

A European lightning density analysis using 6 years of ATDnet data

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Abstract— The Met Office has operated a VLF lightning location network since 1987. The long-range capabilities of this network, referred to in its current form as ATDnet, allow for relatively continuous detection efficiency across Europe with only a limited number of sensors. The wide coverage and continuous data obtained by ATDnet are here used to create datasets of lightning density across Europe. Results of a recent study into 5 years (2008 – 2012) of lightning density data covering Europe are extended here to include data from 2013. The data is used to analyse the characteristics of lightning activity in Europe.

Keywords—flash density, Europe

I. INTRODUCTION

A. Lightning Detection at the Met Office

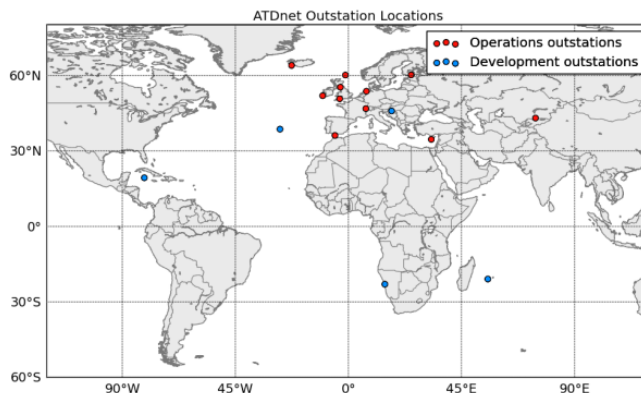
The use of lightning location systems (LLS) across Europe and the wider world for operational meteorology and research purposes is well established. Lightning data is used daily for observing the development and progression of storms, and also in research projects (such as the HyMeX project [Ducrocq, 2013]) in order to gain a better understanding of the processes taking place within storms.

The Met Office has operated its own Very Low Frequency (VLF, 3-30 kHz) lightning location network since 1987 [Lee, 1986]. The system has developed considerably during its operational life, and the most recent version - ATDnet (Arrival Time Differencing NETWORK) - was introduced in 2007 [Gaffard et al., 2007].

ATDnet takes advantage of the long propagation paths of the VLF sferics emitted by lightning discharges, which propagate over the horizon via interactions with the ionosphere. ATDnet predominantly detects sferics created by cloud-to-ground (CG) discharges, as the energy and polarisation of sferics created by CG return strokes mean that they can travel more efficiently in the Earth-ionosphere waveguide, and so are more likely to be detected at longer ranges than typical inter-/intracloud (IC) discharges.

The benefit of longer range relative to higher frequency networks is obtained with lower location accuracy than some other LLSs: ATDnet location uncertainties within the region enclosed by the network of sensors are on the order of a few kilometres, as opposed to a few hundred metres possible with LF/VHF and VLF/LF systems. The location uncertainty of ATDnet makes it suitable for identifying electrically active cells.

One key advantage of the ATDnet approach, however, is the ability to provide relatively continuous coverage over much of Europe, using only a very limited number of sensors. The ATDnet network consists of 11 sensors (referred to as outstations) that regularly contribute to the ‘operational network’, plus sensors distributed further afield, designated ‘development outstations’. The locations and statuses of these sensors, as of May 2013, are shown in Fig. 1. Coverage extends over regions of open water (e.g. the North Sea, the Mediterranean), where the use of short-range networks is limited by the lack of available sensor sites.



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Fig. 1. Locations of ATDnet outstations, as of May 2013.

B. ATDnet detection of flashes

During September – November 2012, a Lightning Mapping Array (LMA) system from New Mexico Tech was set up in the south of France as part of the HyMeX project Special Observation Period One (SOP1) [Ducrocq, 2013]. Part of the aim of this observation period was to obtain data in order to better characterize the performance of operational lightning location systems like ATDnet, and understand which components of lightning discharges they detect.

Figure 2 shows an example of data obtained during a period when a storm passed within the region enclosed by the LMA sensors. A CG flash is detected, that lasted for approximately one second. The three dimensional extent of the flash can be determined by the LMA by detecting VHF sources in developing channels of the flash.

This flash covered an extensive region, travelling several kilometres from the location of the initiation of the flash before connecting with the ground. ATDnet detected fixes at two points in the flash: one at initiation and one when the flash connected with the ground.

The first fix (at approximately 17:41:14.8) was not associated with any channels connecting to the ground apparent in the LMA. Within this storm, ATDnet fixes were often detected without indication of a CG channel at any point in the flash. This has been interpreted as evidence that ATDnet detected cloud-to-cloud discharges.

The later fix detected by ATDnet (at approximately 17:41:15.5) is associated with a channel developing westward before descending towards the ground, indicating the development of a CG channel.

The data associated with this particular storm was analyzed by eye, and detection efficiencies for IC and CG flashes were estimated at approximately 30% and 80%, respectively. The discrimination of flash type was based only on the height of the VHF sources detected by the LMA. To determine a more reliable and representative measure of the detection efficiency of ATDnet would require an automated approach to determining flash type, as complex storms systems with higher flash rates were observed near to the LMA during SOP1, for which the by eye approach would be unreasonably labour intensive.

The analysis of the wealth of data from the HyMeX Special Observation Period One deserves its own paper, and only a summary is provided here. This provides an indication of the performance of ATDnet and the features of flashes that it detects.

C. European Lightning Density

For continental regions with few large bodies of open water, the use of short-range systems allows for continuous coverage. This has been used to provide good quality lightning data across the entire contiguous United States using the National Lightning Detection Network (NLDN) for many years. An interesting use for this data has been to provide continent-wide maps of lightning density, so that annual or monthly characteristics of the distribution of lightning can be analysed, as shown by Holle et al. [2010].

Due to the more fragmented nature of landmasses within Europe, the use of short-range networks to provide continuous Europe-wide lightning data density maps is less feasible, as European seas would lead to decreased detection efficiency and inhomogeneous coverage that would be difficult to account for.

Lightning density has previously been measured over the entirety of Europe using the satellite-borne Optical Transient Detector, or OTD [Christian et al., 2003], onboard the Orbview-1/Microlab satellite. This instrument operated between 1995 and 2000, and was the predecessor to the Lightning Imaging Sensor, or LIS [Christian et al., 1999], of the Tropical Rainfall Measuring Mission (TRMM) satellite.

One key difference between the two systems was that the OTD's orbit allowed it to detect lightning at higher latitudes: the OTD could detect lightning between 75°N and 75°S latitude, whereas the LIS can only detect as far north as the southern Mediterranean (approximately 38°N).

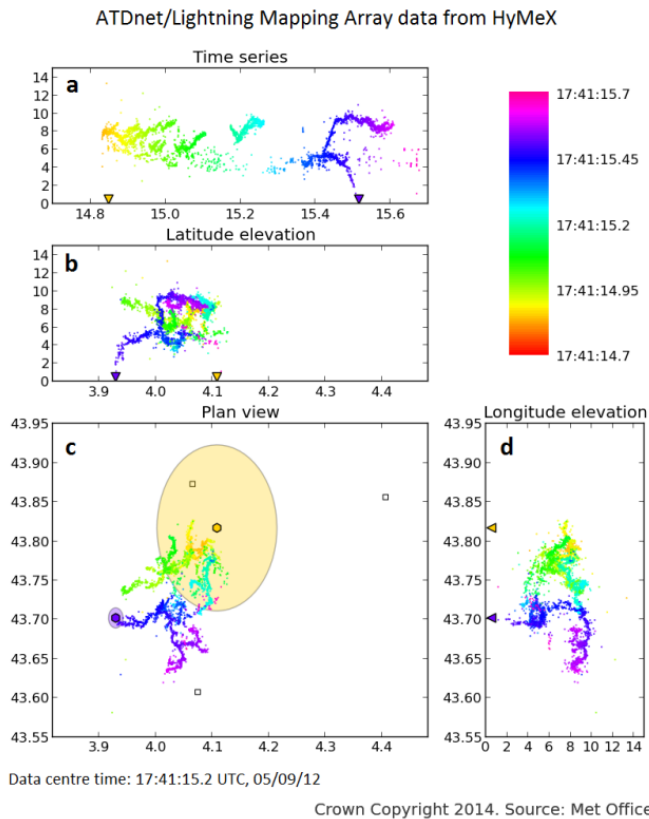


Fig. 2. Example of a flash detected by the LMA, along with two corresponding ATDnet fixes. Black squares represent LMA sensor locations. Filled hexagons/triangles represent ATDnet fixes. Coloured points indicate LMA-detected VHF source locations. a: time series versus altitude. b: longitude versus altitude. c: plan view – coloured ellipses indicate location uncertainty of each ATDnet fix. d: latitude versus altitude.

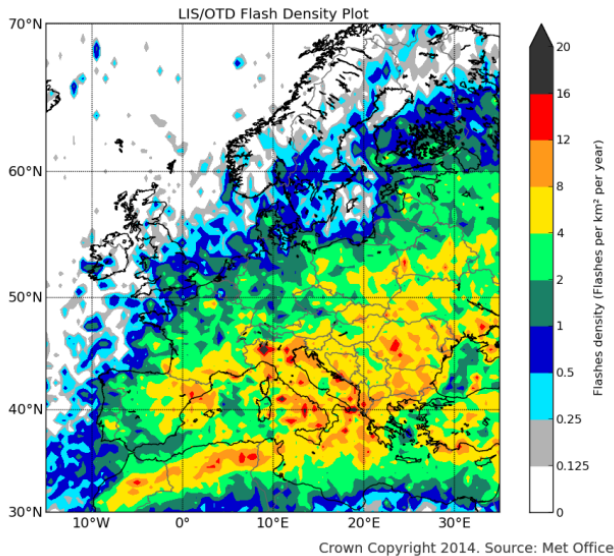


Fig. 3. Lightning density in Europe, estimated from OTD data.

The orbital characteristics of the OTD only allowed for observations at any point on the Earth’s surface for a few minutes per day. This meant that by using data obtained over long periods of time, the lightning density could be estimated by assuming that the observed flash rate during a number of satellite overpasses was representative of the average rate for that location. Figure 3 shows the flash density estimation obtained using this technique. The lack of continual observations, and the variable nature of storms, would however mean that the lightning densities estimated from this approach would be unlikely to accurately match the true lightning density.

This paper aims to provide an analysis of Europe-wide lightning data using relatively continuous coverage provided by the ATDnet network. The approach of Holle et al. [2010] in using data from the NLDN to analyse lightning density in the US for each month in turn has been used as a template.

II. METHOD

A. ATDnet data

In order to create plots that represent the true average distribution of monthly lightning density as closely as possible, several years’ worth of continuous data were required. ATDnet is suitable for this purpose, since it runs as an operational network with very little downtime. Due to modifications to the network when it was re-launched as ATDnet (as opposed to the previous system, simply known as ‘ATD’), data prior to 2008 was not included. As such, 6 years of lightning data from the period 2008-2013 was used to create the density plots. A more detailed analysis, using data from only 2008-2012, can be found in Anderson and Klugmann [2013].

Note that occasional sensor or network outages would affect the density data; however, such outages are rare, and the density of ATDnet sensors is high enough to provide some level of redundancy. Further, it should be noted that no adjustment has been made to the data to account for detection efficiency of flashes.

The length of the data period is suitable for smoothing out the effect of individual storms in most regions, particularly during the summer months, when the majority of storms occur. The effects of unusually strong winter storms, or particularly early/late storms in the usual storm season, are still noticeable in some plots. These effects do not detract from the overall usefulness of the plots themselves, but are an interesting effect that will be discussed later. No spatial smoothing (beyond gridding the data) was carried out on the data.

As mentioned in the introduction, the long-range nature of ATDnet is such that it predominantly detects CG strokes, as the VLF sferics emitted by CG strokes are generally more intense than the sferics emitted by cloud discharges. ATDnet does however detect some more powerful IC discharges, but does not distinguish between IC and CG events. As such, the lightning density plots produced here will be similar to the CG flash distribution of Europe, but the effect of IC discharges in the density could potentially lead to densities in the data presented that are higher than the true CG flash density.

Because of the inability to distinguish between IC and CG discharges, the data presented here can be interpreted as ‘lightning density’, as opposed to ‘flash density’, a term which in the past has been used to specifically refer to CG-only density. It is, however, useful to refer to the fix data correlated together into events using time and space criteria as ‘flashes’, to indicate the fact that these are merged events, despite the fact that this ‘flash’ data may include IC discharges.

The flash density values obtained would be expected to be lower than the values detected by OTD (Fig. 3). The satellite detector would be expected to have a high IC detection efficiency, while also being capable of detecting CG flashes with sufficient vertical extent that the cloud top would be visibly illuminated.

B. Flash Density

The key component of this study was to process the data from its original format into grids of lightning flash density. The first step was to convert ATDnet ‘fixes’ into ‘flashes’.

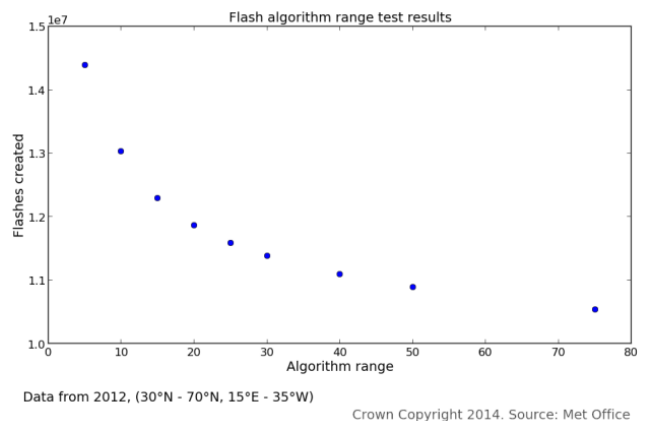


Fig. 4. Total numbers of flashes created when passing ATDnet fix data from Europe in 2012 to a flash creation algorithm, using a variety of space matching criteria.

ATDnet strokes were converted into flashes using the approach derived from that presented by Drüe et al. [2007]. Individual fixes were compared against each other using spatial and temporal criteria. Fixes could then be matched together into a single flash if these criteria were met. In this flash correlation algorithm, no maximum inter-stroke separation time was used.

Figure 4 shows the effect of using correlation ranges between 5 km and 75 km between flashes, using a constant maximum flash duration of one second. The initial drop in the number of flashes at low ranges would be due to fixes from the same flash being correctly correlated together. At larger ranges, the continuing decrease would be more likely to be caused by incorrect correlations of fixes from discharges that were detected within a second of each other, but were not part of the same flash.

When creating the flash density plots for this study, ATDnet fixes that occurred within 20 km of and within one second after another fix ($dt = 1$ second, $dx = 20$ km) were grouped together as a single flash. The range criteria used is more relaxed than was used by some other networks, e.g. the US NLDN [Cummins et al., 1998]. These criteria should capture the majority of fixes that occur within spatially extensive flashes or strokes within the same flash where the error on one or more of the strokes was mislocated by a few kilometres. This range should however be less than the separation between storm clouds, meaning that it would be rare that coincident flashes from separate storms would be correlated together by chance.

Figure 2 of Drüe et al. [2007] indicates that although the majority of fixes are within a flash are likely to be within 10 km of each other, sources in excess of 20 km are still possible from the same flash. Given the 5 km average location uncertainty of ATDnet at the limits of Europe, these time and space correlation criteria seem justified. The location and time of the first fix in the group of fixes was used as the location and time of the flash.

Having created a new dataset of flashes, density arrays could be created. The density in each point of the array corresponds to the lightning density within a box of set latitude/longitude dimensions. The domain used covers 30°N to 70°N, and 15°W to 35°E. After some testing, a resolution of 5 boxes per degree of latitude/longitude was chosen. This corresponds to box dimensions of approximately 22 km by 14 km at 50°N. This allowed 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 box size is also much larger than the anticipated location uncertainty of ATDnet within Europe.

Diendorfer [2008] suggests that, in order for measured lightning density to reflect the true lightning density within a grid box to an uncertainty of at most 20 %, the number of events per grid box should be 80 or more. Using 5 boxes per degree leads to a box area in the range of approximately 419 km² in the south of the domain to 166 km² in the north. This means that densities in the annual data of greater than approximately 0.1 flashes per km² per year are likely to be accurate to within 20 %.

The numbers of flashes in each box for each month over the six year period were counted. This value was then divided by the number of days counted over, and the area of each latitude/longitude box, and then multiplied by 365.25 to give consistent units of flashes per square kilometre per year. Strictly, as the units take the form of events per unit area per unit time, this gives the presented data in units of density rate; to be correct then, the reader should keep in mind that this is average flash density per year.

No correction has been made to the data for spatial variations in the detection efficiency of ATDnet. Although the detection efficiency will vary slightly due to differences in the distance from a stroke to the nearest four ATDnet sensors required to locate a fix, as of yet no model has been created to quantitatively account for this effect. No published, peer-reviewed, Europe-wide assessment of ATDnet detection efficiency has yet been made, although assessments of detection efficiency within France using data from a VHF Lightning Mapping Array are in progress. An internal report on the capabilities of ATDnet in Finland (towards the limits of ATDnet detection capabilities in Europe) suggests a diurnally averaged flash detection efficiency of 50 %, which can be used as an approximate lower limit for ATDnet flash DE across Europe.

A logarithmic scale was used for plotting, as the lightning flash density varies widely across Europe. Some regions, particularly in central Europe and around the Mediterranean, are well known to experience significant numbers of storms each year. On the other hand, the cold seas to the north of the UK experience very little lightning compared with the rest of Europe. The logarithmic scale allowed for lightning data from across the whole of Europe to be visualised in a single plot.

III. ANALYSIS

The analysis of the density plots will be divided into sections for the whole year and then each calendar month.

A. Annual lightning data

A total of 110,084,786 fixes were detected by ATDnet across the defined region of Europe from January 2008 to December 2013. Using the flash correlation algorithm, these were grouped into 71,433,559 flashes, giving an average multiplicity of 1.54. The average flash densities observed between 1 January 2008 and 31 December 2013 are shown in Fig. 5.

The annual flash densities detected across Europe are generally of the order of 0.1 - 4 flashes per km² per year, a broadly similar range to that observed by Holle et al. [2010] for the northern and western contiguous United States. Peak densities in Europe of less than 8 flashes per km² per year are less than the peak values observed in Florida (over 14 flashes per km² per year), however larger sources of heat and moisture, and the physical arrangement of the Florida peninsula itself, make it particularly susceptible to lightning activity.

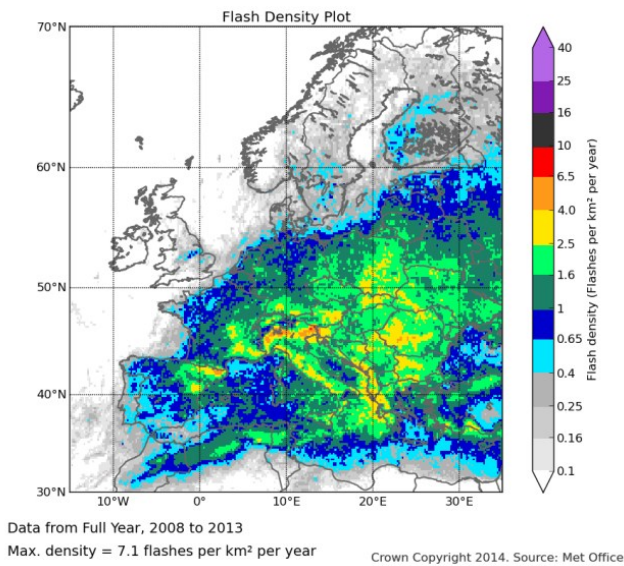


Fig. 5. Average annual lighting density in Europe, based on 6 years of ATDnet data.

There is a clear preference for higher flash densities over land compared to over open water. The monthly analysis shows that lightning in Europe peaks during the summer months, where land surface heating becomes the main source of the instability that leads to thunderstorms.

The distribution of lightning is similar to that observed by the OTD (Fig. 3). As predicted in the introduction, the flash densities observed by ATDnet are lower than those observed by OTD (widely greater than 4 flashes per km² per year), most likely due to the superior IC detection efficiency of the OTD. As ATDnet predominantly detects CG flashes, this is not a comparison of like-with-like; however, assuming that the distribution of IC and CG events are closely related, this is a good check of the reliability of the ATDnet flash density dataset.

B. Analysis by month

1) January

Lightning occurrence throughout Europe is at a minimum in winter, as displayed in Fig. 6, as the lack of solar heating and available atmospheric water vapour reduce the amount of energy available for storms to develop.

Lightning activity over continental Europe is very low. The regions with the highest lightning activity are around the coastlines of the Eastern Mediterranean, along the coasts of Turkey, Greece and the Balkans. Residual heat from the previous summer in the Mediterranean itself provides a source of energy and water vapour for generating convection.

2) February

The distribution of lightning in February (Fig. 7) is very similar to that of January. The occurrence of lightning in the Mediterranean becomes slightly more concentrated along coastlines relative to January, as the instability is only released with the additional forcing of coastal convergence and orographic effects.

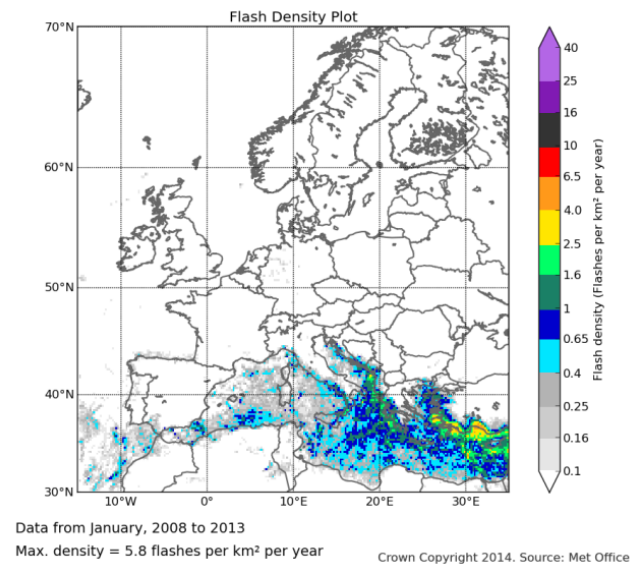


Fig. 6. Average January lighting density in Europe, based on 6 years of ATDnet data.

3) March

March sees the early signs of the resurgence of convection from solar heating (Fig. 8). Coastline lightning density in the Mediterranean is further reduced from February, but activity increases slightly across central Europe. The form of the Atlas Mountains in northern Algeria and Morocco and the Apennine Mountains in Italy are revealed by an increase in lightning density. Northern regions of Europe such as the UK and Scandinavia see little change in lightning between February and March. Despite early signs of increasing activity, the maximum flash density in Europe in March is the lowest of all 12 months.

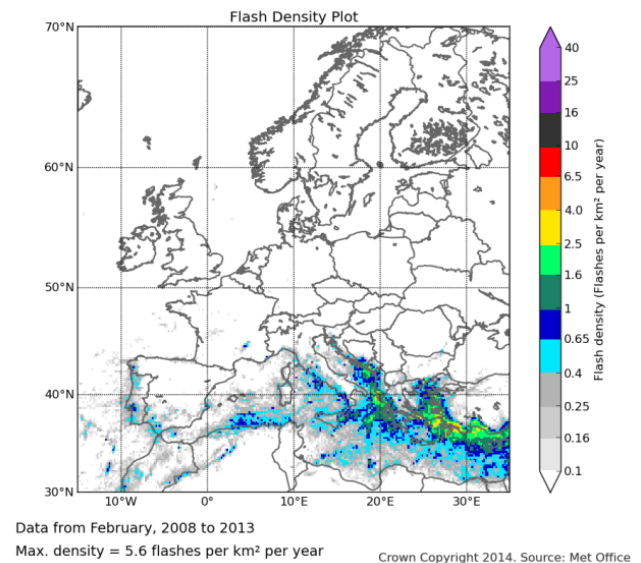


Fig. 7. Average February lighting density in Europe, based on 6 years of ATDnet data.

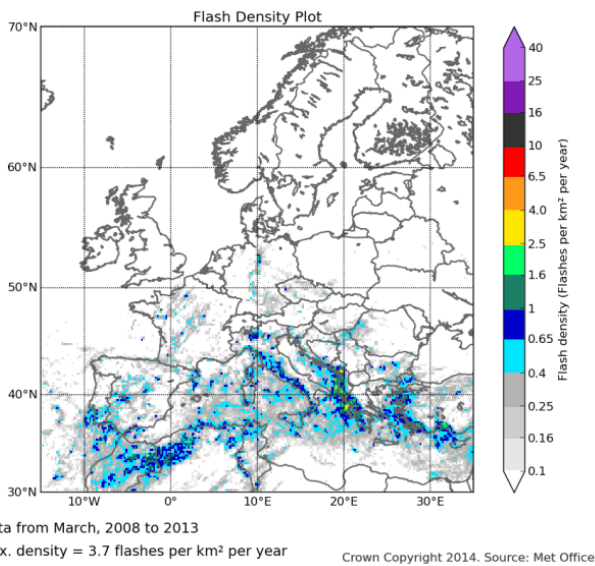


Fig. 8. Average March lighting density in Europe, based on 6 years of ATDnet data.

4) April

The distribution of lightning across Europe takes a noticeable turn between March and April, with the greatest flash densities now occurring over land (Fig. 9). Lightning density over the southern European seas is now reaching a minimum, as residual heat from the previous summer has now been exhausted, and the air begins to warm, reducing instability.

5) May

The increase in lightning density observed in April continues into May (Fig. 10), with the increase covering almost all of continental Europe. Many regions see lightning activity jump by an order of magnitude.

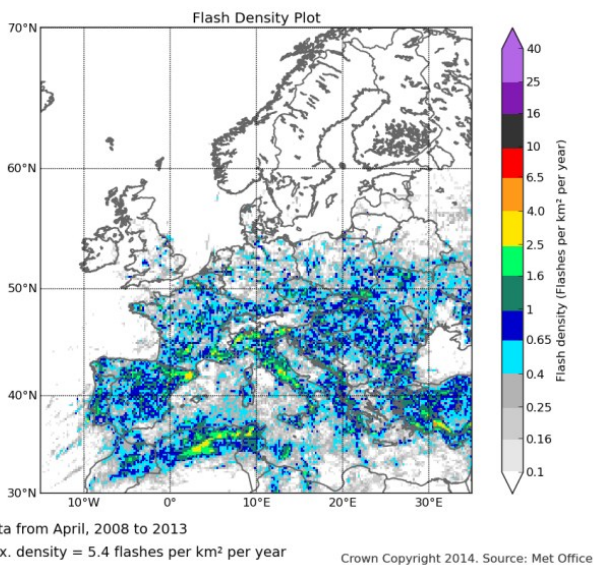


Fig. 9. Average April lighting density in Europe, based on 6 years of ATDnet data.

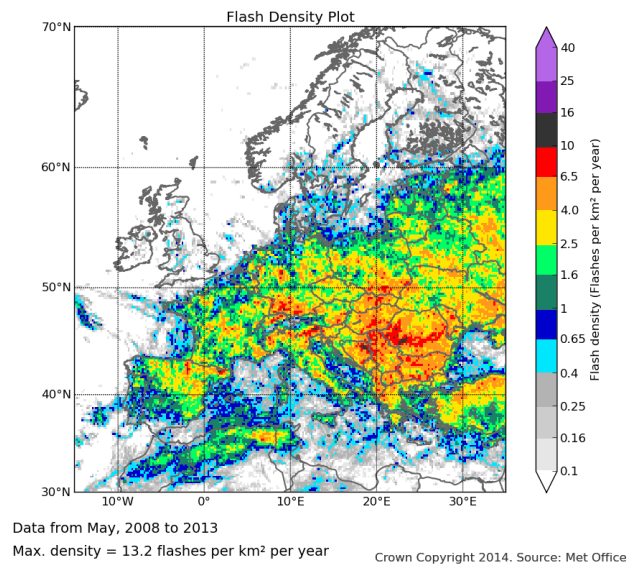


Fig. 10. Average May lighting density in Europe, based on 6 years of ATDnet data.

The first noticeable increases of lightning occur in Scotland, Finland, Norway and Sweden. The central Alps still remain relatively lightning free, however.

6) June

By June, Romania, Bulgaria and Northern Italy demonstrate some of the highest lightning densities in Europe (Fig. 11). Lightning activity along coastlines and over open water is generally low, as the relatively cold water acts as a stabilising influence on the atmosphere.

Individual storm tracks are noticeable in the UK, Sweden and Norway. For example, the relatively well-defined stripe of high lightning density in central England was caused by storms on only one day, on the 28 June 2012.

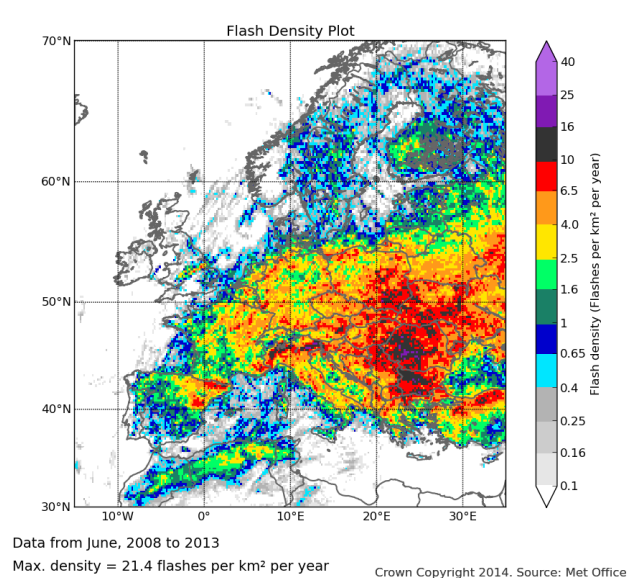


Fig. 11. Average June lighting density in Europe, based on 6 years of ATDnet data.

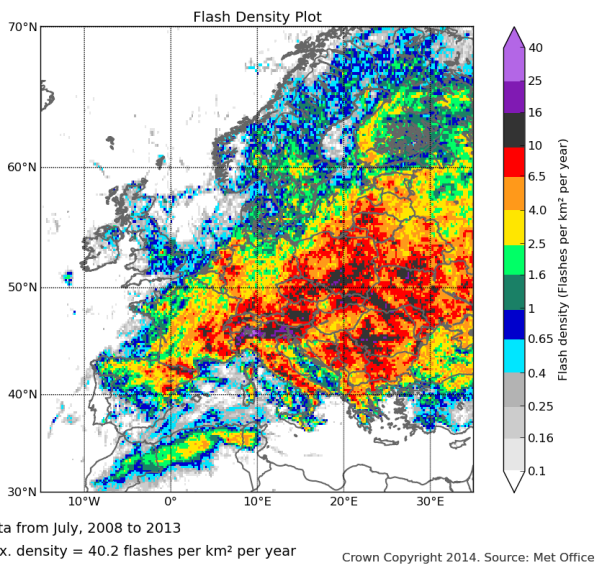


Fig. 12. Average July lighting density in Europe, based on 6 years of ATDnet data.

These storms were uncharacteristically intense for the UK, as can be seen by the way they are still easily distinguishable, despite the density plot consisting of five years worth of June data.

7) July

Lightning densities across Europe peak during July (Fig. 12), with the highest density box averaging almost 4 lightning flashes per km² during the month. The spread of high lightning density generally moves north, with some of the highest European lightning densities now observed in Poland and the Ukraine.

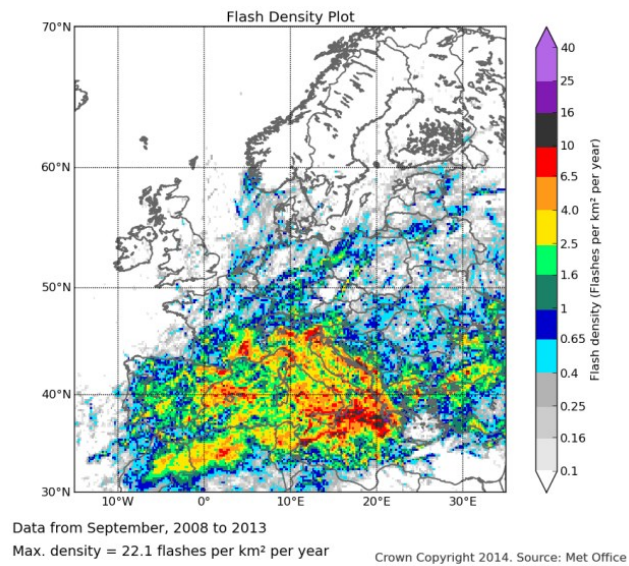


Fig. 14. Average September lighting density in Europe, based on 6 years of ATDnet data.

8) August

Lightning densities begin to drop across continental Europe in August (Fig. 13), as the air temperatures reach their peak and solar heating decreases, generating less instability. Lightning activity is still generally restricted to landmasses.

9) September

September sees a dramatic switch in the distribution of European lightning, as can be seen in Fig. 14. Northern Europe sees a sharp drop in observed lightning, whereas the western Mediterranean sees a sharp increase, particularly along coastlines. Cooler air moving over the now warm waters of the Mediterranean leads to the generation of storms.

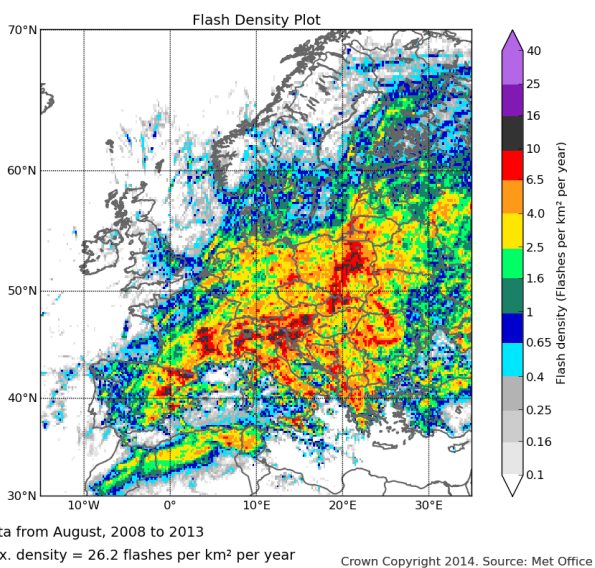


Fig. 13. Average August lighting density in Europe, based on 6 years of ATDnet data.

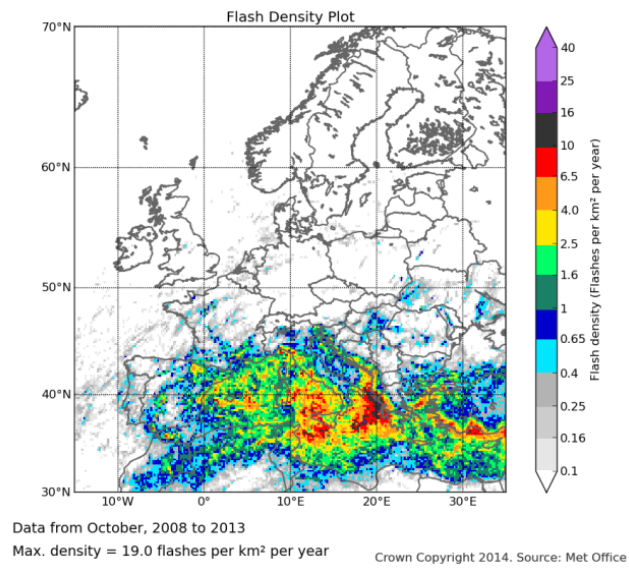


Fig. 15. Average October lighting density in Europe, based on 6 years of ATDnet data.

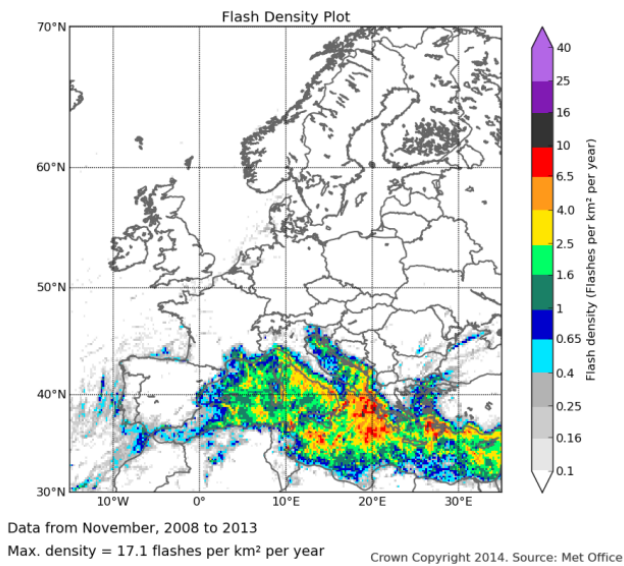


Fig. 16. Average November lighting density in Europe, based on 6 years of ATDnet data.

Lightning densities in the Eastern Mediterranean remain relatively low, however. Lightning densities are still higher over the Alps, Pyrenees and Atlas Mountains than the surrounding regions. Tracks of individual storms are noticeable across Germany, Poland and the Czech Republic, predominantly from storms in 2011.

10) October

Lightning densities across all land regions become low in October (Fig. 15), as lightning activity over the Mediterranean dominates. Lightning activity in the eastern Mediterranean increases in October, leading to more uniform lightning density between Gibraltar and Cyprus than is observed in September.

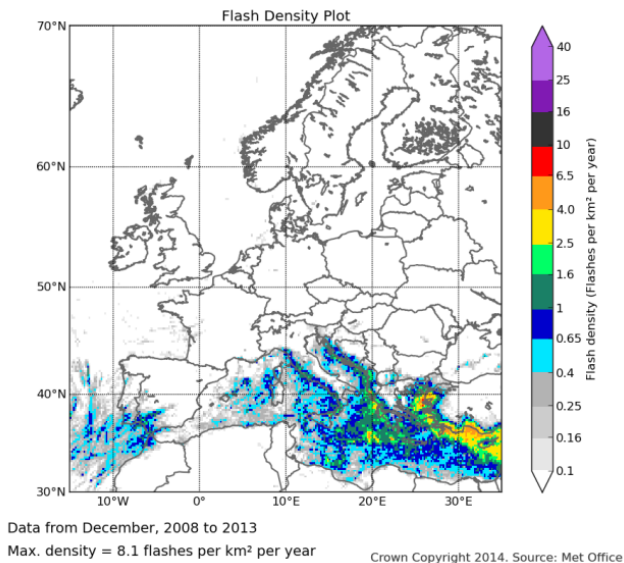


Fig. 17. Average December lighting density in Europe, based on 6 years of ATDnet data.

11) November

The lightning distribution over Europe in November (Fig. 16) is similar to that of October, but with generally reduced flash densities. The last remnants of notable flash densities over land in October, such as storms over Spain and the Atlas Mountains, are no longer observed.

12) December

Flash densities in December (Fig. 17) are now returned to the winter pattern observed in January and February. The distribution of the higher flash densities in the Mediterranean now shift towards the east, with peak densities observed along the coastlines of Greece, Turkey and Cyprus.

13) Summary

The annual pattern of the distribution of lightning across Europe can be summarised as follows. During the winter months at the start of the year, lightning is predominantly restricted to the Mediterranean, where warm waters provide the driver for storm development. In early spring, the land begins to warm, and switch from mainly sea-based to land-based convection begins in southern parts of the continent. By early summer, the majority of lightning is over land, and land-based convection now extends to the north of Europe. The peak month for European lightning is July. Following a slight decrease in lightning occurrence in August, sea-based convection returns extensively to the western Mediterranean in September. In the remainder of the year, land-based lightning density continues to decrease and the regions of highest lightning densities in the Mediterranean spread from west to east.

IV. DISCUSSION

Although the general information presented in this paper may not be of particular surprise to most readers (i.e. that lightning in Europe is most intense over the continent during summer, that higher latitudes experience less lightning than lower latitudes), the ability to analyse the relative intensities of lightning over the European region using continuous and consistent data has not previously been presented.

The ability to carry out seasonal analysis allows for better understanding of processes such as the timing of the mode switch from predominantly land-based to sea-based convection in the autumn. The use of continuous Europe-wide data also means that variations in different regions can be put into a wider context.

The effects of unusually intense storms are visible in most months of data. Had the data from ATDnet been available for a longer period, such effects could be reduced in the flash density analysis. However, data was only used from a period where the performance of ATDnet could be assumed to be relatively homogeneous. Similar analysis could again be carried out in future, in order to repeat the analysis with reduced ‘noise’; however the key results would still be likely to remain unchanged.

It is desirable that, following the calculations of Diendorfer [2008], the number of events per grid cell should exceed 80, in order to provide an estimated uncertainty of the density value of 20% or less. This is achievable for much of Europe in the

annual data, except in the very low lightning activity regions in the Northwest of Europe. In the monthly analysis, however, lightning densities in excess of 1 flash per km² per month are required in the northern limits of the region to achieve this criterion.

Care should be taken then in interpreting the monthly data: it is suitable for observing overall trends; however the actual values in individual grid boxes will be subject to a high degree of uncertainty. The grid box dimensions used (i.e. based on latitude/longitude limits) were chosen based on their simplicity to understand, however the effect that the area reduces with increasing latitude, where the lightning density also decreases, is unfortunate. The fact that lightning density varies by orders of magnitude across Europe makes it difficult to select a grid scheme that both shows sufficient detail in high density regions, that also prevents high uncertainties in low density regions.

Readers should be aware that while the data provides a good representation of lightning density across Europe, there are still factors in the methodology of the way the data is obtained that will mean it does not exactly represent the true European CG flash density, as is true with any observation system. For example, the design of ATDnet means that it will predominantly detect the emissions from CG return strokes. However, VLF systems have been shown to detect a proportion of IC discharges, as observed in data obtained by the WWLLN [Jacobson et al., 2006]. As yet unpublished results obtained by analysing ATDnet data appear to confirm that ATDnet also picks up a proportion of IC discharges, but with reduced detection efficiency relative to CG flashes. The difference in detection efficiency between IC and CG discharges is thought to predominantly be caused by the fact that CG return strokes are generally more powerful than IC discharges, and so are more easily detected at long ranges.

It should also be noted that the detection efficiency of ATDnet has a diurnal variability, attributed to variations in the ionosphere leading to differences in propagation paths of VLF sky waves between the day and night [Bennett et al., 2011]. The difference in path length between the ground wave and successive sky waves leads to bands of reduced spheric signal strength caused by interference between signals with paths differing by $n+1/2$ wavelengths, where n is an integer. The effect is more noticeable at night, due to the height of the ionosphere leading to a greater degree of destructive interference.

The information presented here may be useful in assessing the initial performance of the MTG-LI after its predicted launch in 2018 [EUMETSAT, 2013]. Current plans for the device include introducing a lightning density product, but the accuracy of such a product will need to be assessed against what is currently understood of lightning density in Europe.

Other parties that might also be interested in such information would be insurance providers, and also energy and utilities companies, who might be better able to assess risks associated with storms over broad regions. Due to averaging process used in the paper, however, higher resolution data

would be required for risks for specific sites, due to variations in density shorter than the size of a grid box.

V. CONCLUSION

Lightning density data from across Europe detected using the ATDnet long-range lightning detection network operated by the UK Met Office have been presented. The information provided by the density plots in this paper can be used to gain a greater understanding of the characteristics lightning across Europe. The continual operation of ATDnet will allow for further refinement in future, which can be used to gain a better understanding of the average seasonal activity of thunderstorms in Europe.

ACKNOWLEDGEMENTS

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