and cloud. CG lightning strikes are characterized as positive or negative depending on the net charge of bolt shifts to the ground, (Warner, 2012). If a positive leader with a deficit of electrons connects with a ground and induced surplus of electrons in the ground travel up the channel shifting negative charge away from the ground up into the storm cloud, the ground gains a net positive charge we call this a positive CG.

In the average annual spatial distribution by current, as in other studies, also in Poland, negative flashes prevail in the central part of Poland (Fig. 8A). This distribution is similar to the spatial distribution for both types of charge presented in (Fig. 5). On the other hand, when it comes to flashes with a positive current, these flashes occur unevenly in various parts of the country, however, their increased activity is noticeable in the vicinity of the Carpathian Mountains and the central part of Poland (Fig. 8B). It is worth noting that since 2015 there has been an increased activity of lightning with a positive charge. Importantly, the spatial distribution of positive flashes does not coincide with the general annual distribution presented in (Fig. 6). The peak charge of positive CG's can be ten times more powerful than a typical negative CG and thus considerably more dangerous. Many occur in a positive pool higher in the thunderstorm and the ground because of the greater distance the leaders have to blaze through the resisting air, the return stroke of these positive CG's is often much hotter, brighter and longer in duration. Annual number of positive peak current CG's is presented on (Fig. 9).

3.5. Annual course of positive lightning flash density

Positive lightning flashes are generally the most powerful CG's, reaching temperatures up to 30,000 °C which is roughly five times hotter than the surface of Sun (Uman, 1969). Sometimes a bolt of lightning can leap kilometers away from a storm and it's called a „bolt from the blue". Outdated paradigms suggest these clear air channels leaping out the back of storms were positive in polarity but the latest research using lightning mapping and high-speed cameras have shown most of these startling zaps are indeed negative. Due to worldwide lightning

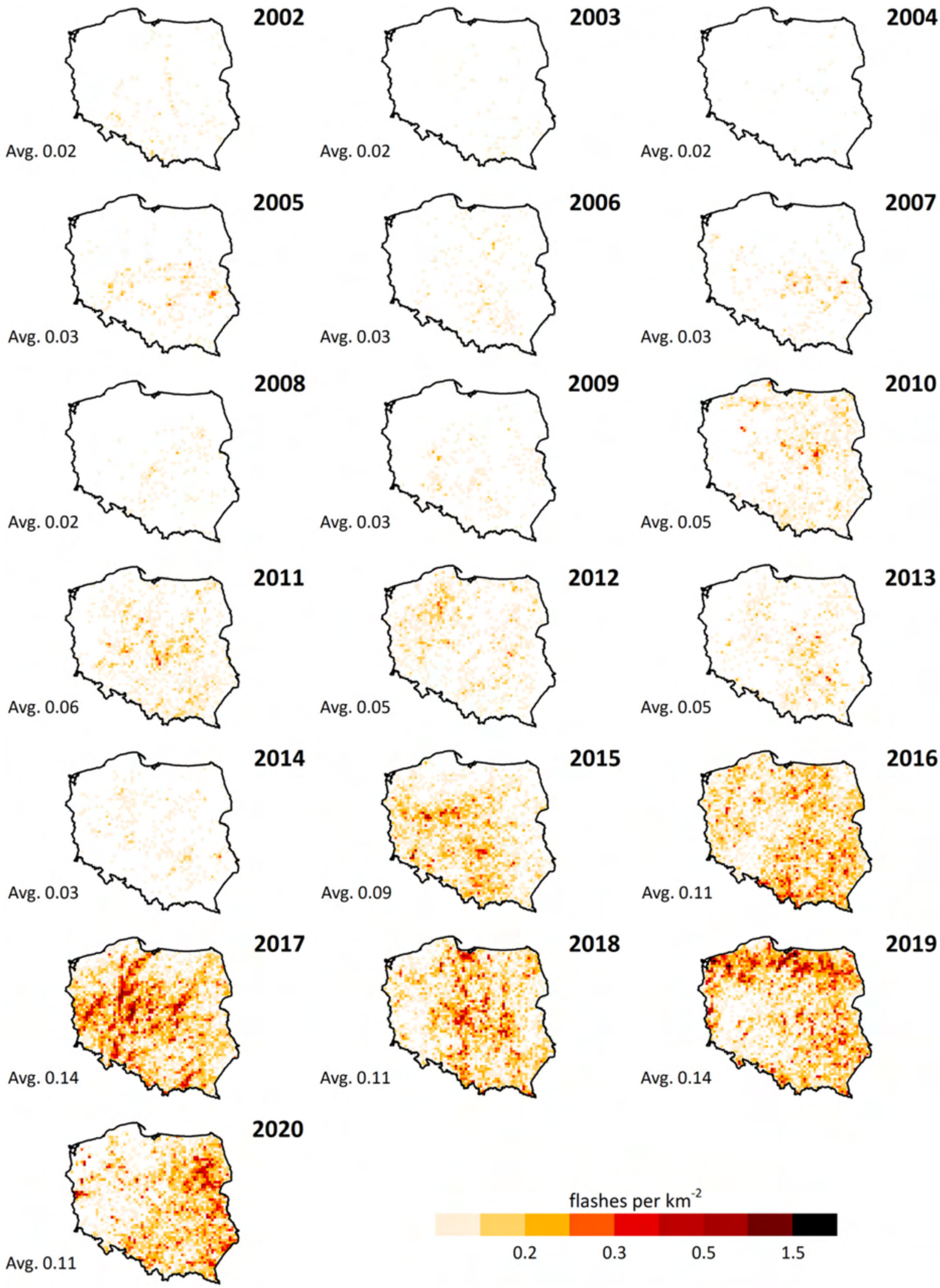

Fig. 9. Annual number of positive peak current CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during 2002–2020. Based on lightning data derived from the PERUN network.

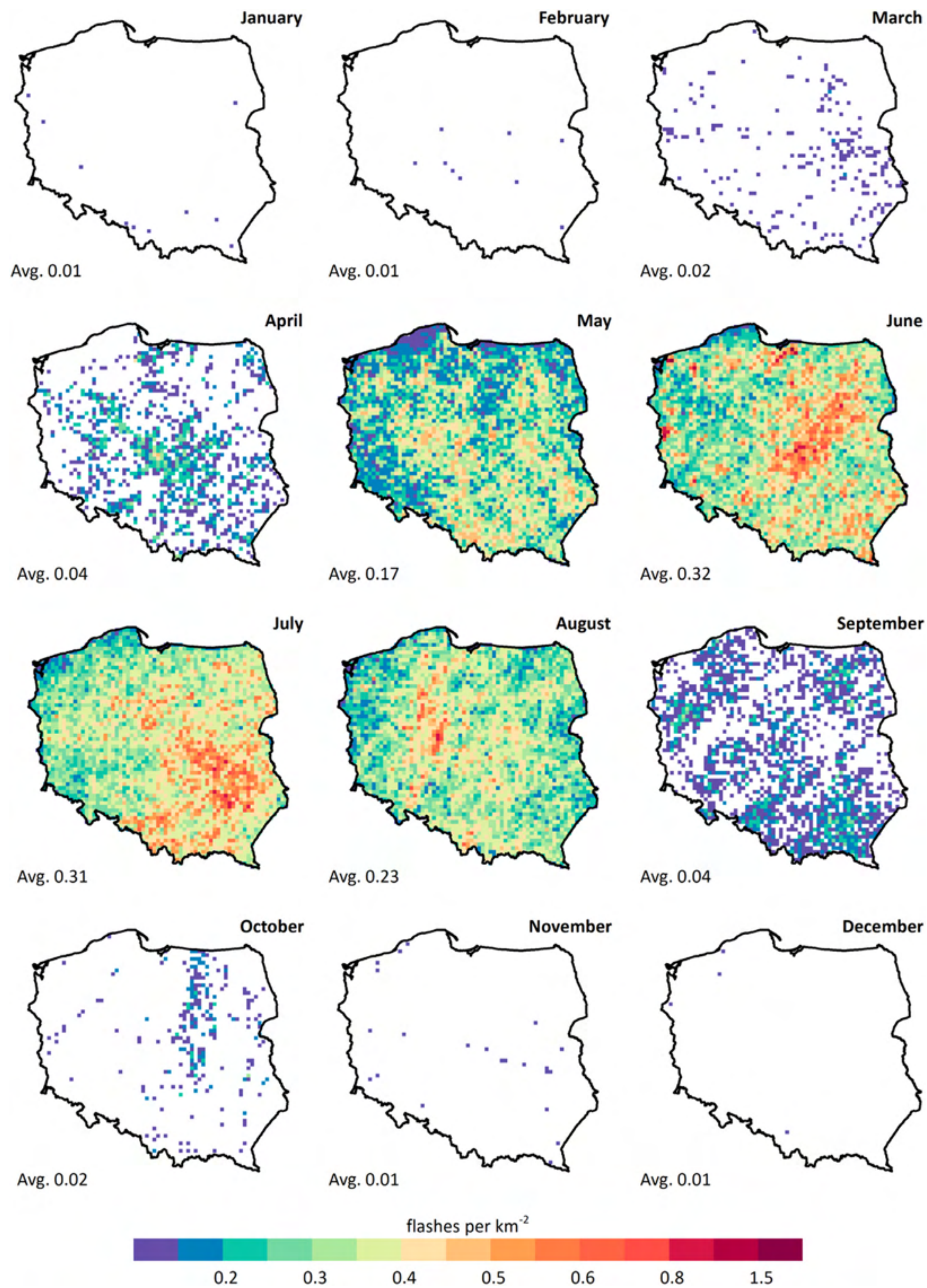

Fig. 10. Average monthly number of positive peak current CG lightning flashes km^{-2}. Computed for 10 km × 10 km grid cells during 2002–2020. Based on lightning data derived from the PERUN network.

CG climatology research it can be stated that positive CG's only account for about five to ten percent of all ground flashes (Taszarek et al., 2015) but in Tornado Alley (USA) they are in a typically common sight just on downstreams of strong storm updrafts (Koehler, 2020). These phenomena occur especially in storm supercells or mesoscale convective systems (MCS). These systems are characterized by long duration throughout the life cycle of the system, high electrical activity and rapid movement. MCS systems are typically formed of several individual storm cells that have been reabsorbed and combined into a single storm cluster (Houze, 2004). MCS systems are not uncommon in Poland. In 2008–17, there were an average of 77 MCSs that lasted typically from 3 to 6 h (Surowiecki and Taszarek, 2020). Spatial distribution of positively charged discharges strongly related to MCS systems. The highest electrical activity of storms is in June, July and August, which translates into the presence of MCS systems in these months (Fig. 10). Especially in June and August, the trails of storms are

Table 1
Methodology for designating areas based on climatic regions and physical-geographical regionalization in Poland.

Symbol	Climatic region	Macroregion	Influence of Baltic sea	Influence of hills and mountains
A	Pomeranian	Koszalin seashore	High	No impact
B	Masurian	Masurian lake district	Moderate	No impact
C	Kuyavian	Chełmno-Dobrzyń lakeland	Low	No impact
D	Mazovian	Central Masovian lowland	No impact	No impact
E	Silesian	Lusatian hills	No impact	Low
F	Sudets	Sudetes	No impact	High
G	Lesser Poland	Silesian upland	No impact	No impact
H	Carpathian	Western Beskids	No impact	High
I	Lublin	Lublin upland	No impact	Low

visible. The most electrically active storm in terms of positive flashes occurred in Poland on August 11, 2017, during which 29% of CG flashes were positive (Sulik and Kejna, 2020). In turn, the most electrically active storm in the history of the PERUN system was the one that occurred on August 10, 2017 (Sulik, 2021). On that day, the Polish part of SAFIR3000 system detected 154,524 CG flashes of which 18% were positive.

3.6. Trends and patterns

In the period 2002–2020, the next warmest years were recorded in the history of meteorological measurements (2014, 2015 and 2019). The strong El Niño phenomenon has raised temperatures not only in Poland but also across Europe (Masson-Delmotte et al., 2021 [IPCC]). The observed increase in temperature by increasing the frequency of storms should lead to an increase in the occurrence of lightning. To determine trends in changes in the distribution of CG flashes, areas directly related to the physical-geographical regions and the climatic regions of the country belonging to them were used. The areas were selected in such a way that they cover various climatic regions of Poland, they differ from each other, for example in average air temperatures or the influence of the Baltic Sea and the Mountains (Table 1). The main motive for this type of treatment was the transitional nature of Poland's climate described by Okołowicz and Martyn (1979). The diverse location of the physical and geographical regions designated by Kondracki and supplemented by Solon et al. (2018) allowed for a detailed and direct identification of trends (Fig. 11). The comparison of the CG flashes values with the selected areas made it possible to state that despite the significant variability from year to year, a statistically significant, growing trend of lightning flashes $p \leq 0{,}05$ was observed (Fig. 12). The lowest sums of flashes were observed in regions A (Pomeranian climatic region) and F (Sudetes). These regions are characterized by relatively low average air temperature values (Kejna and Rudzki, 2021). The greatest changes

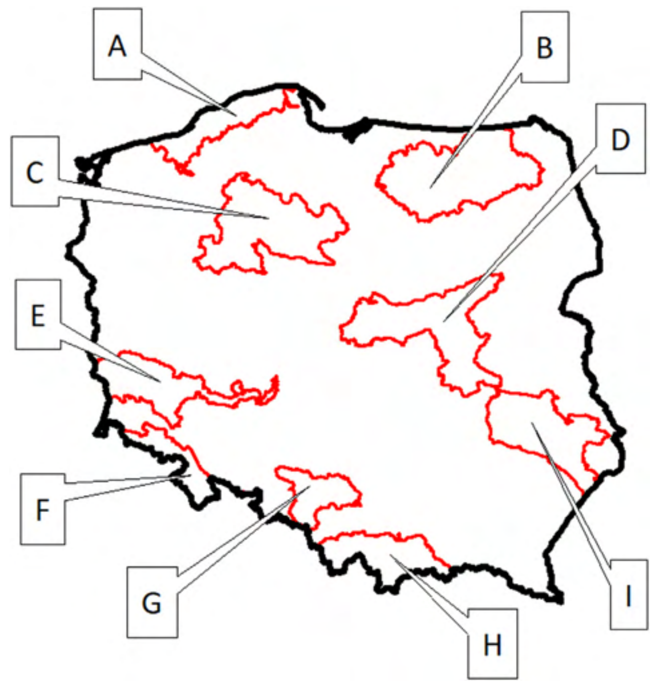

Fig. 11. Regions based on climatological and physical-geographical regionalization of Poland.

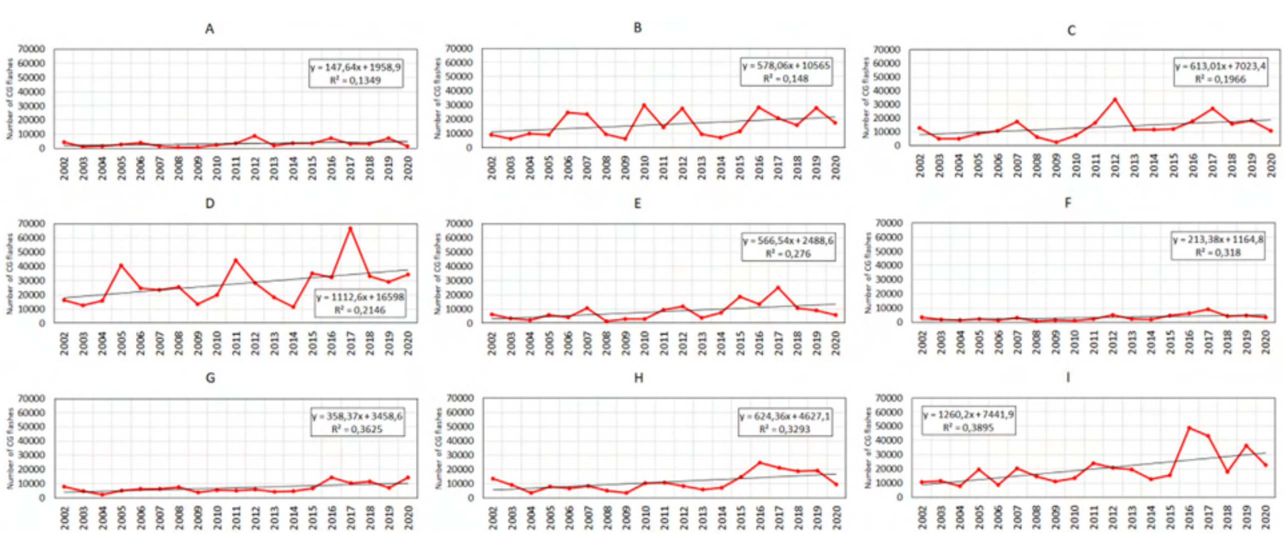

Fig. 12. Annual CG lightning flash values counts. Computed for regions based on climatological and physical-geographical regionalization of Poland. Based on lightning data derived from the PERUN network.

occurred in southern Poland, where thunderstorm days occur the most during the year. As a result of this analysis, it is possible to unequivocally state the increase in the number of CG flashes throughout the country.

4. Summary and final remarks

Progressive climate change over the world, can certainly affect the climate of Poland. Increased attention should be applied to the most dangerous phenomena and threats to human health, life and property. On the example of this research, it was possible to present the second edition of thunderstorm climatology in Poland based on PERUN data. As a result of the analysis nearly 8,626,200 CG flashes over the period 2002–2020, it was possible to reach the following conclusions:

(1) The number of thunderstorm days in Poland increases from the Baltic Sea region (10–15 days) towards the south-eastern part of the country (30–40 days). The spatial distribution of this phenomenon is in fact similar to previous studies carried out by Bielec-Bąkowska (2003) and Kolendowicz (2006), but there is an increase in the number of thunderstorm days in the regions of central and north-eastern Poland.
(2) In Poland, an average of 479,233 CG flashes occurs each year. Importantly, the greatest electrical activity of storms occurs in central Poland, while most of all thunderstorm days are recorded in the south-eastern part. This means that highly electrically active storms do not have to form in the areas with their highest frequency.
(3) It's noteworthy that in the years 2002–2020, in Poland there were at least 8 severe thunderstorm days during which, storms showed significant electrical activity exceeding 50,000 CG flashes in one day (Sulik, 2021).
(4) The most electrically active thunderstorms occurred in 2006, 2008, 2012, 2015, and 2019, of which 2017 was a special year with a record value of 956,793 CG flashes.
(5) The stormy season in Poland usually lasts from May to September, where July is the month with the highest incidence of CG flashes (an average of 9,31 flash $km^{-2} \cdot yr^{-1}$). During the winter period, flashes occur but are sporadic.
(6) In Poland, the vast majority of CG flashes (96%) have a negative current (negative flashes), however, since 2015 there has been an alarming increase in thunderstorms carrying a positive current.
(7) Based on the division into areas correlating with climatic regions, it can be stated that there is a growing trend of CG flashes throughout the country. The greatest changes are visible in the areas of south-eastern Poland.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Comparison of thunderstorm days in Poland based on SYNOP reports and PERUN lightning detection system

Abstract
The research presents a comparison between two methods which are used to identify days on which there are thunderstorms (TDs) in Poland. SYNOP and PERUN lightning network data from the Institute of Meteorology and Water Management (IMGW-PIB) for the period 2002–2020 were used to determine and compare the changes in the number of TDs. To determine the number of TDs using the PERUN data, an appropriate method needed to be created which would allow for the closest possible reference to human perception in relation to lightning. A buffer with a radius of 15 km was used, and TDs were counted when there was at least one flash within the buffer circle. Measurements performed by observers are sometimes not homogeneous and are prone to errors, and thus underestimate the actual number of TDs. As a result of the analysis, the average number of TDs in Poland was found to be 26 (SYNOP) and 30 (PERUN) per year.

Keywords
Thunderstorm • thunderstorm day • lightning • PERUN, SYNOP • Poland

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Introduction

Thunderstorms, which are classified as extreme weather phenomena, are electrometeors (Bielec-Bąkowska 2003). According to the *Meteorological Dictionary* by Niedźwiedź (2003), thunderstorm days (TDs) are days on which atmospheric discharges related to the occurrence of cumulonimbus clouds are observed. Near and distant storms are distinguished: for *near storms*, the time between noting the lightning discharge and hearing the following thunder should not exceed 10 seconds (distance approx. 3 km). Also, according to the AMS *Glossary of Meteorology*, a thunderstorm is defined as 'a local storm, invariably produced by a cumulonimbus cloud and always accompanied by lightning and thunder, usually with strong gusts of wind, heavy rain, and sometimes with hail' (Byers & Braham 1949). Thus, it follows that lightning is inherent to thunderstorms, and must occur in order to speak of the occurrence of a thunderstorm.

Observing the occurrence of thunderstorms is burdened with the problem of the observer's subjective judgment (Bielec & Kolendowicz 2001). With distant thunderstorms, some flashes are visible from miles away, especially at night (Wu et al. 2016). In addition, many weather stations are located in cities, where light pollution of the sky (Lechner & Arns 2013) masks atmospheric discharges, and the noise coming from the environment drowns out the thunder which follows the lightning. In mountainous regions, city centres, and wooded areas, the view of the entirety of the sky is reduced by hills, buildings, or trees. In Poland, difficult conditions for the observation of lightning flashes are found especially in mountainous areas in the south of the country (Fig. 1A). The systematic observation of thunderstorms in Poland are carried out at stations belonging to the Institute of Meteorology and Water Management of the National Research Institute (IMGW-PIB). The results of these observations have been published in many articles (e.g., Kolendowicz 1997, 2006; Bielec 2000; Lorenc 2005; Bielec-Bąkowska 2013; Bielec-Bąkowska et al. 2021).

Lightning detection systems provide more objective data about thunderstorms. These have been introduced in many countries. A lightning detection system has been operating in Poland, since 2002. Initially, it was called SAFIR (Surveillance et Alerte Foundre par Interférométrie Radioélectrique), but it is now called PERUN, in reference to the god of thunder in Slavic mythology. The system now consists of 12 antennas and can detect up to 100 discharges per second with a location accuracy of up to 1 km in the central part of the country, while in border areas this accuracy decreases (Bodzak 2006; Czernecki et al. 2016). PERUN has been included into the European Blitzortung system (Gamracki 2015). On the basis of these data, climatological analyses of lightning discharges have been performed for Europe (e.g. Taszarek et al. 2019), Poland (Taszarek et al. 2015; Czernecki et al. 2016; Sulik 2021; Sulik 2022), and at a regional scale for the Kujawsko-Pomorskie Voivodeship (Sulik & Kejna 2022).

Thunderstorms are among the most dangerous meteorological phenomena, in Poland as in most regions around the world. This is due to the significant damage generated by thunderstorm events each year. The main danger caused by thunderstorms is the risk of lightning strikes, damaging cloud-to-ground flashes, large hail, or at the very least, severe convective wind gusts, which have often caused natural disasters in Poland, for example, on August 10 and 11, 2017 (Sulik & Kejna 2020). Of course, damage from severe weather phenomena has a direct relationship to material and economic losses (Mäkelä et al. 2013).

The progressive increase in air temperatures around the globe is affecting the frequency and strength of extreme phenomena. Even small changes in climate can cause a higher

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frequency of extreme weather events, including thunderstorms (Allen 2018). There is considerable regional variation in the occurrence of thunderstorms worldwide (e.g., Kuleshov et al. 2002; Lavigne et al. 2019; Taszarek et al. 2019; Koehler 2020).

There are also significant climatic changes occurring in Poland (ed. Falarz 2021). During the period 1966-2018, the air temperature increased at a rate of 0.33°C per 10 years. There were regional differences during the period 1951-2018: the warming was greatest in central-western Poland (0.3°C per 10 years) and slightly lower (below 0.2°C per 10 years) in the south-east (Kejna & Rudzki 2021). The greatest warming occurred in winter and summer (Ustrnul et al. 2021). Maximum air temperatures are also increasing; for example, in the summer seasons during the period 1951-2015 they rose at a rate of over 0.4°C per 10 years (Wypych et al. 2017). Despite this, there is no clear signal for an increase in the frequency of thunderstorms in Poland. For the period 1951–2018, an increase in the frequency of TDs was noted only in the eastern part of the country, while in the west the trend was not statistically significant, and at some stations there was even a decrease in frequency (Bielec-Bąkowska et al. 2021).

The purpose of this analysis is to compare the results of storm observations (SYNOP) and lightning detection data (PERUN). The spatial differentiation of the number of TDs in Poland was analysed, as was their variability throughout the year and from year to year during the period 2002–2020.

Dataset and methodology

Reports on TDs from the IMGW database and PERUN network were used for this research. The study used data from 48 IMGW stations (Fig. 1B). As shown in research by Bielec-Bąkowska (2013), these data are mostly homogeneous. Unfortunately, in 2015, visual observations of atmospheric phenomena were interrupted at seven stations (Koło, Legnica, Leszno, Nowy Sącz, Płock, Sandomierz, and Tarnów), while in four stations (Olsztyn, Racibórz, Słubice, and Wieluń) there was a break in observations between 2015 and 2017. Although thunderstorms are a local phenomenon, there is a significant linear regression with nearby stations in the annual and monthly statistics of the number of TDs. The missing data from the above-mentioned stations were supplemented with data from 1966–2014 from neighbouring stations located in similar physical and geographic conditions.

The PERUN lightning detection system, introduced in Poland in 2002, was used to calculate the number of thunderstorm days. This system detects lightning flashes, which are divided into cloud-to-ground (CG) and cloud-to-cloud (CC) flashes using low-frequency electromagnetic waves. In addition to the division into the type of flashes the system allows values such as peak current estimate (kA), current charge time, and multiplicity, among other things, to be determined. The key parameter is the detection and location of the lightning flashes. The system detects flashes using an integrated measurement network consisting of, to date, nine stations in Poland: Gorzów Wielkopolski, Częstochowa, Kalisz, Toruń, Sandomierz, Warsaw, Olsztyn, Białystok, and Włodawa. In recent years, three more stations (Legnica, Chojnice and Kozienice) have been commissioned, and a station in Lesko was planned for 2022 (Gajda 2021) (Fig. 1C). Detected flashes are synchronised and saved using a GPS system. The coordinates of the detected lightning strikes are saved in decimal number format in the WorldGeodeticSystem84 coordinate system (latitude and longitude). In this analysis, to make the correct visualisation and further data calculations, it was necessary to convert the location data from the WGS84 system to the metric reference system PUWG92 (EPSG: 2180) which is applied in Poland.

The R software package (R Core Team 2014) was used to organise the lightning data. Importantly, only cloud-to-ground flashes were used for the study due to the inability of the system to correctly locate cloud-to-cloud flashes. As shown in studies by Cummins et al. (1998), some CG flashes with a charge below 10 kA can be detected by sensors as CC, so such discharges, too, were removed from the database. Importantly, in the case of CG flashes which have a negative current, these types of flashes tend to ‘strike’ several times in the same place during one flash (multistrikes). Therefore, only the first discharge was considered when processing data. According to Bodzak (2006), the location of the detection masts in various regions of the country ensures a location precision up to 1 kilometre, and detection coverage of 95% of the territory of Poland, which results in a discharge detection up to 100 km from the detector. We can therefore conclude that accuracy is best in the central part of the country. In recent years, most stations have replaced the SAFIR3000 system sensors, which have been operating since 2002, with Vaisala TLS200 sensors. In the future, IMGW plans to equip all stations with TLS200 receivers (Gajda 2021). The regular maintenance and updating of the PERUN system, along with the inclusion of three new stations in the network, improved the accuracy of the location of lightning flashes in the centre of the country from the previous 2 km to 0.5 km. And so, the data from the PERUN system is becoming ever more reliable. Analysing the data collected in the database, it can be concluded that the precision for about 88% of Poland is less than 1 km and for 12%, it is more than 1 km (Fig. 1D). This is certainly related to the most recent positioning of PERUN sensors across Poland.

This article analyses the spatial distributions and number of TDs based on SYNOP observations and PERUN atmospheric discharges. The ordinary kriging method, which is used to present discrete data, was used when interpolating the number of TDs using the data from stations. A 1×1-km grid was used to calculate the number of TDs on the basis of data from the PERUN system. A buffer with a radius of 15 km from the centre of each grid was assumed. A thunderstorm day was then counted if at least one lightning flash fell within the buffer circle. The number of thunderstorm days based on PERUN data was determined by taking the actual value from the grid cell from the exact location of the IMGW meteorological station. This provided results comparable with the SYNOP data. This method was carried out for the period 2002–2020 using the ArcPy 2.8 extension for ESRI ArcGIS software. All maps were computed in ArcGIS PRO 2.8.3. A similar methodology was used by Czernecki et al. (2016) using a radius of 17.5 km, and by Taszarek et al. (2019), who used a geographic grid with dimensions 0.5°×0.5°.

The key factor for further comparisons was the calculation of the number of days with lightning strikes in the vicinity of a station. As early as 1988, Changnon (1988) compared the observations of thunderstorms from meteorological stations in the USA with lightning strikes within a radius of 5, 10, and 20 km. Reap and Orville (1990) found that thunderstorms were detected by observers at a distance of 17 km during the day and 26 km at night. In Finland, Mäkelä et al. (2014) found that thunderstorms within a radius of 11.3 km correlated well with observations. Wapler (2013) suggested a radius of 15 km, while Enno et al. (2012) provided a figure of 14.7 km. Changnon (2001) found that the audibility of the thunder reached 8–24 km; while Koehler (2020) used a radius of 5 and 10 nautical miles (9.3 and 18.5 km) in his studies of thunderstorms in the United States.

In Poland, Czernecki et al. (2016) examined the distance at which the atmospheric discharges detected by the PERUN system were observed by humans at weather stations. On the basis of this data from stations in Poland, they obtained distances of 12 to 24 km (17.5 km on average). Also, Taszarek et al. (2019) considered that the appropriate distance for optimal determination of TDs fitted within the range of 15–18 km. This analysis compared the results from the SYNOP station against the

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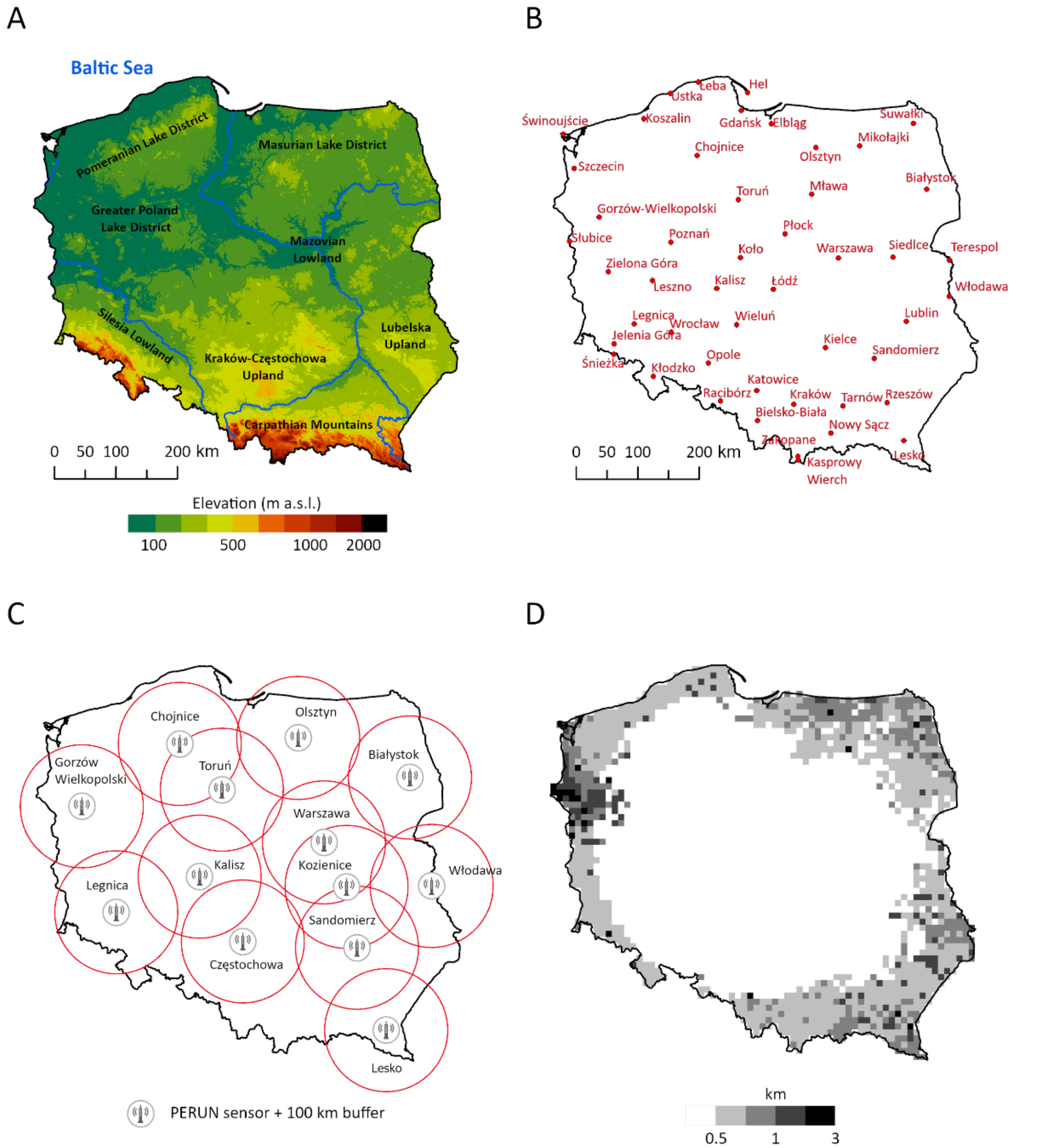

Figure 1. A - Hypsometric map of Poland based on the Shuttle Radar Topography Mission Global Coverage (SRTM3) including geographical regions (source: NASA 2021). B - Location of the meteorological stations used in the study. C - Locations of lightning detection sensors in the PERUN network, with buffer zones. D - Average CG lightning accuracy based on the PERUN database during 2002–2020
Source: own study

PERUN network within a radius of 15 and 17.5 km. It was found that, taking the range of 17.5 km recommended by Czernecki et al. (2016), the average difference in recorded TDs for the 48 stations in Poland was 5.9 days and ranged from 0.8 in Łeba to 17.4 days in Rzeszów. Particularly large differences occurred at stations located in the mountains which had a limited observation horizon. Therefore, this radius was reduced to 15 km. The difference in relation to SYNOP decreased to 4.0 days, ranging from 0.4 days in Hel to 9.9 days in Sandomierz. So, the authors believe that the 15-km radius is the most reliable distance and corresponds best to human perception, and, consequently, better corresponds to the observations made at the stations.

The comparison of the number of TDs from the observations and the PERUN system showed that despite the buffer reduction to 15 km, the average difference for the 48 stations was 4.0 days (SYNOP average 25.9 days, PERUN average 29.9 days). The smallest differences occurred at stations with an open horizon, for example, at the seaside: Łeba (0.4 days), Hel (0.9 days),

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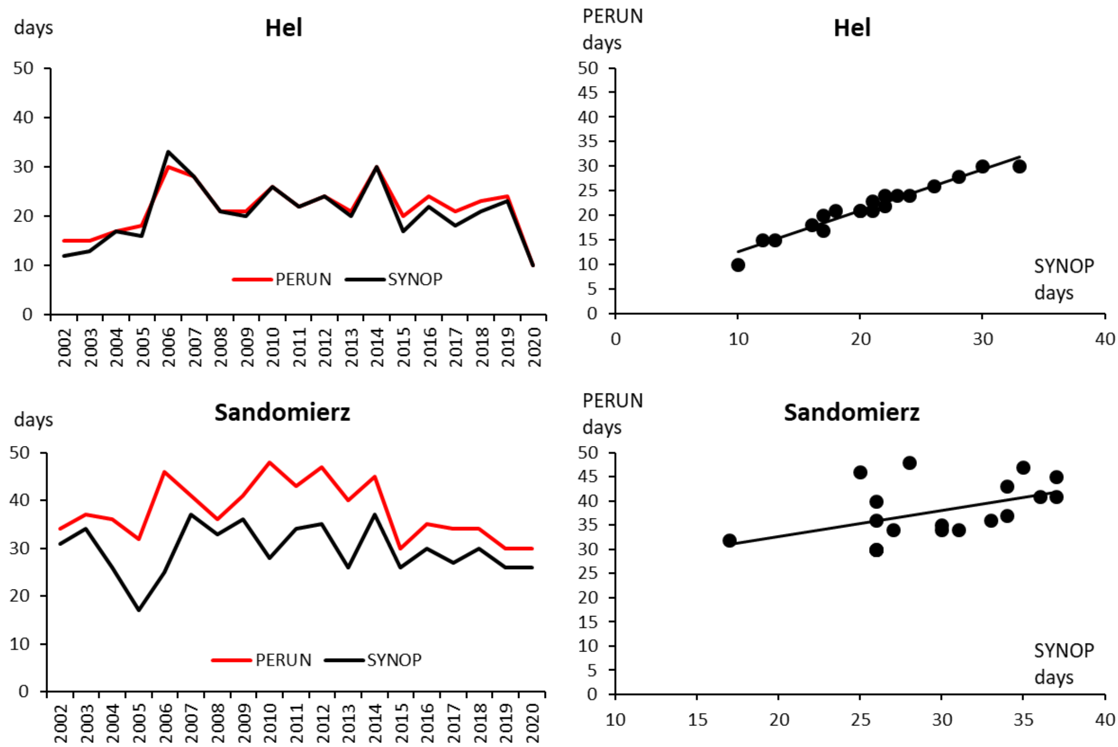

Figure 2. The course of TDs and the correlation between the number of the TDs according to the SYNOP and PERUN data in Hel and Sandomierz during the period 2002–2020
Source: own study

Świnoujście (1.9 days), and Elbląg and Terespol (1.9 days). The greatest differences occurred at stations located in mountain valleys: Zakopane (6.1 days), Lesko (7.3 days), and Rzeszów (7.9 days); and also in cities: Warsaw (6.7 days), Toruń (6.5 days), and Łódź (6.2 days). However, the biggest difference was in Sandomierz (9.9 days). This station is located outside the city and has favourable observation conditions, but these differences persist every year (Fig. 2), which may result from the subjective assessment of the occurrence or non-occurrence of thunderstorms in the vicinity of the station.

There is significant linear regression between the observed TDs and their detection with the PERUN system, reaching a Pearson linear correlation coefficient of r=0.98 in the case of annual sums of TDs for stations at Gdańsk, Gorzów Wielkopolski, and Hel; and 0.97 at the Koło, Koszalin, and Kłodzko stations. The least correlated values are those at the Warsaw (0.32), Rzeszów (0.38), and Sandomierz (0.48) stations.

Results

Average number of thunderstorm days in Poland

There was already some spatial distributions of TDs (based of SYNOP data) available from previous studies carried out between the years 2002 and 2020 in Poland (e.g. Lorenc 2005; Kolendowicz 2006; Bielec-Bąkowska 2013; Bielec-Bąkowska et al. 2021). During the analysed period, most TDs occurred in south-eastern Poland, especially in the Carpathian Mountains (Lesko, 37.8 days; Zakopane, 33.0 days; Nowy Sącz, 32.3 days; and Kasprowy Wierch, 31.7 days) and in the highlands (Kielce, 34.3 days and Lublin, 31.6 days). The lowest number of TDs occurred in the north of Poland, especially on the Baltic Sea coast (Ustka, 16.4 days; Świnoujście, 16.6; and Gdańsk, 17.9 days). The small number of TDs in the Sudety mountains (Śnieżka, 20.6 days) is noteworthy (Fig. 3A).

This spatial distribution is confirmed by the number of TDs obtained from the PERUN system's recording of atmospheric discharges. However, these numbers are, on average, several days higher. The greatest number of TDs occurred in eastern Poland, especially in the mountains and highlands (35–40 days) (Fig. 3B). The lowest numbers were recorded on the Baltic coast and in the Pomeranian Lake District (15–20 days). The patchwork geographical distribution of TDs is noticeable in Poland; there are areas with increased/decreased frequency of lightning flashes, which is related to the local orography or land use (Sulik & Kejna 2022). In some regions, there were differences between the data from the stations and the corresponding grids. According to the PERUN system, a greater number of TDs was recorded in north-eastern Poland. On the other hand, more TDs were observed in Elbląg than the PERUN analysis showed. This may be due to the location of the station, which was moved to Milejewska Góra (189 m a.s.l.) in 2011, from where there are favourable conditions for observing thunderstorms.

According to Sulik (2021), the formation of highly electrically active thunderstorms over Poland is often influenced by a cold atmospheric front associated with a low-pressure centre formed over the North Sea in June–August. Strong storm systems can sometimes reach half of the country's territory and pass through much of it. An anticyclonic circulation occurs more often over the territory of Poland than in other parts of Europe, which may also contribute to the creation of thunderstorms. A prevailing influx of air masses from the west and south is also noticeable over Poland (Araźny et al. 2021).

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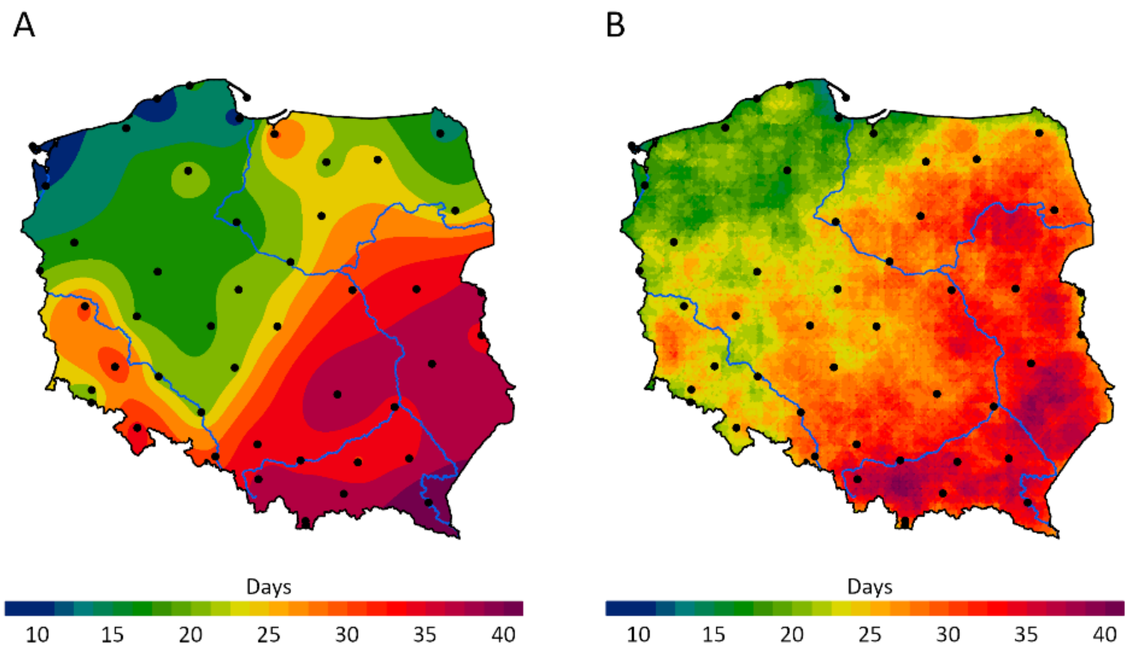

Figure 3. Average annual number of TDs in Poland according to SYNOP (A) and PERUN (B); data during the period 2002–2020
Source: own study

Annual course of thunderstorm days in Poland

Thunderstorms can occur in Poland at any time of the year, and occasionally even in winter. However, the official storm season lasts from May to September (Bielec 2013; Czernecki et al. 2016; Bielec-Bąkowska et al. 2021). Kolendowicz (2006) distinguished four seasons of thunderstorm activity in Poland (increased, maximum, decreased, and sporadic thunderstorm activity). According to observations for the period 2012–2020, the highest number of TDs occurred in July (the average of all stations was 7.1 days) and in May (4.5 days), June (5.7 days), and August (5.1 days). Thunderstorms are less frequent in April (1.3 days) and September (1.4 days) (Fig. 4).

During the remaining months, the probability of thunderstorm occurrence is low. For individual months, the spatial distribution of these phenomena is similar to that for the whole year, with the highest frequency being in south-eastern Poland. At the end of summer (August) and at the beginning of autumn, their number increases at the coast, especially on the Gdańsk Bay coast.

The number of TDs calculated according to PERUN provides more detailed information. The general distribution is similar from month to month. During the period from April to July, an increased number of TDs occur in south-eastern Poland. In June, the Carpathian and Upland regions are notable while in July more TDs occur in eastern Poland (Fig. 5).

In August, the distribution of TDs is uniform across the regions; even at the coast a greater number can be noted. In September, thunderstorms become less frequent; only in the south do their frequency reach as high as 2–3 days a month. In the autumn and winter months, lightning strikes are infrequent.

Trends and variability in thunderstorm days in Poland (2002–2020)

The number of TDs varies by year. Their spatial distribution also changes within individual years depending on the synoptic situation (Kolendowicz et al. 2017). Occasionally, episodes of intense thunderstorms can change a year's spatial distribution of TDs (Sulik 2021). The number of thunderstorm days is lowest in the north of Poland (at the Baltic coast), with about 15 days, and highest in south-eastern Poland, at about 50 days a year (Fig. 6)

As a storm is typically a local phenomenon: at one station the observer will record a day with a storm, but at a nearby station the same thunderstorm will not be recorded. Based on the data from SYNOP reports on TDs, it is not possible to clearly confirm the increase in the number of TDs across Poland. The average annual number of TDs varies from 22 to even as high as 31 days, depending on the year. Analysis of the TD number based on data from the PERUN system shows regularity, confirming the observations made at the IMGW stations.

As in the case of the SYNOP data, the number of TDs can be seen to increase in a direction from the north, southwards towards the Carpathian Mountains (Fig. 7).

The number of TDs based on PERUN data usually differs by 3–4 days relative to observational data. The highest number of TDs occurred in 2014 (average of 36.0 days), and the lowest number in 2005 (average of 24.8 days). Years with a greater frequency of thunderstorms are sometimes separated by years of less activity.

When it comes to changes in the frequency of TDs in Poland, the values obtained from the PERUN detection system (with the exception of one station) showed an increase in the number of TDs throughout Poland. There was an upward trend at 14 stations, ranging from 0.40 to 0.82 per 10 years (Fig. 8B). Elsewhere, the increase in TDs was smaller, but statistically significant.

Based on SYNOP data, a statistically significant increase in TDs was found at 12 stations, reaching 0.39 days per 10 years in Poznań, 0.38 days per 10 years in Słubice, and 0.33 days per 10 years in Białystok. No spatial regularity was found, and at many stations there was even a negative but statistically insignificant trend (Fig. 8A).

As mentioned earlier, sometimes thunderstorms recorded at one station will not be noticed by a station a few tens of kilometres away (Fig. 9). Differences between stations were found when

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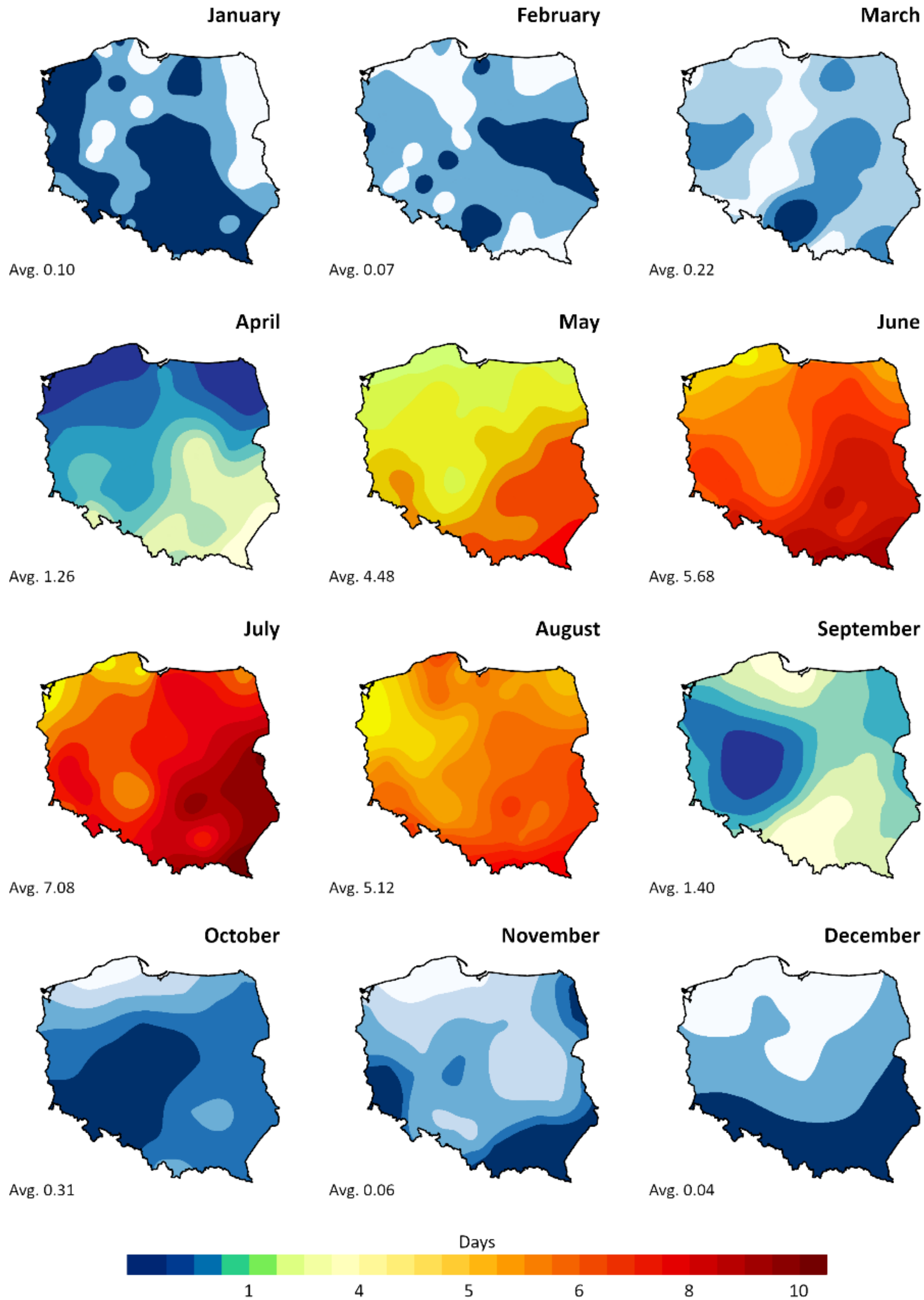

Figure 4. Average monthly spatial variability of TDs in Poland based on SYNOP reports during the period 2002–2020
Source: own study

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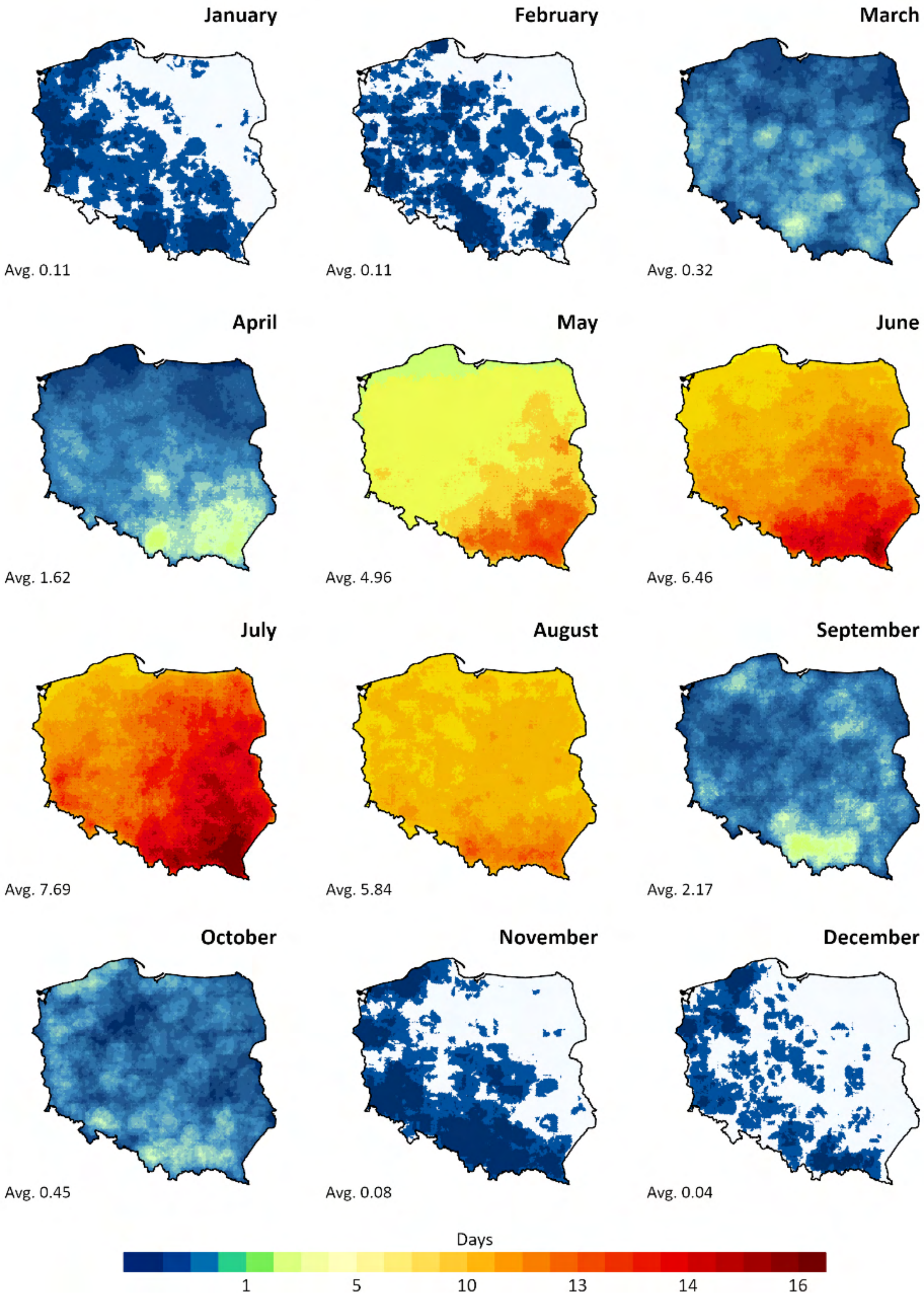

Figure 5. Average monthly spatial variability of TDs in Poland based on the PERUN lightning detection system during the period 2002–2020
Source: own study

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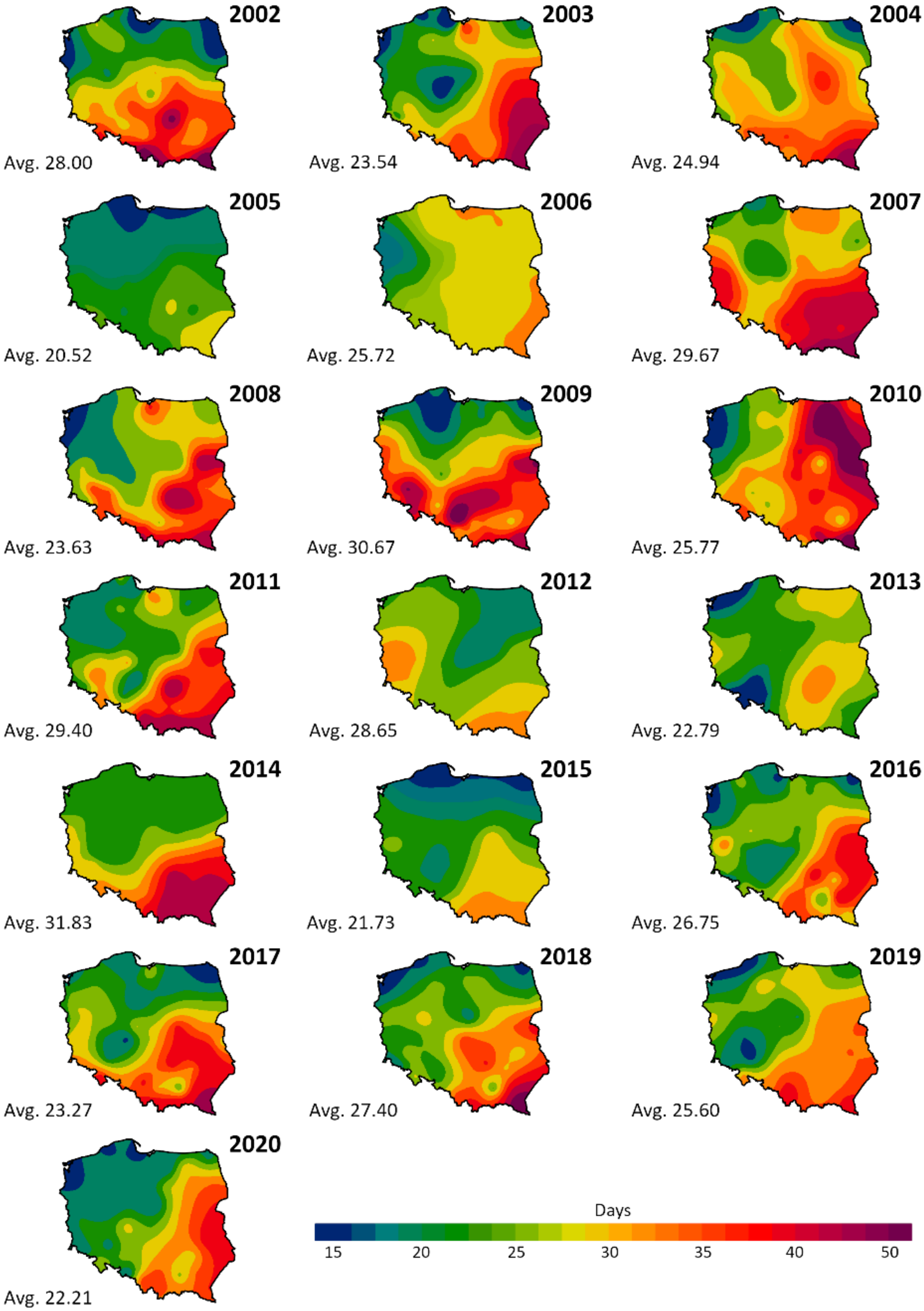

Figure 6. Annual number of TDs in Poland based on SYNOP data during the period 2002–2020
Source: own study

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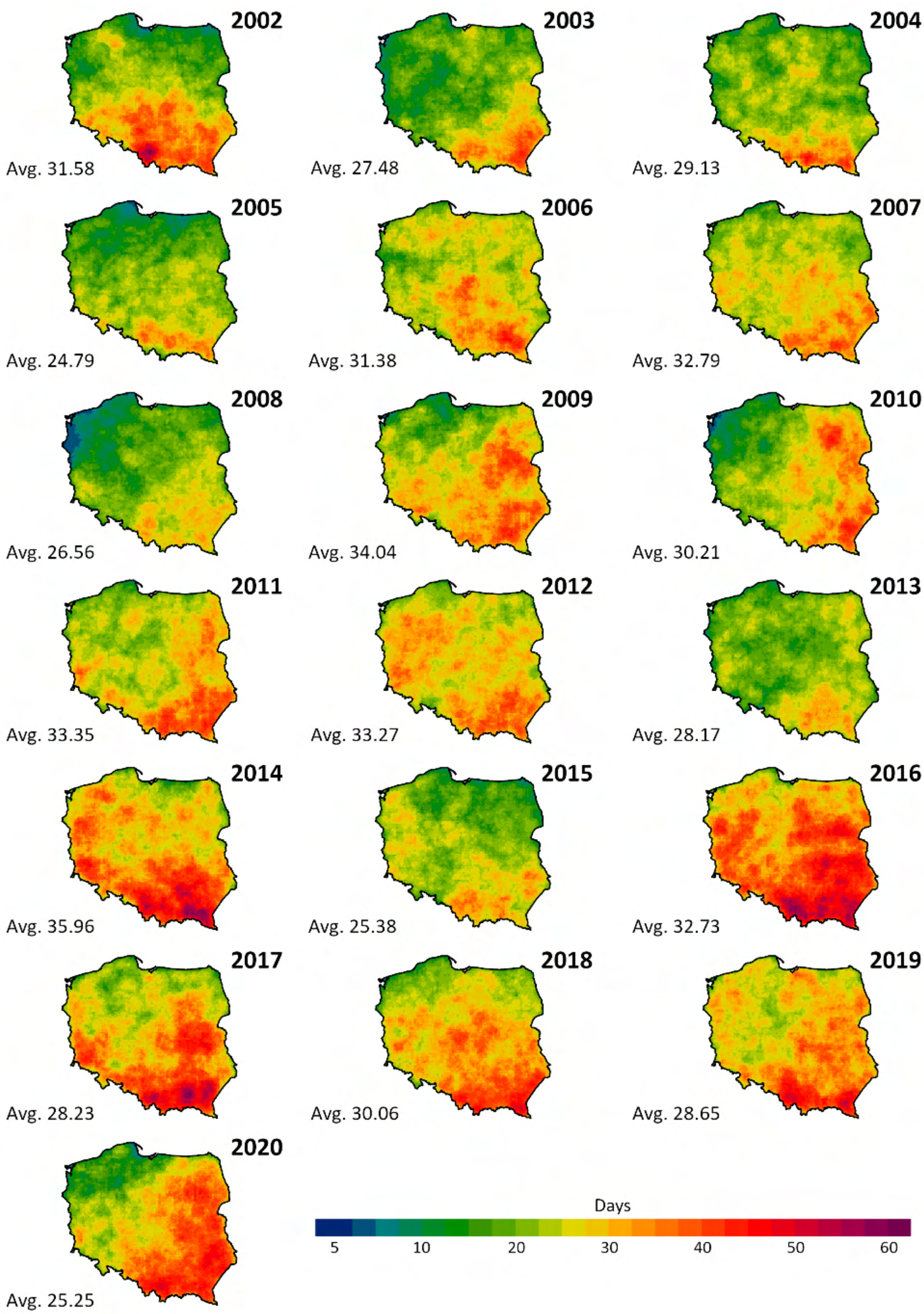

Figure 7. Annual number of TDs in Poland based on PERUN lightning detection system data during the period 2002–2020
Source: own study

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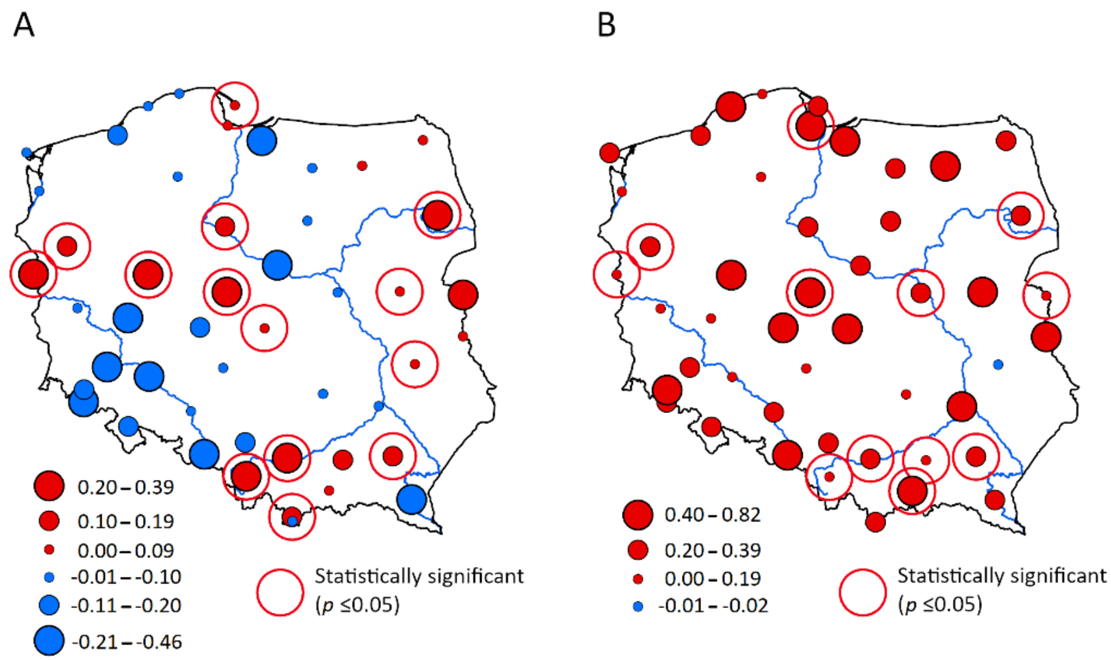

Figure 8. Changes in thunderstorm days per decade in Poland during the period 2002–2020 based on SYNOP (A) and PERUN (B) data. Stations with a statistically significant trend (p≤0.05) are marked by a circle
Source: own study

comparing the trends from the SYNOP and PERUN systems. There were only seven stations at which both methods showed a trend which was similar in direction but often different in value. An upward trend was found for seven stations by the PERUN system, and for five stations by SYNOP, which was not confirmed by lightning detection.

In Poland, thunderstorms occur mainly in the warm half of the year, but now we are observing an increase in TDs in the winter months. Coastal conditions are most favourable for thunderstorms in the cold half of the year. This may be caused by the current climate changes, including changes in prevailing atmospheric circulation and increased air temperature.

Discussion and final remarks

Thunderstorms are extreme weather phenomena. In Poland, thunderstorms most often occur along atmospheric fronts (cool and occluded) with air mass influx of sea origin from the west or north-west (Kolendowicz 2006; Sulik 2021, 2022).

Remote-sensing methods are increasingly used in the study of atmospheric phenomena, the results of which differ from traditional meteorological observations made by humans. In many stations, automatic measurements are introduced which do not ensure the detection of atmospheric phenomena. Hence, it is necessary to link the different series of observational and remote-sensing data on storm occurrence.

The frequency of TDs in Poland was analysed using parallel observational (SYNOP) and lightning discharge detection (PERUN) data from 2002–2020. For each station, the number of TDs was calculated for lightning discharges around the station in a buffer of 15-km radius. The buffer radius suggested by Czernecki et al. (2016) of 17.5 km caused excessive differences between the observed thunderstorms and the values from PERUN. Nevertheless, it was found that the observations (SYNOP) showed a lower number of TDs per year, with differences ranging from 1 to 8 days, compared to the PERUN lightning detection system. This may result from the subjectivity of observations and from significant light and noise pollution around stations located in cities, or due to the horizon being obscured (by hills, buildings, trees). The best compatibility between SYNOP and PERUN occurred for stations on the Baltic Sea coast, which was confirmed in an earlier analysis by Czernecki et al. (2016), who found that in Łeba, an observer could record discharges appearing within an average radius of 24 km. On the other hand, the greatest differences occurred in mountain valleys with limited horizons. The same authors stated that this radius was only 12 km in Bielsko-Biała in the Carpathian Mountains. In cities the conditions for observing thunderstorms are disrupted by the anthropogenic illumination of the sky.

Annual spatial distributions of TDs in Poland during 2002–2020 obtained from SYNOP confirm the results of previous analyses (Kolendowicz 1997, 2006; Bielec 2000; Lorenc 2005; Bielec-Bąkowska 2013; Czernecki et al. 2016; Bielec-Bąkowska et al. 2021). The highest frequency of TDs was found in the south-eastern part of the country, especially in the mountains. The least frequent number of thunderstorms occurred on the coast of the Baltic Sea. Compared to the years 1951–2018, analysed by Bielec-Bąkowska et al. (2021), there were higher frequencies of TDs at some stations, for example, in Lesko, 37.8 days instead of 31.9 days; in Zakopane, 33.0 and 30.6 days, respectively; and in Gdańsk, 17.9 and 14.5 days, respectively. However, there are stations where the opposite situation occurred, for example, for Śnieżka, 20.6 days and 24.0 days, respectively. This is evidence of either climate change or the subjectivity of the lightning observations. The use of the PERUN network allowed these data to be refined, which is confirmed by a previous study by Taszarek et al. (2019) who analysed the distribution of thunderstorms in Europe. The spatial distributions of TDs according to SYNOP and PERUN were similar, but after using a 1×1 km grid, the spatial disposition of TDs was found to be more fragmented. The influence of local factors related to the orography of the area, and the presence

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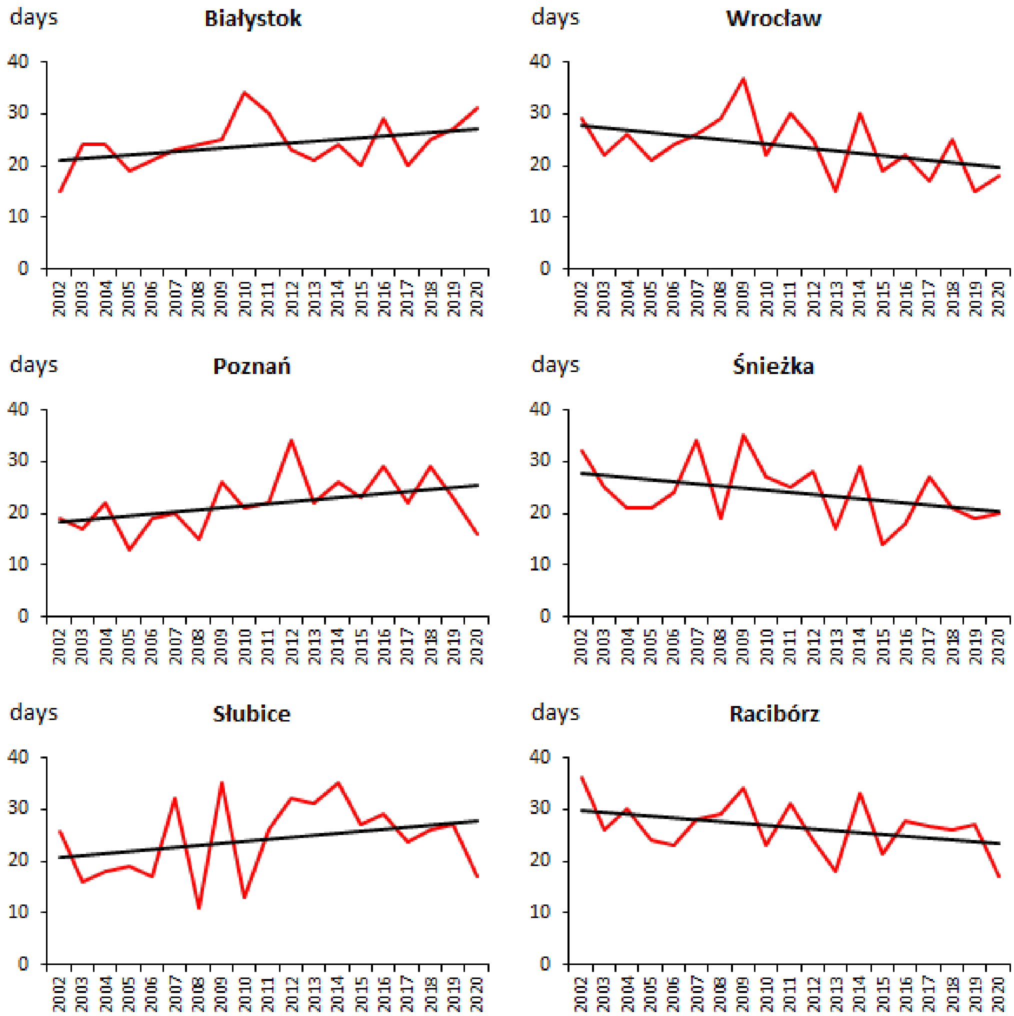

Figure 9. The course of thunderstorm days for selected stations in Poland during the period 2002–2020 based on SYNOP reports
Source: own study

of water bodies, forest complexes, and large agglomerations, is visible (Sulik & Kejna 2022). The obtained distribution of TDs confirms the legitimacy of separating the three storm regions in Poland, including the Baltic Sea coast, an area covering the lake districts of northern Poland, and the plains of western and south-eastern Poland (Kolendowicz 2006).

In the annual cycle, the maximum frequency of TDs in July is prominent (mean, 7.08 days for SYNOP and 7.62 days for PERUN). According to Kolendowicz (2006), the season of maximum thunder activity lasts from May 16 to August 13 on the Baltic Sea coast and until August 18 in the rest of the country. In May and the summer months, the thermodynamic instability of the atmosphere increases, favouring convective movements and the development of cumulonimbus clouds (Poręba et al. 2022). In the autumn (September–October) the frequency of TDs decreases sharply, but there is high frequency of thunderstorms along the Baltic coast. This is confirmed by the research of Taszarek et al. (2019), who found an increase in thunderstorm days during the cold half of the year in the Mediterranean coastal zone.

In many regions of the world, an increase in the frequency of extreme events, including thunderstorms, has been reported (AR6 Climate Change 2021). Studies concerning the variability in the occurrence of TDs have also been conducted in Poland. Research by Bielec-Bąkowska (2003), covering the years 1951 to 2000, did not show a statistically significant trend. More recent data from 1951 to 2018 (Bielec-Bakowska et al. 2021) distinguished western Poland as being characterised by a predominance of negative TD trends (up to 1 day per 10 years) and eastern Poland as having a predominance of stations registering an upward trend (up to 2 days per 10 years). In Kraków, as shown by a series of observations from 1901 to 2018, there was a significant variability in TDs from year to year: there were periods of increased storm activity and calmer periods. The beginning of the twenty-first century shows a downward trend (Bielec-Bakowska et al. 2021). However, in our analysis, spatially diversified trends were found. A statistically significant increase in the number of TDs was found at 14 stations for the period 2002–2020, based on observational data (SYNOP); these do not show any spatial regularity. PERUN data is more objective. They showed an increase in the number of TDs for all stations except Lublin. However, only at 12 stations was this increase statistically significant. Both methods confirm an increase in the number of TDs in many regions of the country. The reason for this may be the greater frequency of thunderstorms during

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the colder half of the year, especially on the Baltic coast (Bielec-Bakowska et al. 2021).

There are also varying trends in TDs and lightning flashes around the world. In a study by Lavigne et al. (2019), based on over 8,000 meteorological stations and satellite lightning detection systems (TRMM - Tropical Rainfall Measuring, LIS - Lightning Imaging Sensor), an increase in TDs was found for the Amazon, Southeast Asia, India, Democratic Republic of the Congo, Central America, and Argentina, whereas, for example, China, Australia, and the Sahel exhibited decreases in the number of thunderstorm days. There was no significant TD trend in the United States during the 1993–2018 period. There were, however, periods with increased storm activity and large differences between individual parts of the country (Koehler 2020). In Europe, the mean annual number of TDs since 1979 has shown an increase over the Alps and Central, South-Eastern, and Eastern Europe, with a decrease over the south-west. (Taszarek et al. 2019). In Australia, there were also different TD trends across individual stations (Kuleshov et al. 2002).

Summing up; it should be stated that the results of the visual observations of thunderstorms and the detection of lightning flashes differ due to the perception and subjectivity of human assessment. Remote-sensing methods are objective and more accurate. Unfortunately, for now, these two storm investigation systems cannot be linked together. Also, the buffer which determines the possibility of observing the storm cannot be clearly determined; it is different for each station, and depends on the subjective opinion of the observer or the limitations of visibility related to the horizon and the light pollution of the sky. Further research in this matter is necessary to better monitor the course and spatial distribution of these phenomena.

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MANUSCRIPT BODY

Kinematic and thermodynamic environment during cloud-to-ground lightning occurrence in Poland

ABSTRACT

This study identifies convective and kinematic parameters positively influencing elevated values of cloud-to-ground lightning flashes (CGs) in Poland. The analysis was carried out using data from the PERUN lightning detection and location system from IMGW-PIB and reanalyses of the ERA5 model from ECMWF for the period 2002-2020. In addition, a spatial-temporal distribution analysis was carried out for the period 1940-2022 covering the key parameters necessary for the appearance of convection. As a result of the study, it was found that thunderstorms most often occur in the summer, but also in the spring there are increasingly favorable conditions for the appearance of organized multicellular systems. CG flashes most often form in a most-unstable convective available potential energy (MU CAPE) environment of about 1300 J/kg along with the present vertical wind shear (0-6 km AGL bulk wind shear) of 13-14 m/s. Using the WMAXSHEAR parameter, it was possible to conclude that overlapping CAPE and DLS values of about 500 m2/s2 imply increased electrical activity. At the same time, a high correlation with the Hail Size Index (HSI) parameter implies a positive relationship with regard to the occurrence of hailstorms and an increased number of CGs generated in the case of supercells. Research also found a gradual increase in air temperature, MU CAPE, MU Mixing Ratio and the MU WMAXSHEAR parameter for the area under study.

KEYWORDS: Lightning, Thunderstorm, Convection, Climate change, Reanalysis data, Poland

1. Introduction

Thunderstorms in Poland mainly occur in the warmer part of the year. Each year, there are about 150 days with thunderstorms in Poland and their frequency increases from the north to the southeast (Sulik and Kejna 2023; Taszarek et al. 2015). The smallest number of thunderstorm days (TD) has been recorded for years in the close Baltic Sea region (10-15 TD) while the highest activity of these phenomena occurs in the southeastern part of the country (35-40 TD). The aforementioned thunderstorm activity falling in the warmer part of the year is characterized by a marked increase from May to the end of August (Fig. 1B). In the cooler part of each year, thunderstorms also occur albeit their number as well as electrical activity remains negligible.

Speaking of thunderstorms, according to the AMS *Glossary of Meteorology* definition, a thunderstorm is a phenomenon classified on the basis of the occurrence of lightning often accompanied by other dangerous phenomena such as strong wind gusts, heavy rainfall and hail (Byers and Braham 1949). On the other hand, the occurrence of thunderstorms is equivalent to the occurrence of lightning, they should be given special attention, which is also done in this study. Earlier studies for the area of Poland concerning the spatial distribution and intensity of lightning discharges have shown that the greatest electrical activity occurs in the area of central Poland, and each year the PERUN system records about 480,000 cloud-to-ground lightning flashes in the entire country (Sulik 2022). The increase in the number of lightning flashes occurring year after year across the country has also been confirmed (Fig. 1A). The constant activity of thunderstorm phenomena is also evident in the number of days with thunderstorms. Thunderstorm phenomena often contribute to a large number of property losses, usually associated with spotty wind gusts in the case of linear formations or large hailfall associated with supercells (Groenemeijer et al. 2017; Taszarek et al. 2019; Pilguj et al. 2019).

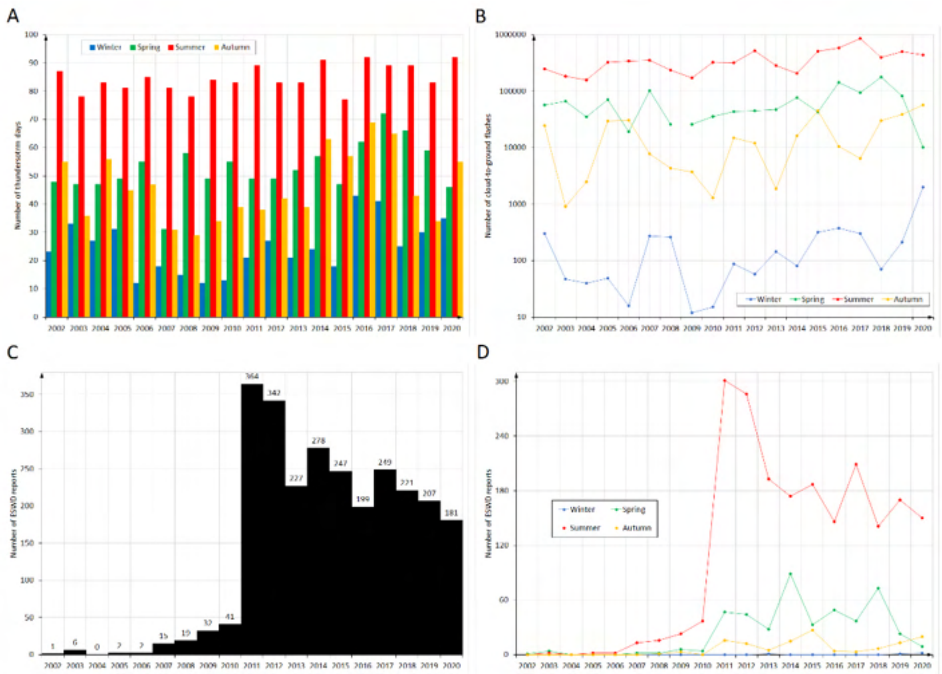

Fig.1. A – Number of thunderstorm days in Poland by seasons derived from PERUN lightning detection system. B – Number of cloud-to-ground flashes in Poland by seasons derived from PERUN lightning detection system. C – Number of damaging lightning reports in Poland derived from ESWD database. D – Number of damaging lightning reports in Poland by seasons derived from ESWD database.

The temporal and spatial distribution regarding the occurrence of days with thunderstorms and their electrical activity can also be seen in reports from the hazardous weather database (ESWD; Dotzek et al. 2009). Thanks to the European Weather Observer (EWOB) system managed by European Severe Storms Laboratory (ESSL), users of the application are able to send information on weather events of various types. The reports shown in Fig. 1C and 1D reflect the occurrence of a phenomenon known as damaging lightning, which is most often property damage caused by cloud-to-ground lightning. Every year throughout Europe, storms cause millions euros of damage, and only in Poland, between 2002 and 2020, 50 people died and 408 were injured as a result of lightning strikes. The topic of a warming climate in relation to violent atmospheric phenomena is still important, and this study aims to determine the thermodynamic and kinematic conditions under which thunderstorms generating cloud-to-ground flashes are formed in Poland.

2. Dataset and methodology

2.1. Lightning data

The data based on the results of recorded lightning was taken from the PERUN lightning detection and localization system managed by Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). The system is part of the European SAFIR (Surveil-lance et d'Alerte Foundre par Interferometric Radioelectrique) system, but the Polish part of the system was nicknamed to refer to the Slavic god of lightning - Perun (Gieysztor 2006). The system has been in continuous operation since 2002 and detects lightning by intra-cloud, cloud-to-cloud and cloud-to-ground. Detection is based on and triangulation technique and. The system applies the technique of detecting the direction of arrival of the DF signal (Bodzak 2006). The entire system currently consists of 13 stations evenly distributed throughout the country (Fig. 2).

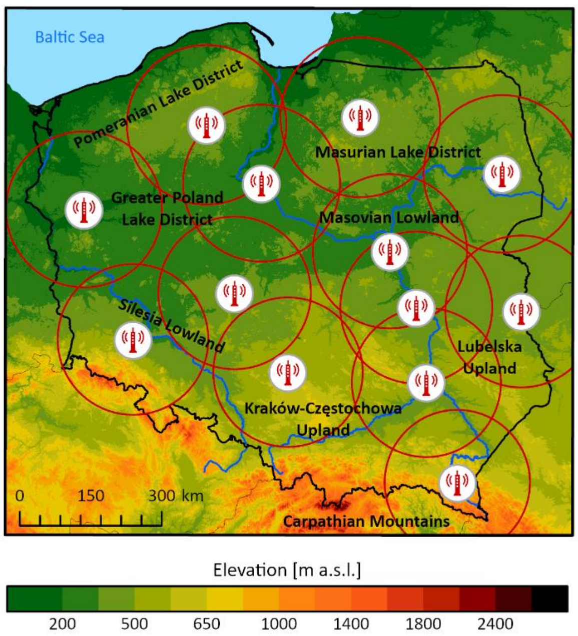

Fig. 2. Hypsometric map of Poland based on the Shuttle Radar Topography Mission Global Coverage (SRTM3; Farr et al. 2007). Symbol points denotes location of the PERUN lightning detection sensors with 100 kilometer buffer zone.

Over 95% of the country's coverage area, the accuracy of discharge detection is less than 1 km, and is being systematically reduced through efforts to replace detectors that enable more precise detection of lightning flashes.

In this research, we are based on a grid of 10 × 10 km (an area of 100 square kilometers) so as to address the discharge-area relationship as precisely as possible (Diendorfer 2008). Previous studies on the spatial distribution of lightning in Poland were also based on the same basic field dimension (Taszarek et al. 2015; Sulik 2021; Sulik 2022; Poręba and Taszarek 2022). In the European area, the authors used different grid sizes, but the 10 × 10 km dimension was most often chosen so as to refer to results from different locations around the world and so that the results would be comparable. The authors of various studies decided on different ranges of years or the dimensions of the base field needed for statistical calculations and the determination of the spatial distribution of the discharges. A number of studies on lightning climatology have been prepared for the area of Europe. The most frequently chosen primary field was a grid of 10 km × 10 km, 20 km × 20 km, 0.1° × 0.1° (approximately 10 km ×10 km), 0.2° × 0.2° (approximately 20 km × 20 km) and 5 km × 5 km (eg., Biron et al., 2009; Betz et al. 2009; Enno 2011; Wapler 2013; Feudale et al. 2013; Kotroni and Lagouvardos 2016; Mäkelä et al. 2011; Novák and Kyznarová 2011; Pohjola and Mäkelä 2013; Santos et al. 2012; Schulz et al. 2005; Soriano et al. 2005; Taszarek et al. 2015; Sulik and Kejna 2022). In the United States of America, Koehler (2020) used a grid resolution of 926 m × 926 m and all counts were summed over subsets to yield counts on a coarser grid with 3704 m × 3704 m resolution. As a result, the maximum CG flash values were found over Tampa, Florida. What important, several locations in California, had no lightning flashes during the 26-yr period.

Due to the lower harmfulness of inter-cloud flashes and the system's errors in detecting them, we decided to use only ground flashes. At the same time, as shown in a study conducted by Cummins et al. (1998), some discharges below 10 kA can often be detected by the system as cloud discharges, so they were removed. Also, if a discharge occurred several times at the same location it was treated as an error and only the first flash was taken into account. The whole raw dataset derived from IMGW-PIB was reorganized in the R programming language (R. Core Team 2014) and all maps were prepared in ESRI ArcGIS PRO 3.1.3 software.

2.2. Reanalysis data

Professional NWP products and, in this case, widely used reanalyses could not be absent from this study. The principle of creating reanalysis is based on combining data from numerical models with observations made at synoptic stations. Added to this are also measurements made by automatic stations or, in this case, vertical atmospheric soundings. The result is a coherent and complete dataset completed using the laws of physics. Data assimilation is done by combining previous predictions with new observations to get the most accurate estimate of the state of the atmosphere. Working backwards, improved versions of the original observations are used which, combined with the lack of timely conditions for the release of the model forecast, has a positive effect on the quality of the final product.

We decided to use a proven and highly accurate reanalysis of convective parameters derived from the ERA5 product managed by ECMWF (ERA5; Hershbach et al. 2020). The study area is the area of Poland, so it was necessary to use a wide range of grids so that the area of Poland is completely covered by the reanalysis data.

The ERA5 data are originally created in the 0.25° grid range and the time span allows mapping meteorological conditions in 1-hour intervals (Table 1.).

Table 1. Characteristics of ERA5 reanalysis data used in research.

Data type	Grid
Horizontal grid spacing	0.25° x 0.25°
Projection	Latitude-longitude
Temporal resolution	Hourly
Horizontal coverage	Poland
Timeframe	1940-2022 2002-2020
Total grid points	500 195
Latitude extent	48.75° - 55.25°
Longitude extent	13.75° - 24.50°

To analyze situations in which lightning is generated, specialized parameters were selected to determine the state of the atmosphere at a given time. The standard parameters were, of course, air temperature, dew point temperature, convective precipitation, precipitable water amount or parameters related to humidity at heights of 0-2 km and 2-5 km above the ground surface. Convective parameters related to thermodynamics and kinematics were separated for the most unstable air parcel (MU) along with virtual temperature correction (Doswell and Rasmussen 1994). Thermodynamic and kinematic variables included in the study are convective available potential energy, convective inhibition, lifted condensation level with height and temperature, lifted index, mixing ratio, geopotential height, bulk wind difference. The specific parameters taken for analysis are WMAXSHEAR and HSI, which have already been used in previous studies related to climatological aspects of convection over Europe. The WMAXSHEAR parameter is used in forecasting severe thunderstorms and consists of components such as a square root of 2 times CAPE multiplied by 0-6 km wind shear and was implemented by Taszarek et al. 2020. The HSI parameter developed by Czernecki et al. 2019 determines the hail size index and is also directed towards the prediction of large hail precipitation over Europe. The selected convective parameters were chosen to best and most accurately represent the conditions of lightning formation. The list of parameters derived from the ERA5 data is presented in Table 2. In addition, the trends of some variables were calculated for the period 1940-2022 so as to show the variability over time of the parameters responsible for convection in Poland.

Table 2. List of convective parameters used in research.

Abbreviation	Full name	Units
MUCAPE	most-unstable convective available potential energy	$J\cdot kg^{-1}$
MUCIN	most-unstable convective inhibition	$J\cdot kg^{-1}$
MULCL H	most-unstable lifted condensation level height	m AGL
MULCL T	most-unstable lifted condensation level temperature	°C
MULI	most-unstable lifted index	K
MUMIXR	most-unstable mixing ratio	g/kg
MUHGT	most-unstable geopotential height	m AGL
MUWMAXSHEAR	square root of 2 times CAPE multiplied by bulk wind difference based on formula from Taszarek et al. (2017)	m^2/s^2
ISO 0 H	0 Celsius isobar height	m AGL
PW	precipitable water amount (entire column)	mm
RH02	0-2 kilometer above ground level mean relative humidity	%
RH25	2-5 kilometer above ground level mean relative humidity	%
BSEFF	bulk wind difference (shear)	$m\cdot s^{-2}$
HSI	hail size index formula from Czernecki et al. (2019)	-
T2M	2 meter above ground level air temperature	°C
TD2M	2 meter above ground level dewpoint temperature	°C
CP	ERA5 1-h accumulated convective precipitation	$mm\cdot h^{-1}$

3. Results

3.1. Cloud-to-ground lightning and thunderstorm days

The spatial distribution of lightning and the number of thunderstorm days varies across Poland. The smallest number of TDs occurs in the Baltic Sea area in the north of the country (10-15 days/year). The largest, in the southeastern part (35-40 days/year)(Fig. 3B). On the other hand, if we look at the electrical activity of thunderstorms we can note their greatest distribution in the region of the central part of the country (Kielce Upland through Masovian Lowland)(Fig. 3A). During the 18 years of PERUN's operation, more than 8,626,000 cloud-to-ground were detected and located in Poland.

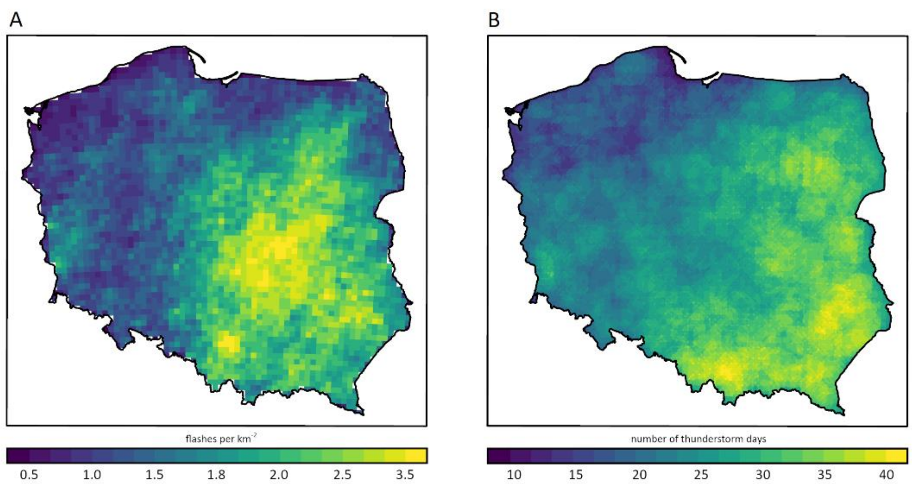

Fig. 3. A – The average annual number of CG lightning flashes km^{-2} computed for 10 km x 10 km grid cells during 2002-2020. B – The average annual number of thunderstorm days during 2002-2020 computed for 1 km x 1 km grid cells within a radius of 15 km from the bin center. Based on lightning data derived from PERUN network.

Thunderstorm activity in Poland in terms of the occurrence of TDs and their electrical activity does not deviate from the climatological regularities that characterize the Polish climate (Kejna and Rudzki 2021). The occurrence of thermal seasons apparently separates warmer from cooler seasons. Thunderstorms are most numerous from May to the end of August, but their number is also pronounced in September. The period from October to March is the period of least thunderstorm activity but also in these months there are instances of uplift of single convective cells. The electrical activity of thunderstorms during the cooler period of the year is sporadic (Fig. 4). In terms of both the number of CG discharges generated and the number of days with thunderstorms, there is a noticeable increase in both variables especially in June and July. As shown in a study by Poręba et al. (2022) containing a similar period of PERUN system operation, the highest thunderstorm activity in terms of hourly cycle falls on 1400-1500 UTC while the lowest on 0700-0800 UTC. Noteworthy is the fact that in autumn electrical activity during the occurrence of night storms is greater than in spring and summer.

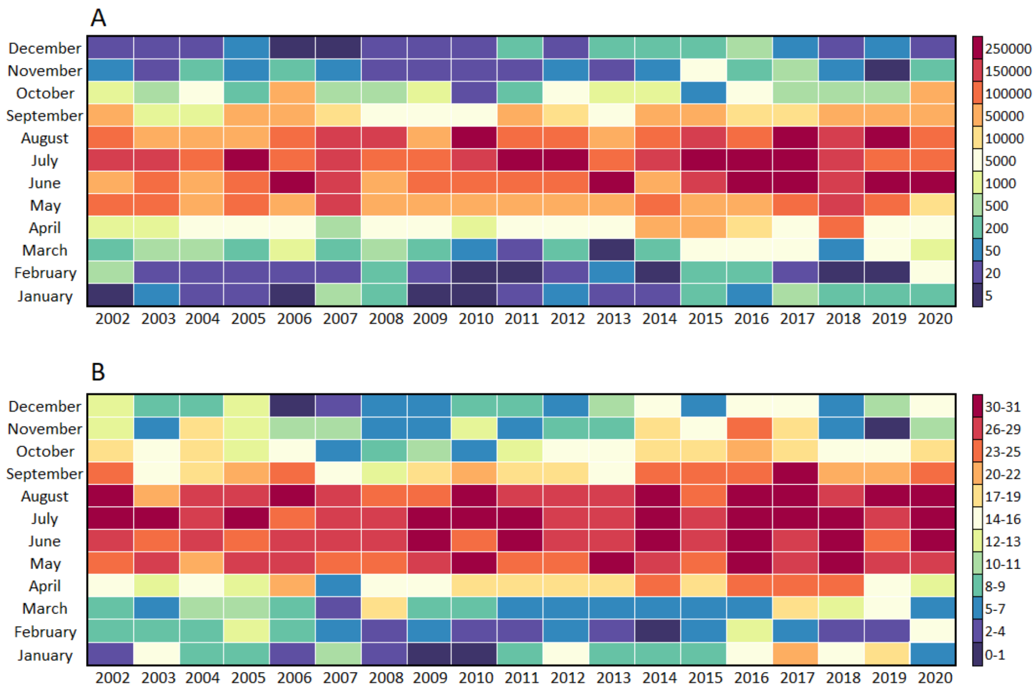

Fig. 4. A – Annual distribution of CG flashes during 2002-2020 by monthly cross-section. B – Annual distribution of TDs during 2002-2020 by monthly cross-section. Based on lightning data derived from PERUN network.

Considering the distribution of the number of CG discharges during the year and especially during specific months, it should be remembered that during 30/31 days with a thunderstorm in the range of an entire month, there may be a different number of discharges. Abnormal numbers of CG discharges are seen primarily in June, July and August. The days with the highest electrical activity in Poland are summarized below (Table 3). During some days with thunderstorms, the electrical activity of Cumulonimbus clouds is very high and such a distribution can determine the number of discharges recorded by the detection system, which sometimes directly affects the annual distribution. When interpreting the meteorological aspects in which thunderstorms generating elevated CG values arise, it is therefore necessary to focus directly on their number and the number of days on which extremes of this type occur.

Table 3. Top 8 days with highest electrical activity over Poland during 2002-2020 period calculated in 10 km x 10 km grid cells derived from PERUN system.

Date	Number of CG flashes	Average number of CG flashes per km^{-2}	Highest number of CG flashes in one 10 km x 10 km grid cell
10.08.2017	154.524	0.50	845
13.06.2019	86.124	0.27	407
02/03.07.2012	80.416	0.25	882
26.06.2006	73.504	0.23	651
19.07.2015	72.030	0.23	325
26.06.2017	69.769	0.22	653
15.08.2008	63.399	0.20	354
11.08.2017	56.510	0.18	482

3.2. Annual variability of CG lighting flash environment

This section of the paper will present the convective conditions at which storm clouds generate ground-based lightning. As already presented in the earlier section, the convective parameters are derived from ERA5 reanalyses and were determined for the number of thunderstorm days in which at least one CG flash occurred, so convection occurring during the cold period such as snow convection was not considered.

The main variables for the uplift of a Cumulonimbus storm cloud are components such as favorable thermodynamic and kinematic conditions. Considering the variables relating to thermodynamics, this is mainly CAPE and Mixing Ratio, which determines a measure of the water vapor content of the air (Riemann-Campe et al. 2009). For both CAPE and Mixing Ratio, larger values determine a more moisture-rich boundary layer, which, along with altitude, may have a greater capacity to release energy through condensation. Even average CAPE values will not be sufficient if there is no initiation of convection positively supported by favorable kinematic conditions. Such can be represented by the Deep Layer Shear (DLS), which is the difference in wind speed at 0-6 km above the ground surface, and the product of the MU CAPE and DLS variables, i.e. WMAXSHEAR developed by Taszarek et al. (2020).

As presented in Fig. 5A, values of discharges above 30,000 in a single day with a thunderstorm occur although they are not very numerous. On the other hand, when it comes to thunderstorms generating about 10,000 discharges they are the most numerous, and this type of system is classified as moderate although a section devoted to this issue is presented in subsection 3.4. However, when it comes to the thermal and kinematic conditions accompanying the generation of CG discharges, they are most often formed under WMAXSHEAR conditions of about 500 m2/s2. Of course, stronger thunderstorm systems occur for values as high as 1,000 m2/s2 but these occur sporadically. The highest frequency of thunderstorms is best described by the relationship for DLS and MU CAPE (Fig. 5B). Potential energy values in the range of about 1500 J/kg are elevated values for the area of Poland, but as can be seen, it is under such conditions that the potential for generating discharges is favorable. The values of kinematic conditions most often fall in the vicinity of 13-14 m/s in the 0-6 km AGL profile. As in the case of the relationship of the number of CG discharges to the WMAXSHEAR index, the key element is the mixing ratio. Mixing Ratio in the range of 13 g/kg when superimposed with favorable thermodynamic parameters represented by WMAXSHEAR above 500 m2/s2 results in increased CG flashes values (Fig. 5C). The most important and crucial aspects of storm cloud development take place above the height of Lifted Condensation Level (LCL) and Level of Free Convection (LFC). On the other hand, the layer near the surface also shows variables that indicate an increased potential for CG flashes. This is favorably influenced by an elevated air temperature above 27°C and a dew point temperature around 19°C (Fig. 5D).

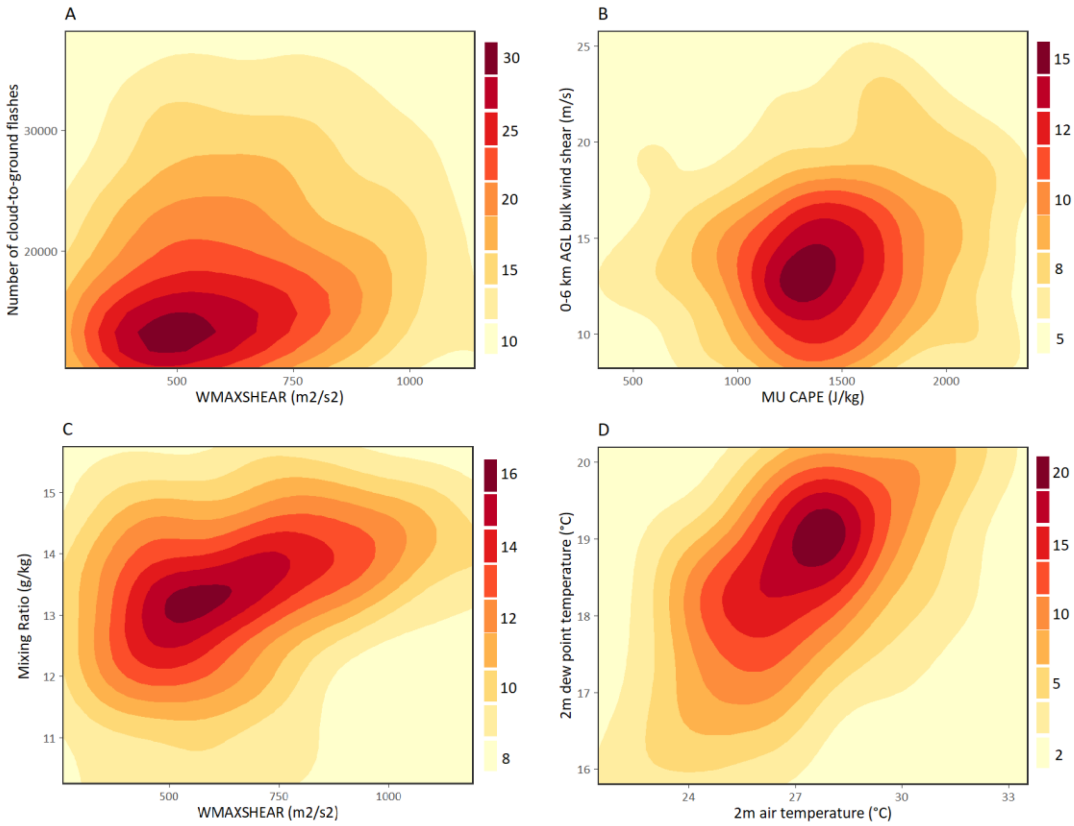

Fig. 5. A – Relationship between number of CG flashes and WMAXSHEAR. B – Relationship between wind shear and MU CAPE. C – Relationship between Mixing Ratio and WMAXSHEAR. D – Relationship between 2m dew point temperature and 2m air temperature. Computed from PERUN and ERA5 data for thunderstorm days over period 2002-2020).

In the process of cloud-to-ground flashes formation, an essential component is the moisture contained in the lower troposphere (Farnell and Rigo 2020). In the process of lightning formation, an essential component is the moisture contained in the lower troposphere (Farnell and Rigo 2020). The aforementioned moisture and updraft favorably influence the formation of hail inside the convective core. Therefore, the Hail Size Index (HSI) developed by Czernecki et al. (2019) was used in the study. Previous studies have proven that hail is formed inside the Cumulonimbus cloud due to strong vertical motion within the ascending current as a result of rapid cooling of water droplets contained in the troposphere (Allen 2018). As confirmed by studies on supercells or linear systems, the moisture content, thermal gradient in the vertical profile of the troposphere is regulated by vertical wind shear which simultaneously contributes to updraft velocity. Higher vertical velocity promotes not only lightning but also hail precipitation (Doswell 2001; Coffer and Parker 2015; Lin and Kumijan 2021). Consequently, storm cells and especially supercells, which typically produce large hail precipitation, generate greater amounts of ground discharge. Also, moderate DLS and WMAXSHEAR values are noted in supercell structures (Fig. 6A). Also when it comes to supercell thunderstorms generating large hail, these very structures are mainly responsible for heavy rainfall often exceeding 40 mm/h (Fig. 6B) or the appearance of a tornado. It can therefore be assumed that the occurrence of a supercell additionally benefits from increased electrical activity. A study performed by Poręba et al. (2022) also showed a positive relationship between Supercell Composite Parameter (SCP) and HSI.

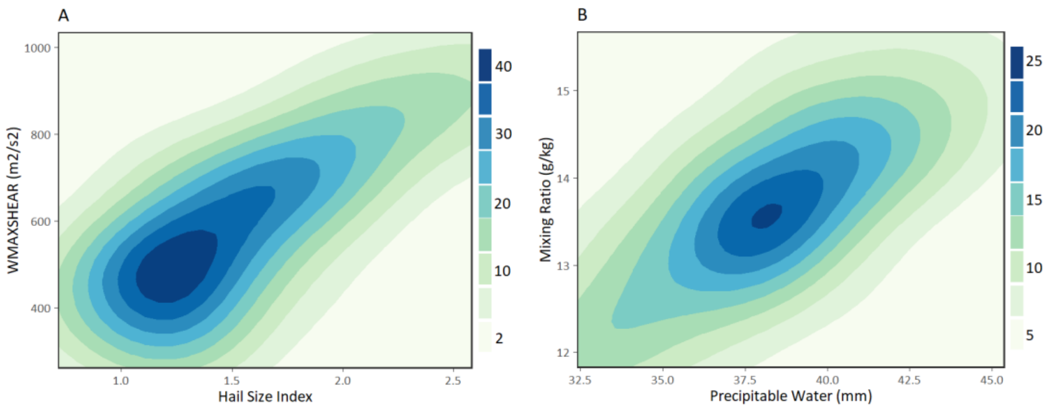

Fig.6. A – Relationship between WMAXSHEAR and HSI. B – Relationship between Mixing Ratio and Precipitable Water Amount. Computed from PERUN and ERA5 data for thunderstorm days over period 2002-2020.

As mentioned earlier, the main and most intense thunderstorm activity in Poland occurs during the warmer period of the year in the months of May through September. This is when the parameters favorable to convection are particularly elevated. In summer, even relatively moderate CAPE values combined with moderate wind shear create the potential for electrical activity. In spring, thermodynamic and kinematic conditions tend to occur with low values when they are virtually nonexistent during autumn and winter. The negligible activity of thunderstorms in autumn and winter manifests itself mainly in the form of linear convective systems characterized by stronger wind gusts, less often by an increased number of CG flashes (Celiński-Mysław et al. 2020)(Fig. 7). As for the DLS and Mixing Ratio during the occurrence of thunderstorms, these variables are also most prominent in summer. The process of discharge formation is closely related to moisture content. As Wang et al. (2018) also notes, the larger the moisture deposits in the lower troposphere, the faster the separation of charges in the storm cloud. When Relative Humidity (RH) increases above 60%, there is a significant increase in CG discharges relative to IC. The distribution and ratio of DLS to Mixing Ratio by season is shown in (Fig. 8).

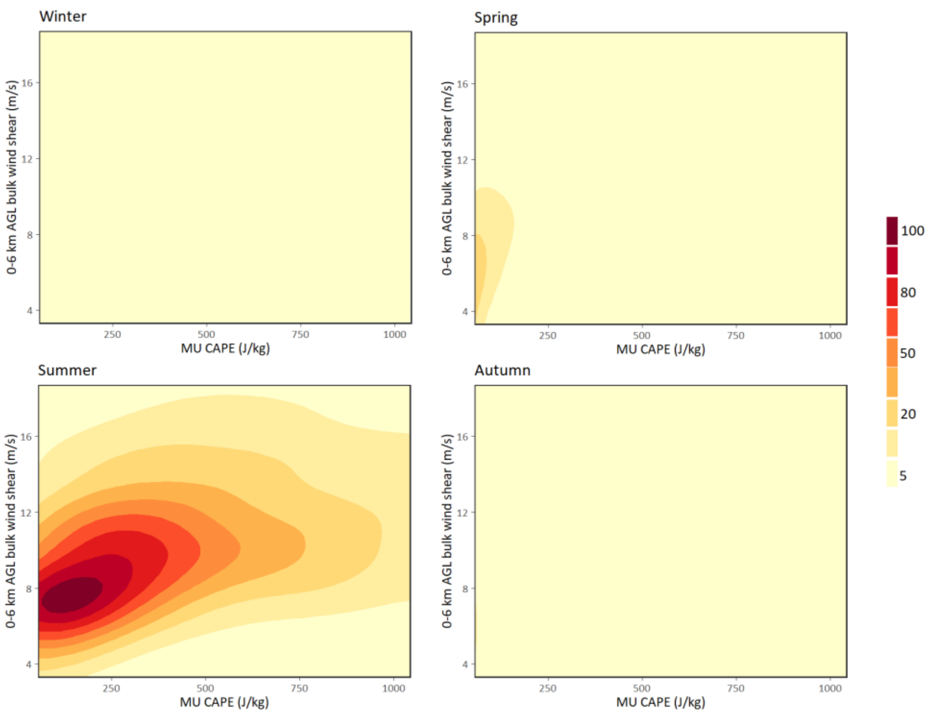

Fig.7. Seasonal variability of DLS and MU CAPE for thunderstorms environment over Poland. Derived from ERA5 data.

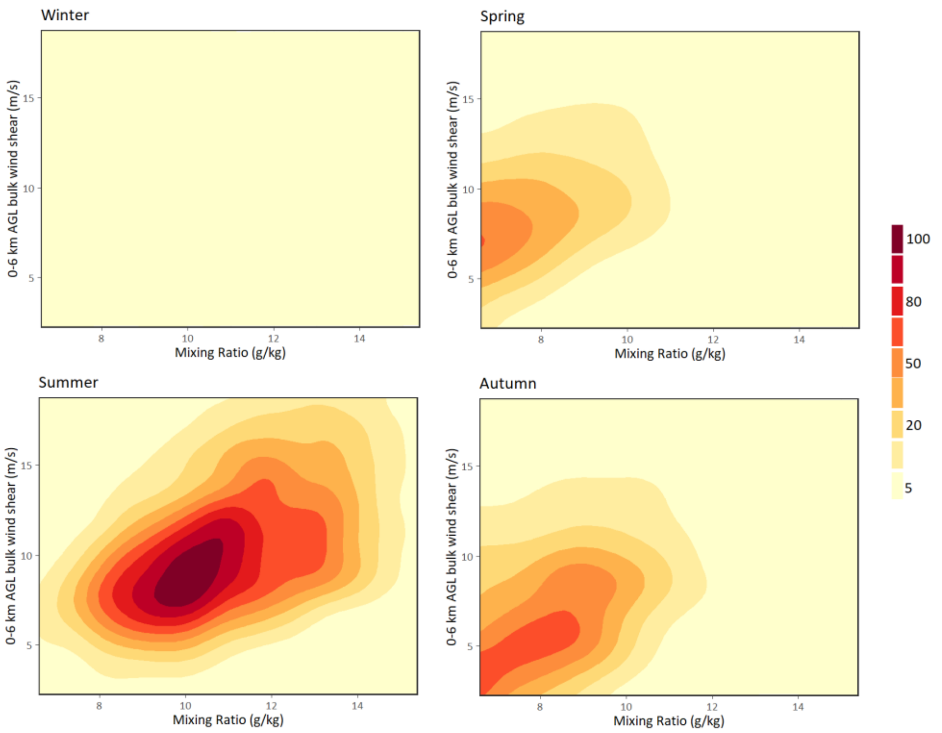

Fig.8. Seasonal variability of DLS and Mixing Ratio for thunderstorms environment over Poland. Derived from ERA5 data.

3.3. Favorable conditions for deep moist convection

Undoubtedly, the most important factors enabling the formation of thunderstorms are sufficient moisture, unstable air mass and wind shear. However, for convection to occur, it must be initiated (Doswell 2001). The factors that initiate convection most often occur in the form of atmospheric fronts from the summer months (Sulik 2021) while in winter, terrain and orographic forcing play a key role (Kolendowicz 2012). Manifested climate change is visible primarily through increasing air temperature near the earth's surface. Increasingly, heat records are being recorded not only in the warm season but also in winter, and systematic air temperature is evident throughout the country (Fig. 9).

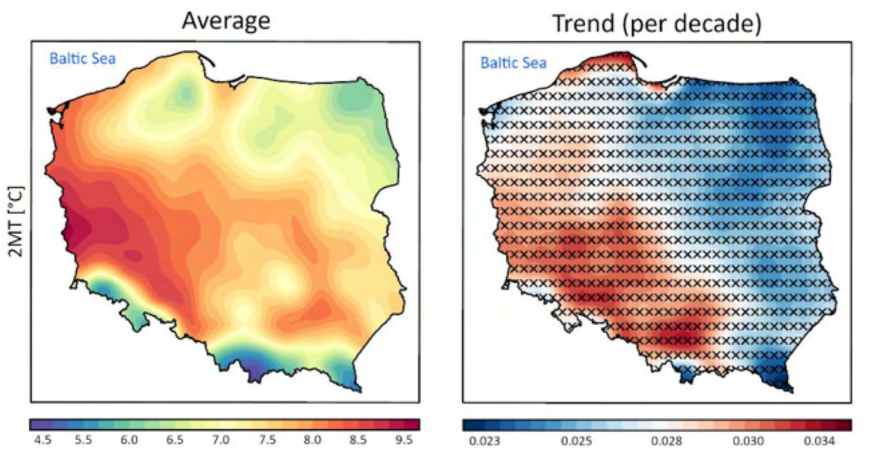

Fig. 9. Spatial distribution of average air temperature from 1940 to 2022. Long-term trend are derived from annual values in hourly resolution and corresponding Sen's slope. An x marks denote statistically significant trend. Computed from ERA5 reanalysis data.

Rising air temperature leads to an increase in the heat capacity of the atmosphere. As a result, larger and larger deposits of moisture can be stored. On the other hand, increasing air temperature can contribute to a decrease in relative humidity, which is so essential for the formation of thunderstorms.

In order to reproduce as accurately as possible the thermodynamic and kinematic conditions for the occurrence of specific values of CG discharges, the types of probability of occurrence of a given number of CG were separated. The probability was divided into 3 types such as severe, enhanced, moderate. The severe case refers to the most electrically active storms, whose value of generated CG flashes in one day is greater than 50,000. Enhanced refers to storms with activity between 10,000 and 50,000 flashes, while moderate is defined as storms that generate between 5,000 and 10,000 CG's in a daily interval.

By analyzing specific variables and the number of cases between them, it is possible to determine favorable parameters affecting the corresponding electrical activity of thunderstorms. The most intense thunderstorms are formed in the MU CAPE environment in the range of 1900-2100 J/kg and in the presence of kinematic conditions in the form of DLS from 16 to 20 m/s (Fig. 10). In contrast, however, when it comes to the cases of enhanced and moderate category storms, a very similar environment is evident in both the values of unstable air mass and wind shear at 0-6 km AGL. These types of thunderstorms can form in the

MU CAPE environment usually above 1000 J/kg not exceeding 1500 J/kg with the simultaneous presence of DLS around 11 m/s.

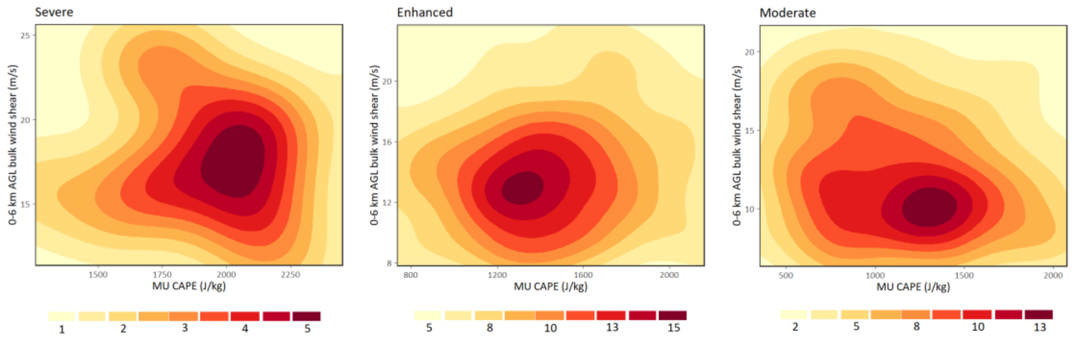

Fig. 10. Relationship between DLS and MU CAPE for the probability of increased electrical activity. Severe – lightning activity over 50.000 CG flashes/day. Enhanced – between 10.000-50.000 CG flashes/day. Moderate – between 5.000-10.000 CG flashes/day.

The ratio of mixing of moist air with dry air for the three analyzed storm types is similar to each other, ranging from 13 g/kg to about 15 g/kg in severe storms. However, the greatest changes are seen in the WMAXSHEAR parameter where storms generating enhanced CG values form in conditions ranging from 800 m2/s2 to 1300 m2/s2. For enhanced and moderate storms, the values of this parameter are between 400-700 m2/s2 (Fig. 11).

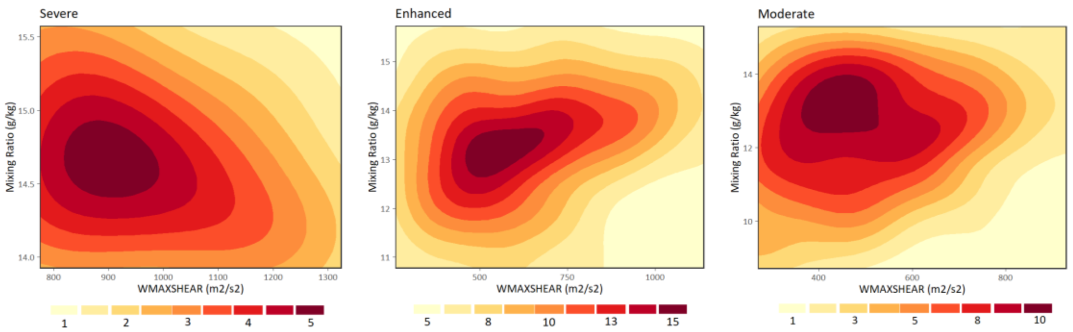

Fig. 11. Relationship between Mixing Ratio and WMAXSHEAR for the probability of increased electrical activity. Severe – lightning activity over 50.000 CG flashes/day. Enhanced – between 10.000-50.000 CG flashes/day. Moderate – between 5.000-10.000 CG flashes/day.

Since thunderstorm phenomena are formed in a rather complicated and complex way, the environment in which they form cannot be represented by a single variable. Among the most important are instability, moisture content and vertical movements. It was therefore decided to present the following variables necessary for convection to occur in relation to the number of flashes formed on one panel (Fig. 12). Similar distributions can be observed for humidity conditions (Mixing ratio, Dewpoint temperature and Precipitable water). Humidity is important enough because severe thunderstorms usually occur in an environment of elevated dew point. Low values of this variable effectively inhibit the release of latent heat and significantly reduce the threat of organized multicellular systems. Advection of a significant portion of moisture to the boundary layer positively increases the instability of the atmosphere.

An additional factor supporting convection is the relatively lifted condensation level (LCL), which, when overlapped with the WMAXSHEAR or DLS parameter, causes an increase in the velocity of the elevated air parcel and the simultaneous release of the energy it contains (Fig. 12 A, B). Convective instability is triggered when dynamic lift from the surface to mid-levels produces moist adiabatic lapse rates of air lifted from the lower troposphere and dry adiabatic lapse rates of air lifted in the middle troposphere. At the same time, strong vertical movements and the presence of fractions of water, ice, ice crumble cause the formation of hail, which has a strong effect on the formation of lightning.

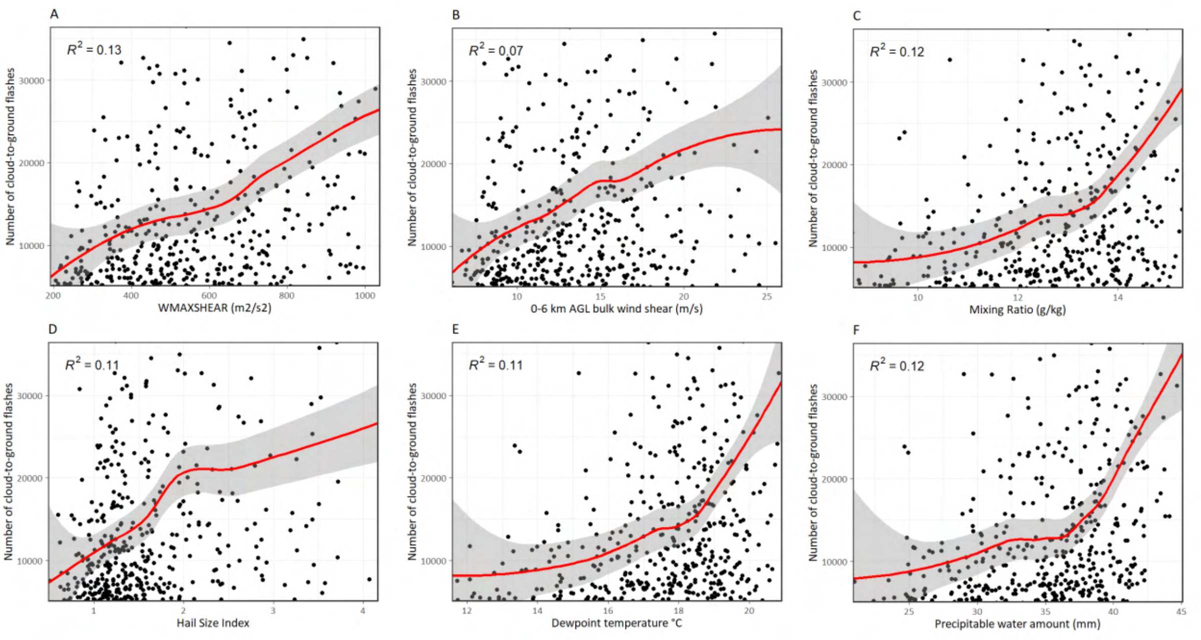

Fig. 12. Relationship between convective parameters and cloud-to-ground lightning flashes for A – WMAXSHEAR (product of DLS and MU CAPE). B – DLS (Deep Layer Shear). C – Mixing Ratio. D – Hail Size Index. E – 2 meter dewpoint temperature. F – Precipitable water. The red line denotes locally estimated scatterplot smoothing.

Extended storm systems, including supercells, often result in hail. Referring to previous studies, they showed a positive relationship in the CG and hail relationship. The number of discharges increases when hailfall occurs (Lang et al., 2000; Soula et al., 2004). Elevated instantaneous electrical activity (lightning jump), can also be linked to hail formation inside the convective core (Williams et al. 1999, Kane 1993). In turn, as noted by Changnon (1988), storms generating hail precipitation of a cold front nature are characterized by increased electrical activity. Hail production inside the Cumulonimbus cloud is therefore crucial, and as analysis has shown, the parameter for estimating hail size HSI (Czernecki et al. 2019) correlates very well with thermodynamic and kinematic parameters (Fig. 13). An unstable air parcel exists when such a parcel becomes warmer than its surroundings and at the same time gains lift due to positive buoyancy force. An additional factor supporting vertical displacement is wind uplift, that is, the change in wind speed and direction with altitude. Relating CAPE and DLS to the HSI parameter, we obtain a correlation at a satisfactory level, although the best choice for determining the relationship regarding CG formation and associated hail is the WMAXSHEAR parameter containing thermodynamic as well as kinematic variables (Fig. 13C). As confirmed in an earlier study by Taszarek et al. (2020), the frequency of hazardous convective phenomena is increasing over Europe with the development of WMAXSHEAR and low-level lapse rates.

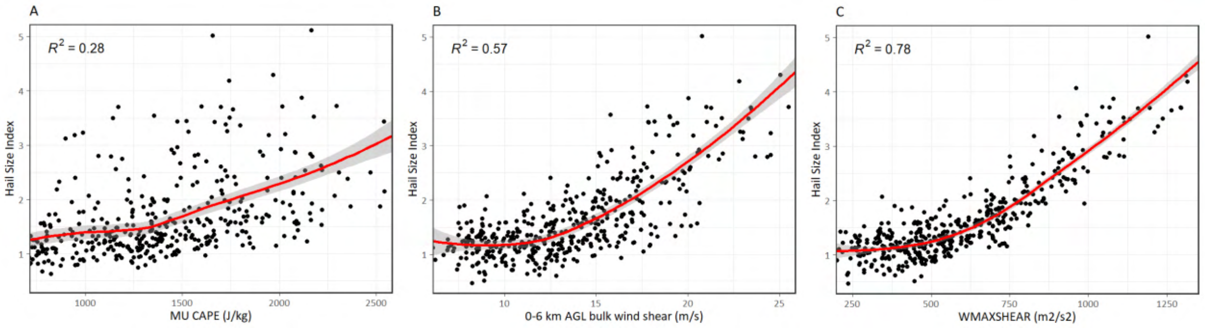

Fig. 13. Relationship between convective parameters and Hail Size Index for A – MU CAPE. B – DLS (Deep Layer Shear). C – WMAXSHEAR (product of DLS and MU CAPE). The red line denotes locally estimated scatterplot smoothing.

3.4. Spatial-temporal changes of convective parameters

Determining the convective conditions that favor the formation of Cumulonimbus clouds is crucial to understanding the processes taking place in the troposphere. It is no less important to determine the spatial and temporal changes taking place over the years in a given area. The latest climate report of the Intergovernmental Panel on Climate Change (IPCC 2023) confirmed a statistically increasing trend in air temperature measured at 2 meter above ground level. Moreover, the largest sweeps regarding spatial distribution are occurring on land. Climate change associated with increasing air temperature is indirectly associated with changes in the convective environment in the higher parts of the troposphere and may favorably influence the development of hazardous storms (Brooks el al. 2003; Taszarek et al. 2017; Taszarek et al. 2020). In the area of Poland, the parameters related to convection over the years correspond to the number of storms. Only in the case of Mixing Ratio in the area of the Tatra Mountains lower values can be observed than it occurs in the mountainous area of southeastern Poland (Fig. 14). Higher elevations result in greater dry stability and thus this can lead to increasingly steep vertical air temperature gradients.

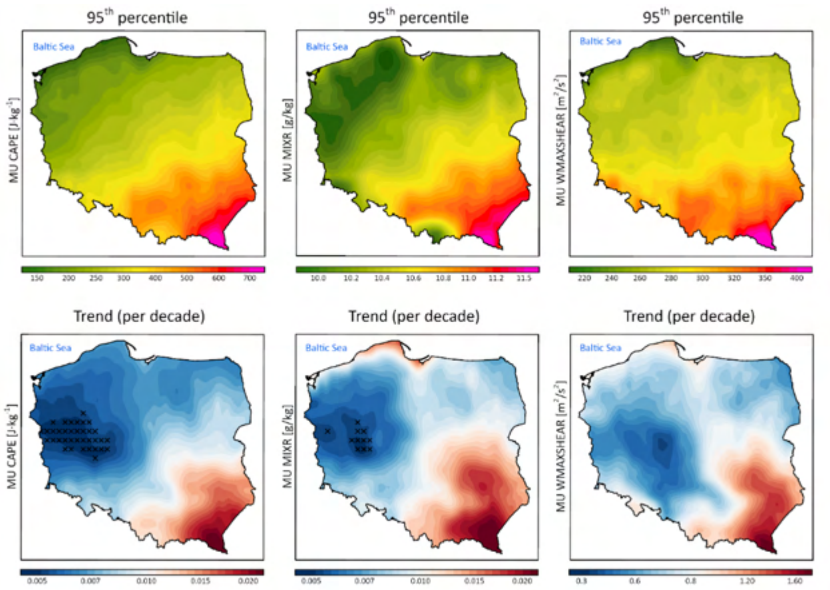

Fig. 14. 82-yr climatology of 95th MU CAPE, MU Mixing Ratio and MU WMAXSHEAR for Poland. Long-term trends are derived from annual values in hourly resolution and corresponding Sen's slope (values denote change per decade).

However, the increase in air temperature also leads to a decrease in relative humidity and thus deeper and deeper mixing of the boundary layer (Byrne and O'Gorman 2016). However, it is important to keep in mind that the mere presence of an unstable air parcel is not sufficient, and for convection to occur, the processes that initiate it must also be present. Vertical wind shear is extremely important in terms of the organization and evolutionary potential of uplifted storm cells (Allen et al. 2015; Pucik et al. 2015), and in this study it was vectorized by the difference in wind speed and direction between the ground surface and a height of 6 km due to the typically highest updraft velocities in storm cloud in this section. The overlap of potential energy along with vertical air movement indicates a continuous increase in these parameters on the Polish scale and a systematic increase even greater than the alarming increase in air temperature (Fig. 15).

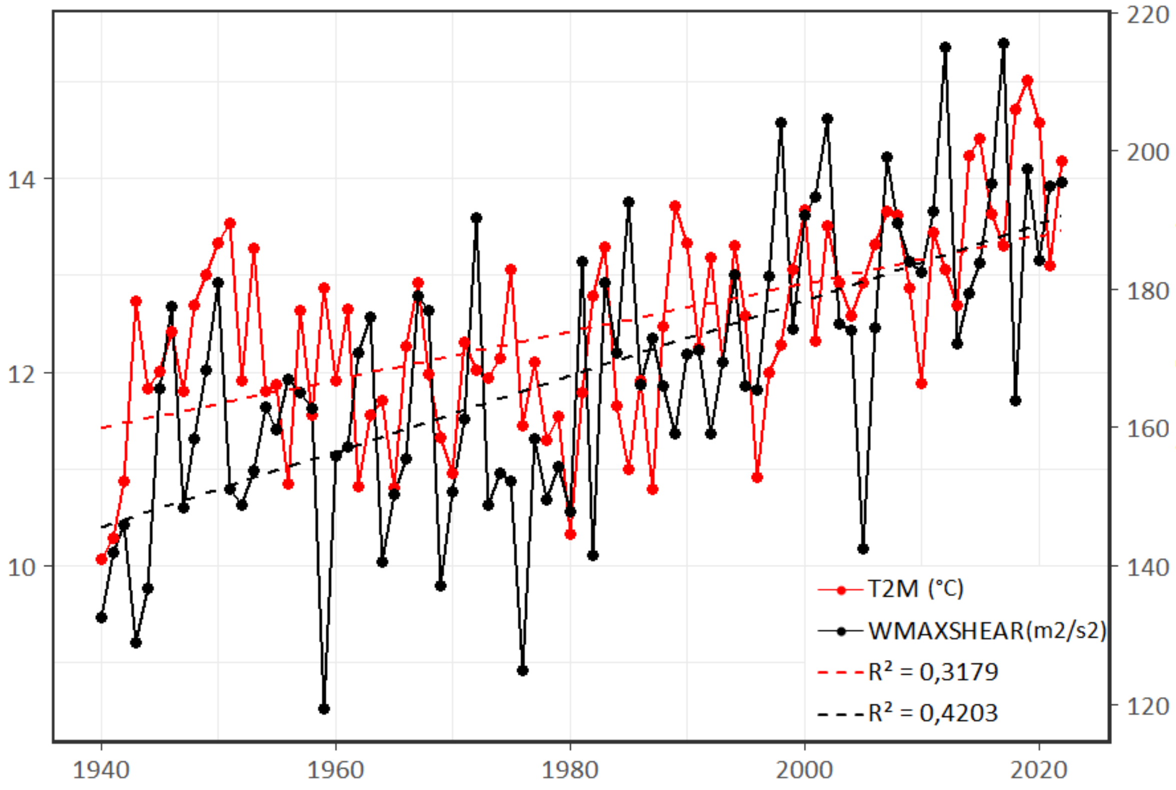

Fig. 15. Time-course distribution of 2 meter air temperature [T2M] and 0-6 km AGL wind shear with CAPE [WMAXSHEAR] in 1940-2022 period for area of Poland. The dashed line indicates a trend for two factors.

As shown in the study by Taszarek et al. (2020), an increase in this indicator is also evident in northwestern Europe which may be the reason for the shift in the jet stream due to the weakening thermal gradient between the midlatitudes and the Arctic (Pena-Ortiz et al. 2013; Coumou et al. 2015). In addition, the climatology of the WMAXSHEAR factor for Europe clearly indicates that severe storms most often occur in summer in the corridor from northeastern Spain through parts of Central Europe, Italy or the Balkan Peninsula (Taszarek et al. 2020). In contrast, in spring, positive trends were recorded for most of Europe (including Poland), which confirms that favorable conditions for deep convection are also increasingly common in spring. These changes may be mainly due to an increase in potential energy, moisture using constant DLS values.

Knowing the convective and kinematic conditions, it was decided to simulate and reconstruct the number of days with thunderstorms for the period 1940-2022 based on ERA5 data (Fig. 16). The spatial distribution by season is very similar to the spatial distribution of the number of days with thunderstorms calculated using data from the PERUN lightning detection and localization system for 2002-2020. In summer and spring, the number of days with thunderstorms increases toward the southeast, while in autumn thunderstorms mainly occur in close proximity to the Baltic Sea. This is related to the increased temperature of the sea and the simultaneous possibility of convection on land (Sulik and Kejna, 2023). At the same time, in winter, the occurrence of thunderstorms in Poland is local in nature and is mainly associated with the western circulation, which provides an influx of an unstable portion of air from the north (Konarski et al. 2008). Winter is also a period when dangerous phenomena can be observed in the form of thunderstorms in the form of linear systems with embedded scour lines (Celiński-Mysław et al. 2020).

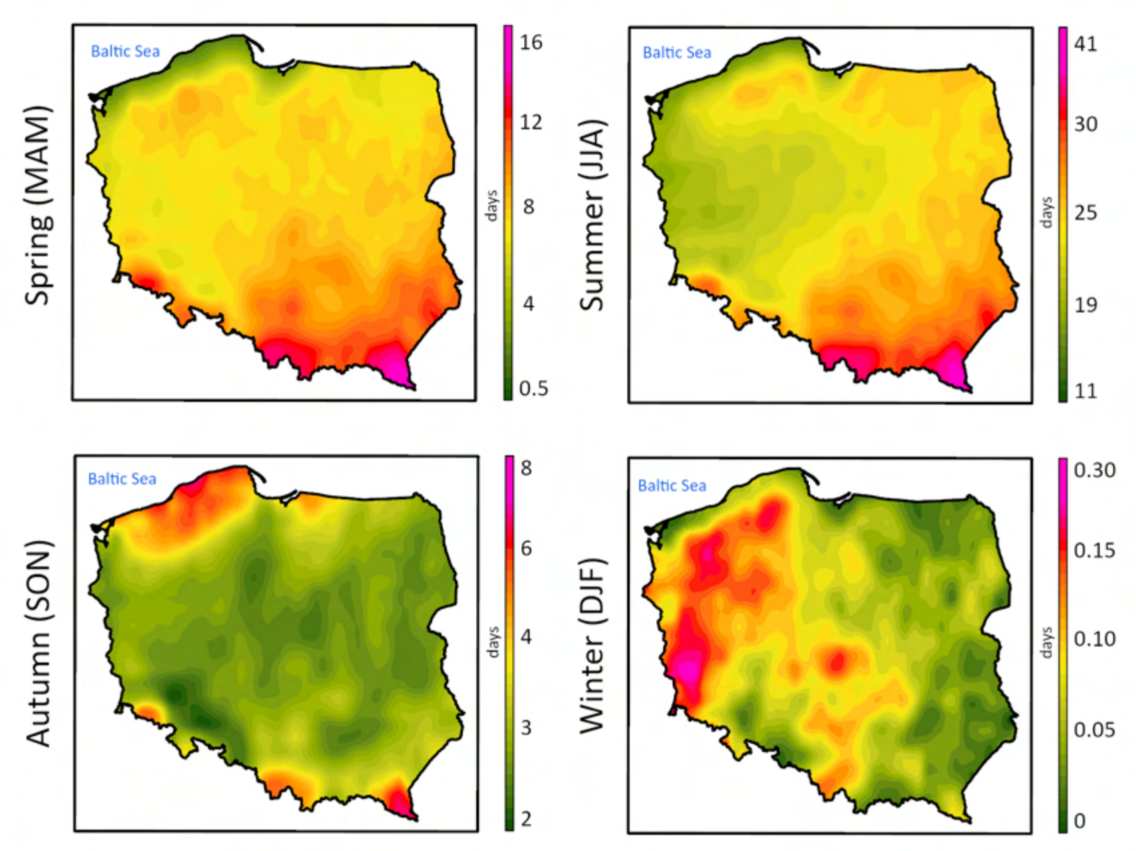

Fig. 16. 82-yr climatology of thunderstorm days in Poland for seasons. Thunderstorm environment is considered when CAPE > 150 J/kg and CP > 0.1 mm/h. Computed from ERA5 reanalysis data.

4. Discussion and final remarks

Each year, about 150 days with thunderstorms are recorded throughout Poland. At the same time, storm cells generate various amounts of lightning and their number and spatial distribution is slightly different each year (Sulik 2022). During the studied period of the 2002-2020 interval, the PERUN system detected and located more than 8 million CG flashes, which were used in this study. The intensity of generated flashes and their number associated with storm cells was necessary to reconstruct the convection environment in which cloud-to-ground flashes are generated. Data from ERA5 reanalyses were used for this task. As a result of the analysis conducted on the determination of thermodynamic and kinematic conditions for the generation of cloud-to-ground lightning by Cumulonimbus clouds in the area of Poland, the following conclusions can be stated:

1) The average number of days with thunderstorm is about 30 days. The least number of days with a thunderstorm occurs in the northwest (10-15 days) and the most in the southeast (35-40).
2) Each year there are an average of about 480,000 CG flashes.
3) 96% of all detected CG flashes have a negative current.
4) The highest electrical activity occurs in the areas of central Poland.
5) The highest number of thunderstorm days and electrical activity accrue to July.
6) During the 2002-2020 period, there were 8 days with thunderstorms, during which the sum of CG flashes exceeded 50.000 CG flashes.
7) CG flashes are most common in WMAXSHEAR environments around 500 m2/s2.
8) MU CAPE values in the range of 1.000 to 1.500 J/kg, combined with DLS in the vicinity of 13 m/s, are very favorable for the potential to generate CG flashes.
9) The chance of increased electrical activity increases when the air temperature is around 28 °C and the dew point temperature is above 18 °C.
10) WMAXSHEAR parameter positively correlates with Mixing Ratio in the range of 12-14 g/kg.
11) WMAXSHEAR correlates very well with the Hail Size Index which translates into increased generating of CG flashes.
12) A steady increase in the WMAXSHEAR can be noted.
13) An additional positive aspect of the occurrence of elevated CG discharge values are supercells forms characterized by strong updraft speed, rotation and the potential to generate large hail precipitation.

A detailed study covering the area of a country compared to the area of the whole of Europe shows regional dependencies in the formation of cloud-to-ground flashes on a local scale. Also noteworthy is the fact that forecasting hazardous weather phenomena such as severe wind gusts, torrential rainfall or large hail is extremely important but is still quite a challenging task due to the changing climate. The tasks of forecasting and delineating areas at risk of hazardous weather events also include assessing the likelihood of lightning. Despite the continuous development of technology, issued warnings and forecasts, there is still, especially during the storm season, a flow of information about those killed or injured by lightning, as evidenced by data from the ESWD database. Improving knowledge related to the environment in which CG flashes are form will allow even more precise determination of the area at risk and protection of the population.

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