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Lightning flash density in Europe on the basis of 10 years of ATDnet data

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***Abstract*—The first decadal lightning flash climatology for Europe is presented using ATDnet long-range lightning detection network operated by the Met Office. The annual flash density was between 0.5 and 3.0 flashes per km^2 y^{-1} in most of Europe with a maximum of 7.8 flashes km^2 y^{-1} in the northeast of Italy. Most of the continental Europe experienced 20–40 thunderstorm days annually but up to 87.6 TDs occurred in a small area on the border of Armenia and Turkey. That clearly exceeds the previous estimates of European thunderstorm frequency. Most of the study area had a mid-latitude specific summer maximum in lightning activity whereas the Mediterranean had an autumn maximum. The highest lightning frequency was observed during the afternoon hours and the lowest frequency at night.**

Keywords—ATDnet; flash density; Europe

I. Introduction

Lightning location systems (LLS) are widely used for operational meteorology and research purposes. Archived lightning data allow for detailed studies of the climatological aspect of thunderstorms and lightning.

In Europe, a lot of national [e.g. Taszarek et al., 2015; Novák and Kyznarová, 2011; Schulz et al., 2005] and some regional [e.g. Kotroni and Lagouvardos, 2016; Mäkelä et al., 2014] studies on lightning climatology have been published. At the same time only a few continental scale studies are available. Poelman et al. [2016] examined European lightning climatology during 2006–2014 using the data of European Cooperation for Lightning Detection (EUCLID). Anderson and Klugmann [2014a; 2014b] used five and six years' worth of ATDnet data to investigate the spatial and temporal patterns of lightning in Europe between 2008 and 2013.

ATDnet is a Very Low Frequency (VLF) long-range LLS operated by the Met Office since 1987. The network locates lightning discharges using the Arrival Time Difference (ATD) method [Lee, 1986]. The current ATDnet consists of 10 sensors in and around Europe (Fig. 1) operating at the central frequency of 13.733 kHz. The effective range of ATDnet encompasses Europe, northern Africa, and northern parts of the Atlantic Ocean.

ATDnet sensors detect atmospherics (sferics). Sferics are electromagnetic waves in the VLF range that propagate in the earth-ionosphere waveguide and are generated by cloud-to-ground lightning (CG) return strokes and powerful cloud lightning (IC) pulses [Rakov and Uman, 2003]. The system takes the advantage of the long propagation paths of sferics to cover large areas with only a limited number of sensors. For that reason ATDnet detects lightning over remote areas including seas and the oceans much more efficiently than short-range systems. The decrease in ATDnet detection efficiency outside the perimeter of the system is also slower compared to short-range networks. For example, a lot of lightning is detected in South America and over the Atlantic Ocean despite having sensors only in Europe [Enno et al., 2018].

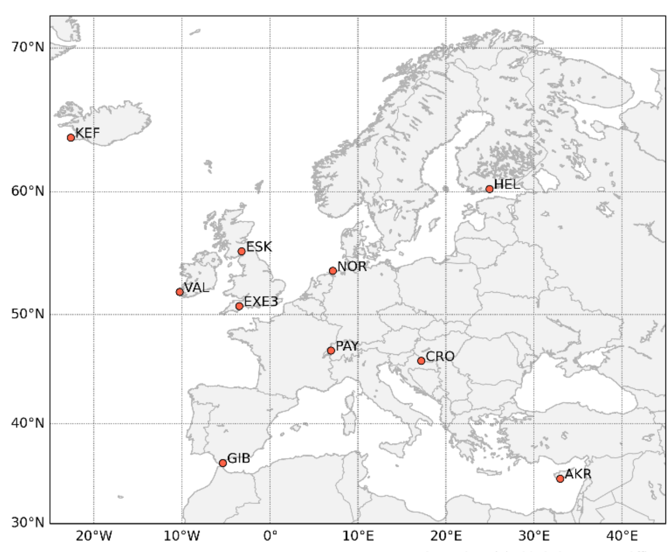

Fig. 1. The study area and locations of ATDnet sensors.

The most important limitation of long-range lightning location systems is often considered to be location accuracy. ATDnet location uncertainties within its perimeter in Europe are on the order of 1-2 kilometers, as opposed to a few hundred meters possible with short-range systems. However, such location errors are small enough for mapping the climatological patterns of lightning occurrence.

Another issue characteristic to LLSs in general are periodic upgrades. Old sensors have been replaced by new ones and additional sensors have been installed in order to increase detection efficiency and location accuracy. Such changes inevitably make data inhomogeneous and therefore affect the results of longer studies. However, since the last major upgrade at the end of 2007 ATDnet configuration has been rather stable in Europe meaning that 10 years' worth of relatively homogeneous data are now available. The aim of the present study is to use the data and provide the first decadal lightning climatology for Europe during a period of 2008–2017.

Section 2 describes ATDnet and its data. Section 3 represents the main results. Section 4 provides a discussion of the results and Section 5 concludes the study.

II. Data and Methods

The study area (Fig. 1) encompasses Europe together with its adjacent seas and the eastern part of the North Atlantic Ocean and is defined as 30°N–72°N and 25°W–45°E. This is a slightly expanded version of the area used by Anderson and Klugmann [2014a; 2014b].

ATDnet detections, also referred to as 'fixes', correspond to either CG lightning return strokes or powerful cloud lightning pulses. The first step of the study was grouping ATDnet fixes into flashes. The approach presented by Drüe et al. [2007] and adjusted to ATDnet data by Anderson and Klugmann [2014a] was used. ATDnet fixes that occurred within 20 km of and within 1 second after another fix were grouped together as a single flash. There were more than 148 million ATDnet flashes in the study area during 2008–2017.

When interpreting the results it must be taken into account that ATDnet does not discriminate between different types of lightning. The system was originally designed to detect CG lightning and it does so with up to 90% flash detection efficiency in Europe. However, it has been also shown that ATDnet detects up to approximately 25% of IC flashes [Enno et al., 2016]. This means that the used dataset contains mainly CG flashes but also some IC flashes. The exact fraction of cloud flashes is impossible to measure. It is expected to be greater in the middle of the study area and decrease towards the edges as cloud flashes generally emit weaker sferics harder to detect far from ATDnet sensors. In addition, there are natural spatial variations in IC-CG ratio.

Despite having some cloud lightning in the dataset the results are still expected to reflect the spatial distribution of CG lightning. However, the flash density values are likely to be somewhat higher compared to only CG lightning statistics. The effect is assumed to be more pronounced in the middle of the study area.

All spatial statistics were computed using 0.2°x0.2° grid cells with dimensions of approximately 22 km by 14 km at 50°N. This spatial resolution was adopted from Anderson and Klugmann [2014a; 2014b] as it allows for the resolving of features such as mountain ranges, large valleys and coastal effects, without the plots becoming too 'noisy' due to the effects of individual, localised storms.

The results were not corrected for spatial variations in ATDnet detection efficiency as there is currently no detection efficiency model for the whole study area. However, comparisons against other lightning locations systems shed some light on ATDnet capabilities. The best detection efficiency is expected within the perimeter of the network where up to 90% of CG and 25% of IC flashes are detected [Enno et al, 2016]. Smaller detection efficiency variations are possible in this area due to differences in the distance from a stroke to the ATDnet sensors but they have not been examined in detail.

Outside the perimeter of the network ATDnet detection efficiency is expected to decrease gradually with increasing distance of the nearest sensors. The only available large scale study is an ATDnet comparison against the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) [Enno et al., 2018]. Due to orbital parameters of the TRMM satellite the study are was limited to 38°-38°S. Thus, it only overlaps with the southernmost part of the data domain of the present study. It shows rather uniform ATDnet detection efficiency over the Mediterranean and the Atlantic Ocean between 30°N and 38°N. A decrease in detection efficiency is evident towards 30°N in northern Africa and 45°E in the Middle East.

III. Results

A. *Annual flash counts*

During 2008–2017 ATDnet detected 148 703 779 flashes in the study area. The annual number of flashes was typically in the order of 13–15 million (Fig. 2). The only notable exception was 2014 with 18.7 million flashes. In general, the annual totals were surprisingly stable except for the maximum in 2014 and somewhat lower activity in 2008 and 2017.

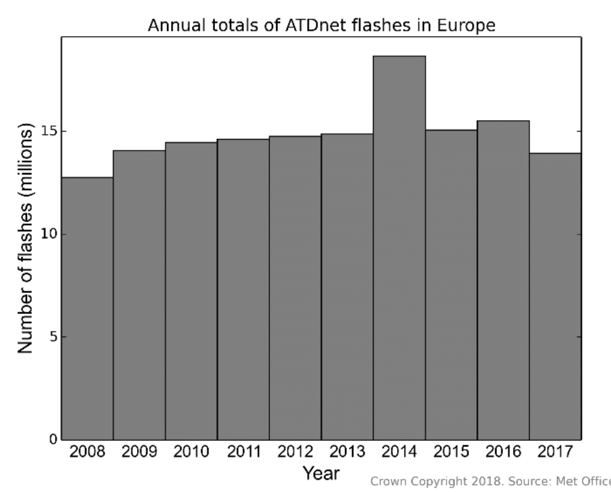

Fig. 2. Annual numbers of ATDnet flashes in Europe during 2008–2017.

B. *Flash density*

In most of Europe the annual flash density was between 0.5 and 3.0 flashes km^2 y^{-1} (Fig. 3). Lower values were observed in Scandinavia, Finland, northwestern Russia and the British Islands. Higher lightning density was characteristic to southern European mountain ranges, such as the Alps, Pyrenees, Apennines and Carpathians. The highest average annual flash density of 7.8 flashes km^2 y^{-1} occurred in a small area located in the southern foothills of the Alps in the northeast of Italy.

Land-sea contrast was obvious with very little lightning over the Atlantic Ocean. Local minima were also found over the Mediterranean, the Black Sea and the Baltic Sea. However, European seas were all characterized by much higher lightning incidence than the Atlantic Ocean. Some parts of the Mediterranean around Italy, Greece and Turkey exhibited notably high density of 1.2-3.0 flashes km^2 y^{-1}. Even higher lightning activity was observed along coastal mountain ranges in the west of Italy and the Balkans.

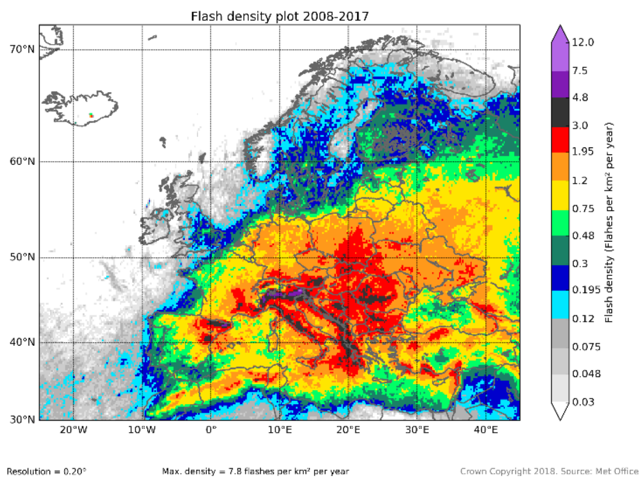

Fig. 3. Average annual ATDnet lightning flash density in Europe during 2008–2017.

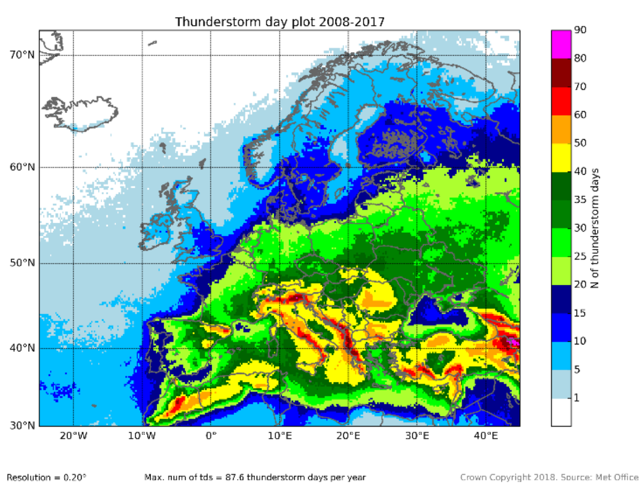

Fig. 4. Average annual number of thunderstorm days in Europe during 2008–2017.

C. *Thunderstorm days*

The frequency of thunderstorms was assessed by computing thunderstorm days (TDs). In the present study a day was deemed to be a TD when at least two ATDnet flashes occurred within 20 km from the center of a grid cell within 24 hours from 00:00 to 23:59 UTC. Cases with only one flash within 20 km were omitted to avoid overestimation due to ATDnet outliers, i.e. flashes with very large location errors accidentally placed hundreds or thousands of kilometers from their true locations. It is unlikely to have more than one outlier within 20 km from a grid cell center on the same day.

Most of the continental Europe experienced 20–40 TDs annually (Fig. 4). Lower thunderstorm frequency was characteristic to the British Isles, northern Europe and the North Atlantic Ocean. Large areas of the Atlantic Ocean where lightning density was almost negligible still had a few TDs annually.

Higher numbers of TDs were concentrated to mountainous areas in the southern part of the study area. These include the Alps, Pyrenees, Apennines and Caucasus in southern Europe and the Atlas mountains in northern Africa. All the mountain ranges had regions with more than 60 TDs. The highest thunderstorm frequency was found in a small area in Caucasus on the border of Armenia and Turkey with up to 87.6 TDs annually. Another regions with at least 80 TDs was in the southern foothills of the Alps in northeastern Italy where the highest lightning density in Europe was observed.

D. *Flash density per TD*

Flash density per TD is the ratio of annual flash density to the annual number of TDs. It is a useful measure of storm intensity, i.e. how many flashes can be expected on an average TD. The parameter was computed by dividing the flash density grid (Fig. 3) by the TD grid (Fig. 4).

Normally, daily flash density values did not exceed 0.1 flashes per km^2 per TD (Fig. 5). Areas with highest daily flash density were scattered over central and southern Europe. The contrast between higher and lower latitudes was smaller compared to the annual flash density. Some regions with relatively high daily flash density were found as far north as in western parts of Finland. This indicates that intense storms can occasionally happen even at high latitudes where flash density and thunderstorm frequency are low. Over the oceans the pattern was noisier. There were some small regions with notably high daily flash density on the background of generally lower values. Such regions were found even to the north of the Arctic Circle.

A small exceptional area with extremely high daily flash density of 4.1 flashes per km^2 per TD was observed in the southeast of Iceland around the Grímsvötn volcano. This is related to the volcanic lightning during the eruption from 21 to 23 May 2011. In just three days more than 11 thousand ATDnet flashes were detected in the region that otherwise rarely experiences any lightning (Fig. 3).

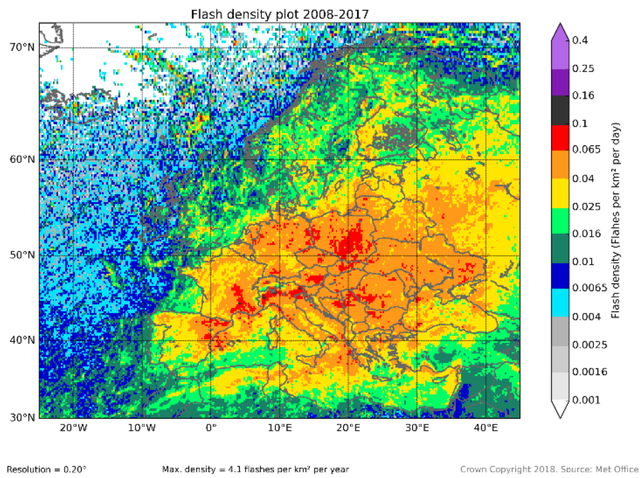

Fig. 5. Average ATDnet lightning flash density per thunderstorm day in Europe during 2008–2017.

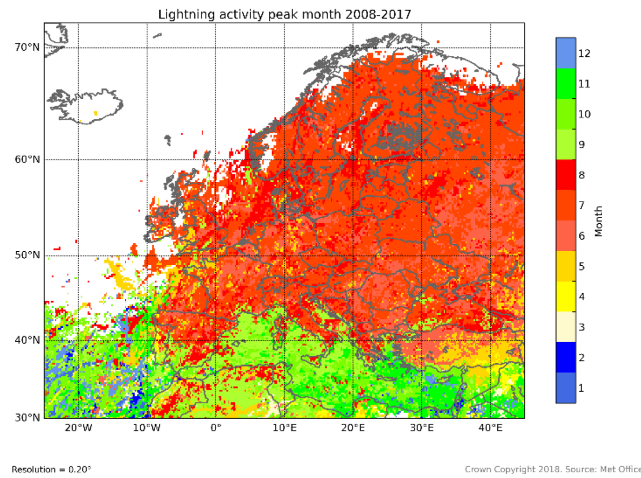

Fig. 7. Peak month of lightning activity in Europe during 2008–2017. White – less than 100 flashes per grid cell during the study period.

E. Monthly lightning

Monthly distribution of lightning typical to mid-latitudes with a summer maximum and winter minimum was observed (Fig. 6). The most active month was July (32.3 million flashes) with roughly 20 times more lightning than in the least active month February (1.7 million flashes). The start of the main thunderstorm season was relatively sharp as the total number of flashes increased by more than five times from April to June. Following the maximum in July the decrease in lightning activity was notably slower and lasted till the start of the winter minimum in December.

In most of the continental Europe the month with highest lightning activity was either June, July or August (Fig. 7). Different seasonal distribution of lightning was observed over the Mediterranean where the maximum occurred in autumn. The western part of the Mediterranean had an earlier maximum in September and October whereas the eastern part of the sea experienced a later lightning maximum in November and December. Autumn maximum was also characteristic to the part of the Atlantic Ocean to the west of the Iberian Peninsula and Morocco.

F. Hourly lightning

Diurnal distribution of lightning was characterized by a clear afternoon peak and a nighttime minimum (Fig. 8). The highest lightning activity was observed between 13-15 hours UTC and the lowest activity between 23-02 hours UTC. Hourly numbers of flashes were approximately five times higher during the daytime maximum compared to the nighttime minimum.

The hour of maximum lightning activity was computed for each grid cell and plotted on a map in order to examine the land-sea contrast in the diurnal distribution of lightning (Fig. 9). Note that all times of the peak lightning activity in Fig. 9 are in local time. Local solar noon differs by approximately five hours between the eastern and western border of the study area. Thus, peak times in UTC would result in a bias towards earlier maximum in the east and later maximum in the west of the study area. To remove the bias, one hour was added to peak times of all grid cells located between 7.6–22.4°E, two hours were added to peak times of cells located between 22.6–37.4°E etc. In the same way hours were subtracted to the west of the zero meridian.

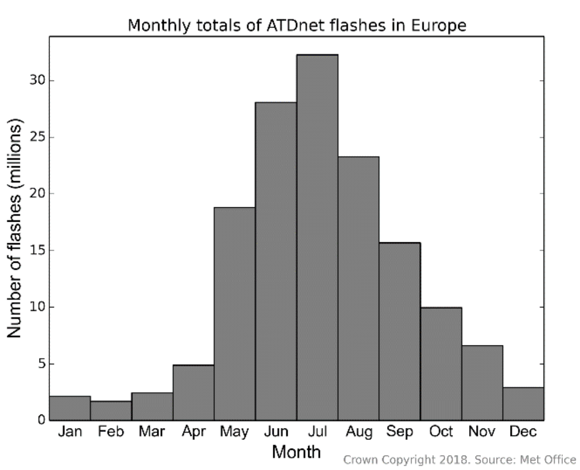

Fig. 6. Monthly total numbers of ATDnet flashes in Europe during 2008–2017.

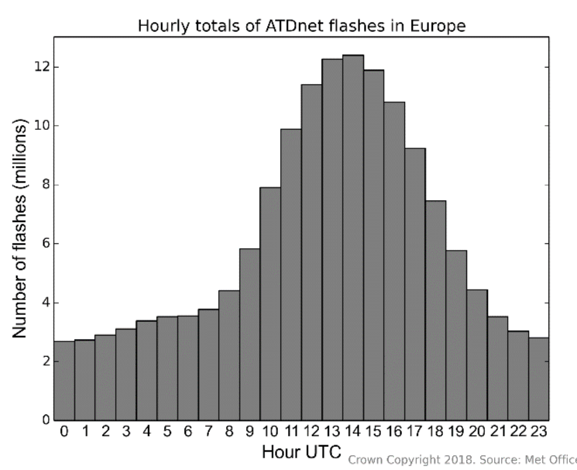

Fig. 8. Hourly total numbers of ATDnet flashes in Europe during 2008–2017.

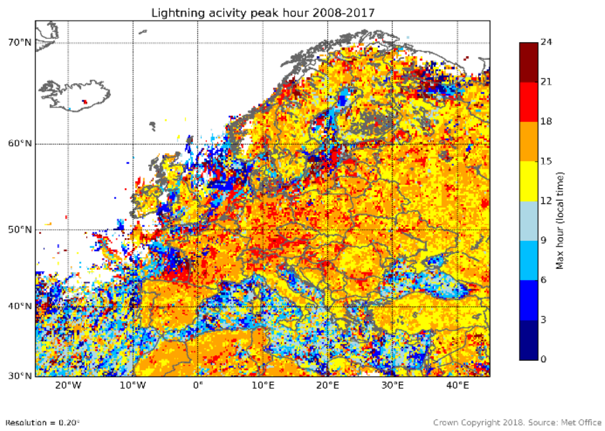

Fig. 9. Peak hour of lightning activity in Europe during 2008–2017. White – less than 100 flashes per grid cell during the study period.

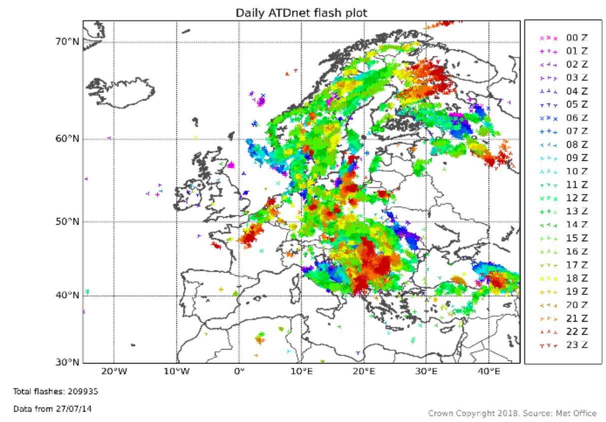

Fig. 10. ATDnet flash locations colored by hour on 27/07/2014, i.e. the day with the highest number of ATDnet flashes during the study period.

Clear land-sea difference appeared in the diurnal distribution of lightning. An afternoon maximum was characteristic to the continental Europe whereas morning maximum prevailed over water. The contrast was especially obvious along the coast of the Mediterranean and the Black Sea. Somewhat different pattern appeared over most of the Baltic Sea where lightning activity peaked during late evening hours and only the northernmost part of the sea (the Gulf of Bothnia) exhibited a morning maximum. Parts of the North Sea and Bay of Biscay also had peak lightning activity before midnight.

G. *Extreme events*

Ten days with the highest flash counts in the study area are listed in Table 1. All of them occurred from June to August. The most active lightning day in Europe during the study period was 7 July 2014 with 209 935 ATDnet flashes.

It can be seen that 7 July 2014 was characterized by a large amount of high-latitude thunderstorms in Europe with most of Norway, Sweden and Finland covered by storms tracks (Fig. 10). There was also a relatively large area with intense thunderstorms spanning from central Europe to the Balkans.

TABLE I. DAYS WITH THE HIGHEST ATDNET FLASH COUNTS IN EUROPE DURING 2008–2017.

Date	N of flashes
27 July 2014	209 935
17 July 2010	208 768
3 August 2014	206 089
20 July 2011	205 964
9 June 2014	205 448
15 August 2008	203 509
19 July 2011	202 591
5 August 2014	202 511
8 August 2015	200 442
2 July 2009	198 983

IV. DISCUSSION

More than 148 million ATDnet flashes were detected in Europe during 2008-2017. The annual totals of flashes (Fig. 2) were found to be much more stable than in many local and regional studies [e.g. Schulz et al., 2005; Mäkelä et al., 2014]. It is likely that the larger size of the study area minimizes the influence of regional weather patterns that often change from year to year, especially at higher latitudes.

The highest flash density and thunderstorm frequency was observed over mountain ranges in the southern part of the study area (Fig. 3 and 4). This can be explained by the combination of stronger solar heating at lower latitudes and orographic lifting. In addition, a source of moisture is needed for thunderstorm development. That explains why all the lightning and TD hotspots are located within a few hundred kilometers from the nearest sea. Long narrow regions with high flash density and thunderstorm frequency along the coast of Italy, Turkey and the Balkans are good examples of areas where warm moist air from the Mediterranean is forced to rise by local orography.

Northern parts of the study area experience weaker solar heating and much shorter thunderstorm season. At the same time flash density per TD in parts of Finland and Scandinavia can be comparable to that in central and southern Europe (Fig. 5). This indicates that if the conditions are right then significant storms can happen even that far north. Therefore, it can be assumed that it is mainly the higher frequency and not much greater intensity of storms that causes significantly higher annual flash density at lower latitudes.

Even the areas in the North Atlantic Ocean and Arctic Ocean with less than one TD per year can occasionally experience intense storms (Fig. 5). However, such events are probably so rare that the study period is far too short to reveal their true spatial pattern. This probably explains the noisy appearance of the average flash density per TD map over the oceans.

ATDnet European lightning density pattern is similar to that of EUCLID during 2006-2014 [Poelman et al. 2016]. Both systems observed the highest lightning activity in the northeast of Italy. ATDnet maximum lightning density (7.8 flashes km^2

y^{-1}) was somewhat higher than EUCLID maximum density (~6 flashes km^2 y^{-1}). The main reason behind the difference is probably the presence of some cloud lightning in the ATDnet dataset whereas Poelman et al. [2016] used only cloud-to-ground flashes.

The finding that some mountainous areas in southern Europe have 80-88 TDs is interesting and somewhat unexpected (Fig. 4). It has been generally assumed that there are no more than 40 TDs annually in Europe [WMO, 1956]. Our results show that this number is true for low lands whereas most of the mountain ranges are characterized by higher thunderstorm frequency. There could be multiple reasons behind this apparent discrepancy.

Firstly, one may point out that WMO [1956] used human observations of thunderstorms which might not be comparable to TD numbers computed on the basis of ATDnet flashes. The assumption was checked by comparing some local and regional thunderstorm statistics with the results of the present study. For example, Enno et al. [2014] found 14-29 TDs in the Baltic countries on the basis of human observations during 1950-2004 which is in line with 12-30 TDs found in our study. Similarly, the annual frequency and spatial pattern of ATDnet TDs in the United Kingdom agrees closely with the statistics of human observations during 1971-2000. Moreover, the present study and WMO [1956] have very similar northern borders of areas with more than 20 and more than 10 TDs. Thus, it can be assumed that ATDnet TDs are generally comparable with human observations of thunderstorms at weather stations.

The second and more likely explanation is related to certain limitations of human observations. Mountains can be obstacles for audibility of thunder and seeing lightning [Changnon, 1989; 1992]. Given that the density of stations is normally lower in the mountains it is very likely that human observers miss many storms and underestimate the number of TDs. This is not so much of an issue in lowlands and plains where storms are easier to see and hear. That explains why the discrepancy between the present study and WMO [1956] manifests itself mainly over mountain ranges.

Another interesting issue is relatively low flash density in the area in Caucasus where the highest annual number of TDs was observed (Fig. 3). Despite of having slightly more TDs the region experienced approximately three times lower flash density than northeastern Italy. It is probably related to its location near the eastern edge of the study area which means larger distances from most of ATDnet sensors and lower detection efficiency. In addition, it is also possible that the nature of storms is somewhat different in Caucasus compared to Italy. The area is surrounded by high lands and experiences much drier climate compared to Italy. Thus it might be that an average storm in Caucasus produces less lightning and/or larger fraction of cloud lightning but checking this assumption is beyond the scope of the present paper.

The annual course of lightning activity (Fig. 6) follows the solar heating and underlying surface temperature pattern of the continental Europe. Most land areas experience the peak lightning activity from June to August (Fig. 7) when temperatures are highest. The same if true for the Baltic Sea, the North Sea and most of the Black Sea. On the contrary, the Mediterranean experiences a later autumn maximum in lightning activity. This is related to convection caused by cooler air from continental Europe moving over the still warm waters of the Mediterranean. The western part of the Mediterranean has peak lightning activity about two months earlier than the eastern part as the water cools slower in the eastern part of the sea.

Diurnal distribution of flashes generally follows the daily solar cycle (Fig. 8) with an afternoon maximum and nighttime minimum. A different diurnal cycle was observed over the seas where the lightning activity peaked predominately in the morning (Fig. 9). This is probably related to the sea surface which tends to be warmer than the air above it at night and early in the morning. In addition, thunderstorms at sea can be triggered by land breezes at night [Virts et al., 2013].

The timing of the afternoon peak is in line with the observations of EUCLID [Poleman et al., 2016]. However, the minimum lightning frequency was found to be around midnight according to ATDnet but at 7 hours UTC according to EUCLID. The difference can be partly due to a smaller fraction of lightning over the seas in the data of Poleman et al. [2016]. EUCLID is a short range system with its detection efficiency lower over the seas where the morning lightning maximum was observed. Moreover, the study area of Poleman et al. [2016] was smaller and excluded the eastern part of the Mediterranean, the Black Sea and the North Atlantic Ocean. Another potential issue is the lower ATDnet detection efficiency at night. The system is tuned to perform best under daytime ionosphere meaning that somewhat less lightning is detected at night whereas short range systems like EUCLID are free of that bias.

V. Conclusions

The first decadal lightning flash climatology for Europe during a period of 2008–2017 is presented using ATDnet long-range lightning detection network operated by the UK Met Office. The ATDnet dataset contains mainly cloud-to-ground lightning but some cloud lightning is also included as the system does not discriminate between types of lightning.

More than 148 million flashes were detected in Europe during the study period. The annual flash density was between 0.5 and 3.0 flashes km^2 y^{-1} in most of Europe with a maximum of 7.8 flashes km^2 y^{-1} being located in the northeast of Italy. Most of the continental Europe experienced 20–40 TDs annually. Much higher thunderstorm frequency of more than 60 TDs per year was observed over mountain ranges in southern Europe. A small area in Caucasus on the border of Armenia and Turkey had even up to 87.6 TDs annually. These numbers clearly exceed the previous estimates of European thunderstorm frequency.

The seasonal distribution of lightning peaked in summer in the continental Europe and in autumn over the Mediterranean. Diurnal cycle of lightning was characterized by a clear afternoon maximum and nighttime minimum over land. At sea the diurnal cycle peaked during morning hours.

The results of the present study have a variety of potential uses from risk assessment to validation of the present and future satellite-based lightning sensors.

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