Met Office

Comparison and characterisation of ATDnet versus LIS for the period of 2008 to 2014

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Abstract

The era of geostationary lightning detection is about to start and thus it is important to know how the observations of ground based Lightning Location Systems (LLS) and satellite based optical sensors compare. ATDnet is the Met Office ground based LLS; it has a potential to provide complementary data to geostationary lightning sensors in the future. However, firstly it is necessary to have a good understanding of the similarities and differences of ATDnet data and of optical observations from space.

In the present study ATDnet flash detection efficiency (DE) relative to the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) is evaluated. LIS and ATDnet observations during 2008-2014 within LIS data domain (38°N-38°S; 180°W-180°E) are compared. A LIS flash was considered to be detected by ATDnet if at least one ATDnet detection had occurred within 25 km of any group in a LIS flash within 330 ms before, during or after a LIS flash.

The results revealed that ATDnet performed best over the Mediterranean and the East Atlantic where 20-30% of LIS flashes were detected. ATDnet detected 10-15% of LIS flashes over the West Atlantic and 5-10% in northern and western Africa. More distant regions like South America and the South Atlantic had ATDnet-relative DE values of approximately 5%. ATDnet also detected some lightning in the eastern seaboard of the US and in central and southern Africa. Sharp contrast in relative DE appeared between land and water with higher values over the Atlantic and the Mediterranean. Diurnal cycle in ATDnet-relative DE with minimum at night was observed in areas closer to Europe such as the Mediterranean and the North Atlantic. ATDnet-relative DE increased gradually during the study period over most of the study area.

It was found that the average number of ATDnet fixes per detected LIS flash was 1.23 and 15% of the detected LIS flashes had more than one linked ATDnet fix. The results also revealed that ATDnet fixes linked to LIS flashes most frequently occurred 1-2 ms before the start of the corresponding LIS flash. LIS flash characteristics such as the maximum number of events per group, maximum group area and total flash area had clear impact on ATDnet DE.

Some storms were characterized by very low and some by remarkably high ATDnet DE. It was found that poorly detected storms typically had weaker flashes and/or they occurred at night when ATDnet DE is lower.

The results of the present study are generally encouraging given that virtually all the study area was located outside the ATDnet perimeter and that LIS is capable of detecting all type of lightning discharges whereas ATDnet was primarily designed to detect cloud-to-ground lightning return strokes. Despite their very different observing principle ATDnet and LIS often detected the same flashes. The methodology and scripts developed during the present study could be used to combine ATDnet data with geostationary lightning imager's data.

1. Introduction

1.1. Introduction to ATDnet

ATDnet is a Very Low Frequency (VLF) long-range lightning location system (LLS) operated by the Met Office. The network locates lightning discharges using the Arrival Time Difference (ATD) method (Lee 1986). The current ATDnet consists of 10 sensors (also referred to as "outstations") in and around Europe (Fig. 1.1) operating at the central frequency of 13.733 kHz.

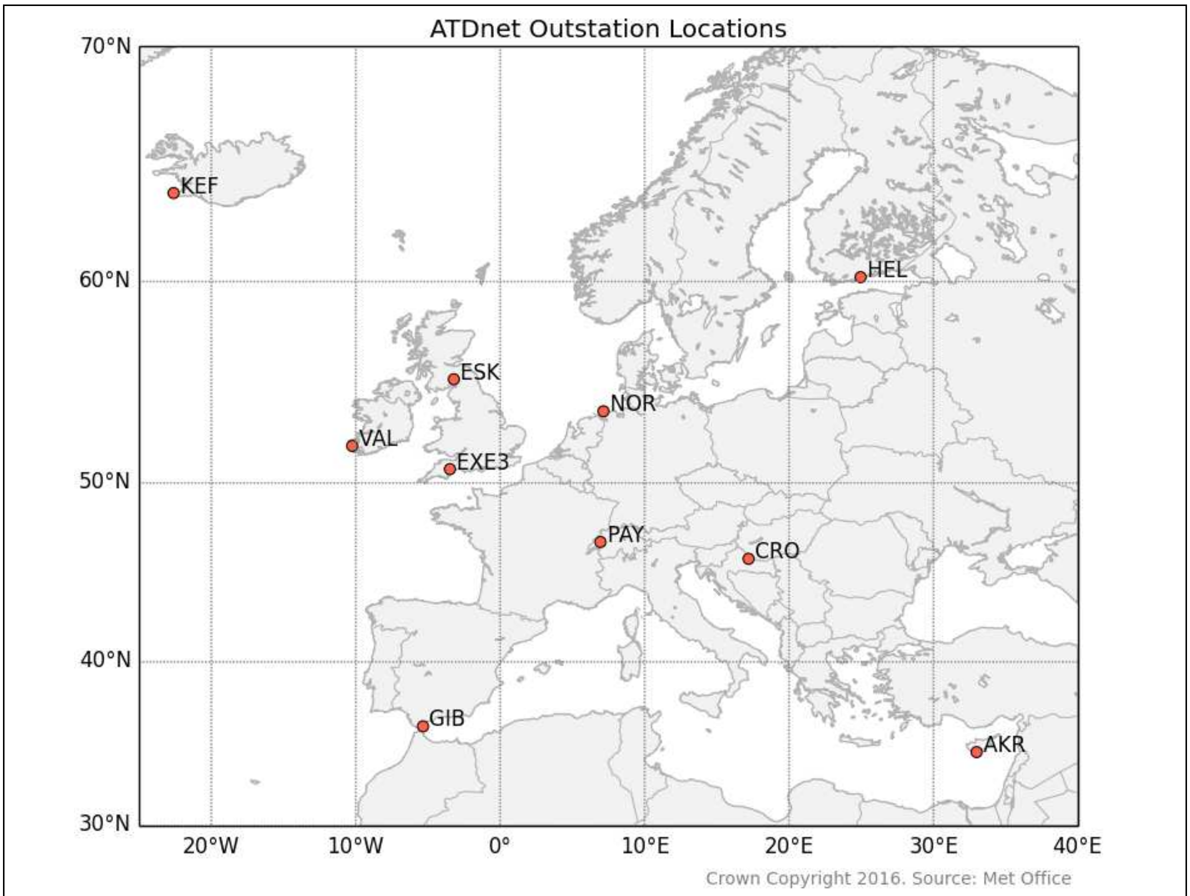

Figure 1.1. Locations of ATDnet operational outstations in 2016.

ATDnet sensors detect ''atmospherics'', also referred to as simply "sferics". Sferics are electromagnetic waves in the VLF range that propagate in the earth–ionosphere waveguide and are generated by cloud-to-ground (CG) return strokes (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. ATDnet detections are referred to as ''fixes'' and they correspond to CG return strokes or intra-cloud (IC) pulses. Fixes are located using data from a minimum of four ATDnet outstations. For each fix one of the stations that received the waveform of the corresponding lightning process is flagged as the reference station. The reference station is selected depending on the quality of the waveform and its proximity to the centre of the network. Waveforms from different outstations are correlated and the arrival time difference of waveform peak amplitudes is computed for each possible reference station/other station pair. Each arrival time difference together with the geographic coordinates of the corresponding outstations determine a continuous line around the world of all of the possible stroke locations for this particular ATD. At least three lines (four contributing stations) are needed for an unambiguous fix location solution where the intersection point of all the lines is the fix location (Fig. 1.2). ATD lines are often referred to as “hyperbolas” because of their shape on conventional maps.

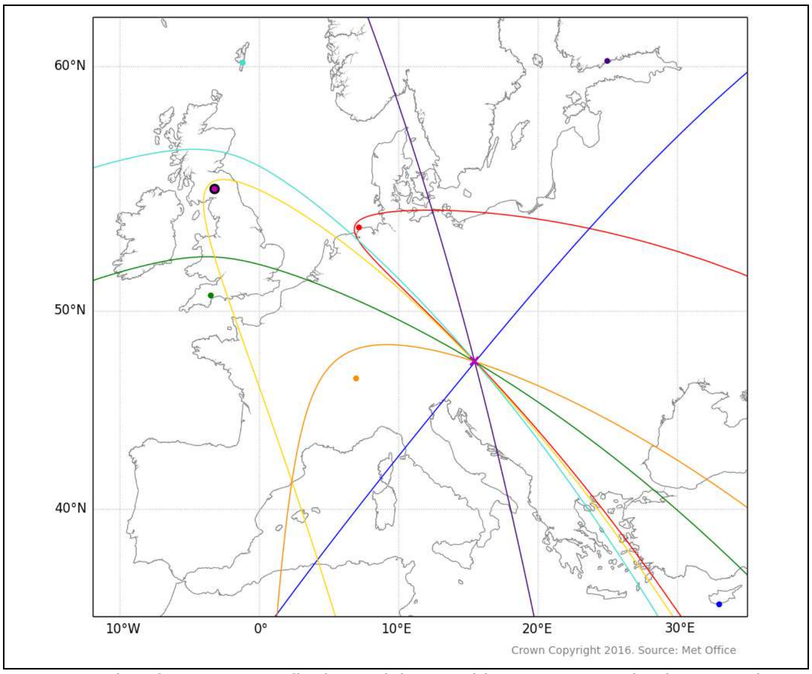

Figure 1.2. Example of an ATDnet fix (cross) located in Europe as the intersection point of seven arrival time difference hyperbolas.

ATDnet first became operational in 1987 with its main focus being CG lightning detection. CG lightning is responsible for most of the lightning damage and it is also easier to detect for a long range LLS as CG strokes tend to emit more powerful sferics in the VLF range than cloud lightning pulses (e.g. Cummins and Murphy 2009). The effective range of ATDnet encompasses Europe, northern Africa, and northern parts of the Atlantic. The system also detects some lightning in central Africa, South America, the South Atlantic, the eastern coast of North America and in Asia (Fig. 1.3).

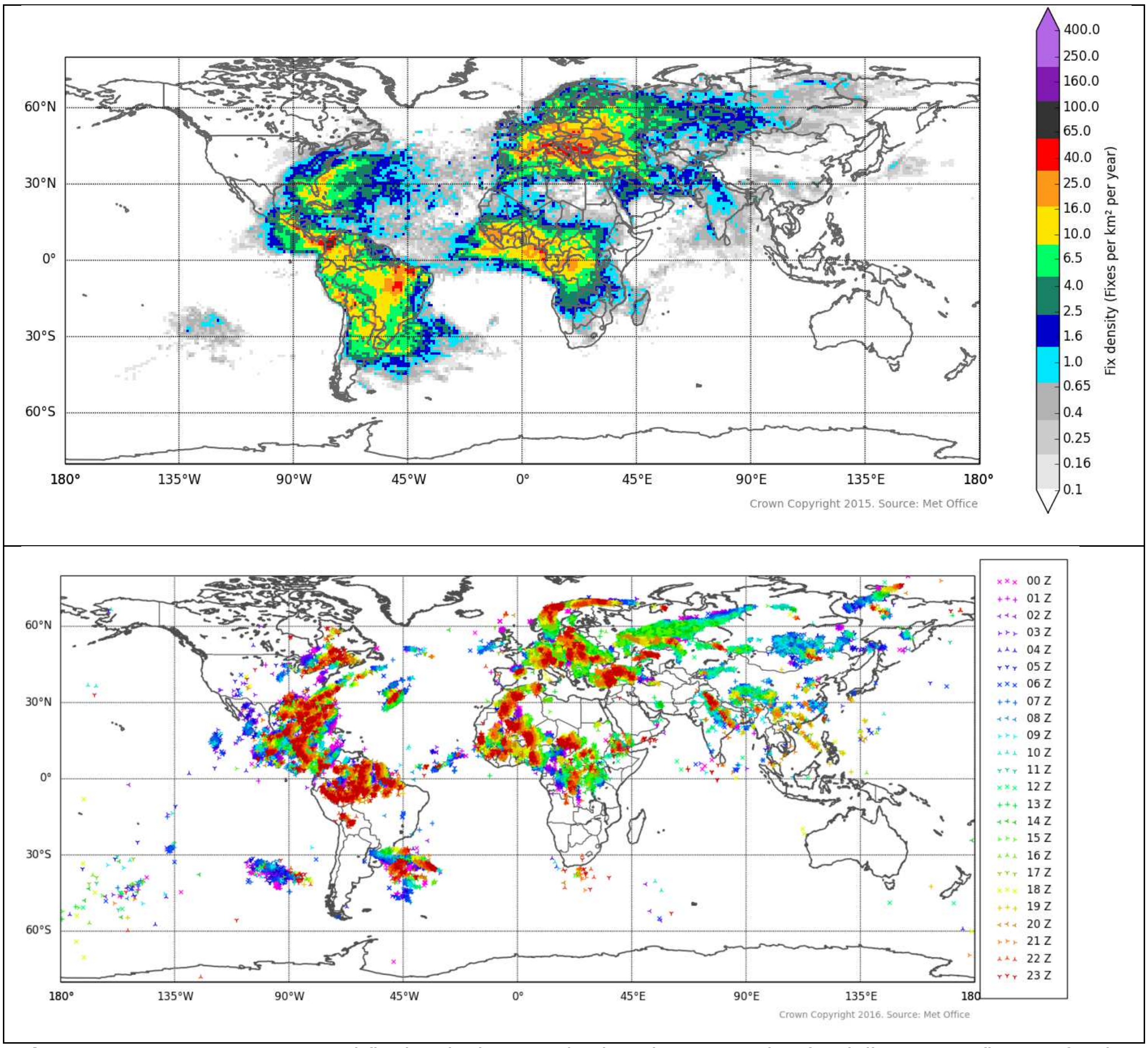

Figure 1.3. ATDnet annual fix density in 2014 (top) and an example of a daily ATDnet fix map for the 4th August 2014 with fixes coloured by the hour of occurrence (bottom).

1.2. ATDnet location accuracy and detection efficiency

1.2.1. ATDnet location accuracy

ATDnet location accuracy (LA) is mainly dependent on the correct modelling of the propagation velocity of sferics and accurate waveform correlation. The current ATDnet system uses fixed propagation velocity but the real speed of sferics has been demonstrated to vary due to the influence of sky waves and ground effects (Liu et al. 2016). Long propagation paths may result in waveform distortion which in turn can compromise the waveform correlation process and introduce errors into arrival time differences. The network geometry plays also an important role in LA. Within the network perimeter ATD hyperbolas are often nearly perpendicular to each other resulting in smaller location errors. At greater distances from the network hyperbola intersection angles are shallow leading to larger location errors along the direction of hyperbolas.

The ATDnet theoretical minimum location errors associated with a 10 µs random error in arrival time differences are shown in Fig. 1.4. Those figures are derived also assuming that all 10 operational sensors are contributing to the calculation of the fix location, and that in this case Payerne is used as the reference station.

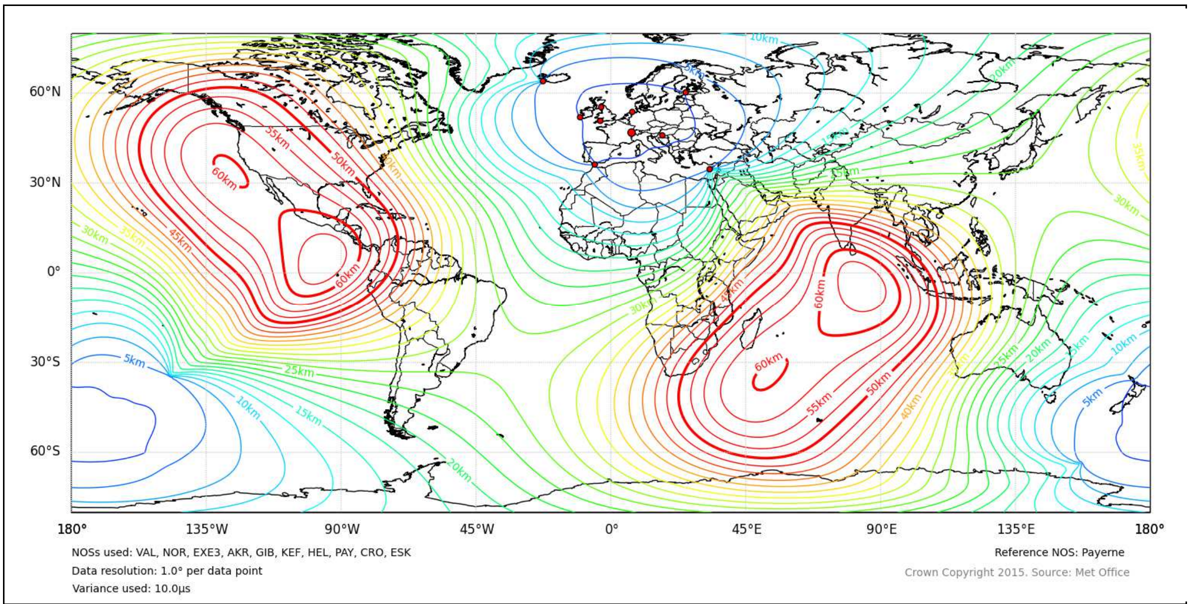

Figure 1.4. ATDnet theoretical minimum location errors in km associated with a 10 µs random error in arrival time differences. It is assumed that all operational sensors are used and Payerne is selected as the reference station.

Real location errors are often higher than those predicted by Fig. 1.4 as fixes are seldom derived using contribution from all ATDnet sensors. Bennett et al. (2010) assessed ATDnet location error by using CG data of short range LLSs as ground truth. Four relatively short time periods (approximately 10 days each) during the late 2007/early 2008 were studied. The analysis encompassed three study areas in Europe (France, southern Finland and Austria) and one in South America (Brazil). In Europe the observed distances between coincident lightning locations of ATDnet and short range systems were 1-2 km higher than the prediction of the theoretical location accuracy model. In contrast it was found that in Brazil the theoretical model overestimated location errors. This was attributed to long sea-tracks between Europe and Brazil characterized by relatively uniform waveguide characteristics and lower velocity variations.

1.2.2. ATDnet detection efficiency

ATDnet detection efficiency (DE) has been analysed against different types of lightning location systems mainly in Europe. Most of the studies carried out so far have been relatively limited in space and/or time.

Bennett et al. (2010) found that ATDnet detected approximately 50-90% of CG strokes detected by short range LLSs over Western Europe and in Finland during the day. At night, ATDnet DE was found to be below 50%. It was also demonstrated that CG strokes with higher peak currents were much more efficiently detected by ATDnet. The detection efficiency for large (> 60 kA) CG strokes was found to be equally between 60-80% in Finland and in Brazil. This indicates that sferics generated by strong CG return strokes propagate for thousands of kilometres without falling below the detection threshold of ATDnet.

ATDnet and WWLLN (the long-range World Wide Lightning Location Network as described by Lay et al., 2004) were compared in the tropical Atlantic during January and July 2010 (Bennett 2011). Both networks showed similar spatial pattern of lightning but ATDnet detected approximately three times as much strokes as WWLLN.

Poelman et al. (2013b) validated ATDnet against 57 negative CG flashes, with a total of 210 strokes that were video recorded in Belgium in August 2011. ATDnet detected 88% of the flashes and 58% of the return strokes (75% of first return strokes). ATDnet was compared to a regional network employing SAFIR sensors (Surveillance et Alerte Foudre par Interférometrie Radioélectrique) operated by the Royal Meteorological Institute of Belgium (RMI) and a sub-continental network operated by Météorage (MTRG) during May to September 2011 and 2012 (Poelman et al. 2013a). The results revealed that ATDnet detected 60% of SAFIR flashes in the Benelux and 66-80% MTRG flashes in France and Benelux. The most interesting finding was that at least 25% of MTRG cloud flashes were detected by ATDnet. This indicated that ATDnet might detect more cloud lightning than had been assumed earlier.

Recently Enno et al. (2016a) further investigated the possibility of cloud flash detection by ATDnet by validating ATDnet against a Lightning Mapping Array (LMA) in the south of France. Three storms in September 2012, with a total of 281 CG and 1324 IC flashes, were examined by using LMA source plots and ATDnet fix data. ATDnet was found to have detected approximately 90% of CG and 24% of IC flashes indicating that the system is capable of locating any significant storm in Western Europe even if mainly or only ICs are produced. ATDnet overall DE (including all CG and IC flashes) varied from 35-56% between the studied storms and depended on the fraction of ICs. The storm with the highest (lowest) IC fraction had the lowest (highest) overall ATDnet DE. Vertically longer cloud flashes were found to have been detected much more efficiently than IC with small vertical extent. It was also demonstrated that most of the ATDnet IC detections were related to the initial breakdown which is an early and often vertical part of IC (Nag et al. 2009). Long vertical cloud lightning channels probably emit vertically polarized sferics which are strong enough to be recorded by ATDnet sensors.

1.3. Introduction to LIS

The Lightning Imaging Sensor (LIS) was an instrument on the Tropical Rainfall Measuring Mission (TRMM) satellite (Christian et al., 1999b), launched into a low-earth orbit (350 km) in November 1997. The orbit was subsequently boosted to 400 km in 2001 to increase mission lifetime, with no impact on DE (Cecil et al. 2012). TRMM's orbit had an inclination of 35° that allowed for the detection of lightning between 38°N and 38°S. LIS field of view (FOV) was 580x580 km, and a nadir resolution of 4 km decreasing to 7 km at the edges of the field of view (Christian et al., 1999a).

LIS consists of an optical staring imager, which detects lightning activity by identifying changes in the brightness of clouds illuminated by lightning between successive time steps of 1.8 milliseconds. It is able to detect lightning even in bright, sunlit clouds by using a narrow band filter centred at a wavelength of 777.4 nm. All types of lightning (CG and IC) produce optical pulses which are detectable from space. The instrument records the time and location of a lightning event as well as its radiant energy (Christian et al., 1999b). Figure 1.5 shows the average annual distribution of lightning observed by LIS.

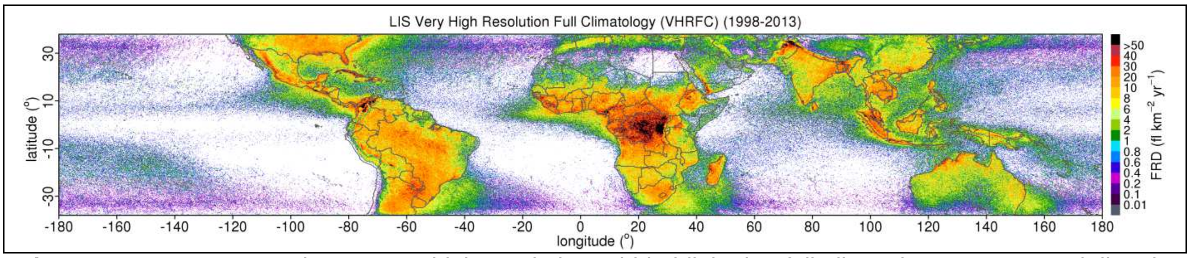

Figure 1.5. LIS 0.1 degree very high resolution gridded lightning full climatology 1998-2013 (Albrecht *et al.* 2016).

Daytime reflection of solar radiation leads to a reduction in optical lightning detection efficiency. As such, LIS was predicted to have a detection efficiency of 93±4% during the local nighttimes, dropping to nearer 73±11% around local noon (Boccippio *et al.* 2002). LIS was able to detect CG and IC lightning but it was no designed discriminate between different types of flashes as the statistical distributions of the optical characteristics for CG and IC overlap substantially. However, it has since been shown that the mean values of these distributions differ making it possible to estimate the fraction of CG and IC in a large sample of LIS data (Koshak, 2010). On the basis of this observation, mathematical models have been developed for LIS flash type discrimination (e.g. Koshak and Solakiewicz, 2015).

The Lightning Detection and Ranging (LDAR) system was used to assess LIS performance by Ushio et al. (1999). It was found that LIS detected 57% (24 out of 42) of ground flashes and more than 80% of cloud flashes. The New Mexico Tech Lightning Mapping Array (LMA) was used to validate LIS in Central Oklahoma (Thomas et al. 2000). The LIS overpass occurred about an hour after local midnight on 11th June 1998. During the 90 second period of the overpass LIS detected 84% (108 out of 128) of flashes detected by the LMA. Flashes that extended to the upper part of the cloud above 7 km were found to be detected by LIS much more efficiently than those confined below 7 km altitude. Almost all IC having an upper level component were detected by LIS. Meanwhile about 60% of CG discharges were detected by LIS and many of the detected CG were hybrid discharges with high-altitude components.

1.4. Validating ground based networks against LIS data

Over recent years, LIS dataset has been increasingly used for validating ground based networks. The main advantage of LIS over ground based networks is its relatively long period of consistent observations with stable performance (Buechler et al. 2014) and its spatially uniform coverage over land and the oceans. Thus, LIS dataset is suitable for measuring the performance of ground based lightning location systems over vast remote and/or oceanic areas where reliable ground truth data are hard to obtain. It could also be used for measuring the impact of upgrades e.g. validating improvement of the DE of ground based LLS over time. The main limitation of LIS is that its spatial domain only encompasses tropics between 38°N and 38°S and areas at higher latitudes, such as Europe, are not covered.

Table 1.1 provides a summary of all the ground based LLS validation studies against LIS that have been reported so far in the literature.

Table 1.1. DE of ground based LLSs relative to LIS.

Network	Study Period	Western Hemisphere	North America	South America	Oceans	Reference
Long range networks						
WWLLN	2009	6.0	8.0	2.3	12.3	Rudlosky and Shea 2013
WWLLN	2010	6.8	7.6	4.1	13.9	Rudlosky and Shea 2013
WWLLN	2011	8.1	8.7	4.8	15.2	Rudlosky and Shea 2013
WWLLN	2012	9.2	10.7	4.9	17.3	Rudlosky and Shea 2013
WWLLN	Jan 2010 - Jun 2011	11.0	13.2	6.2	16.4-18.9	Thompson et al. (2014)
GLD360	2012	25.3	33.4	17.5	33.0	Rudlosky (2014)
Short range networks						
ENTLN	Jan 2010 - Jun 2011	28.5	63.3	2.2	2.5-3.0	Thompson et al. (2014)
ENTLN	2011	21.6	50.3	5.4	25.4	Rudlosky (2015)
ENTLN	2012	28.0	60.0	11.3	35.7	Rudlosky (2015)
ENTLN	2013	31.4	67.4	11.5	41.2	Rudlosky (2015)

LIS dataset was used to validate WWLLN in the Western Hemisphere (38°N-38°S, 0°-180°W) during 2009-2012 (Rudlosky and Shea, 2013). WWLLN detected 7.5% of the LIS flashes in the study area during the study period. WWLLN's DE was approximately three times greater over the oceans than over land and areas with the highest DE occurred exclusively over the oceans. It was demonstrated that WWLLN relative DE increased from 6% during 2009 to 9.2% during 2012. The average number of WWLLN strokes per detected LIS flash was 1.5 and 28.5% of matched flashes had more than one WWLLN stroke. Detected LIS flashes had clearly more events and groups, longer durations, and larger areas than non-detected flashes.

Thompson et al. (2014) demonstrated the differences between long-range and short-range lightning location systems by comparing stroke data from both the WWLLN and the Earth Networks Total Lightning Network (ENTLN) to LIS lightning group data. An 18-month study period from 1st January 2010 to 30th June 2011 was examined. The study area encompassed the Pacific, the Atlantic and the Americas between 39°S to 39°N and 164°E to 17°W. Coincidence percent (CP) values were computed by dividing the number of LIS groups with at least one coincident WWLLN or ENTLN stroke by the total number of LIS groups.

As shown by Thompson et al. (2014), long-range LLS WWLLN had the highest coincidence percent values over the oceans where lightning discharges are assumed to be stronger and VLF propagation conditions are better. Furthermore, short range LLS ENTLN exhibited the highest CP in the continental US where most of the sensors are located. In total WWLLN and ENTLN detected 11.0% and 28.5% of all LIS groups in the study area, respectively. In North America ENTLN detected 63.3% and WWLLN 13.2% of LIS groups. Over the oceans ENTLN detected only 2.5-3% of LIS groups whereas WWLLN detected 16-19%.

Data from the Global Lightning Dataset 360 (GLD360), WWLLN, and ENTLN were evaluated against LIS by Rudlosky (2014). The study area covers the LIS field of view (38°N to 38°S) in the Western Hemisphere (0° to 180°W). WWLLN detected 9.2% of the LIS flashes in the study area during 2012 whereas ENTLN detected 28.0% and GLD360 25.3% of the flashes. ENTLN and GLD360 exhibited the highest DE in North America whereas the performance of WWLLN was clearly better over the oceans.

Rudlosky (2015) evaluated ENTLN against LIS during 2011-2013 within the LIS field of view in the Western Hemisphere (38°N-38°S, 0°-180°W). The relative flash DE of ENTLN increased from 21.6% in 2011 to 31.4% in 2013. The best regional performance was found over the southern contiguous US. Large day-to-day variations in ENTLN detection efficiency were observed on the background of seasonal cycle with higher DE in winter. It was also demonstrated that certain LIS flash parameters such as maximum number of events per group and maximum group area exhibited much larger average values for CG flashes compared to IC flashes.

A cross-validation between the US National Lightning Detection Network (NLDN) and LIS were presented by Zhang et al. (2016). A Bayesian approach was used to estimate the absolute detection efficiencies of both systems. It was concluded that the upper bound absolute flash DE of LIS and NLDN were 81.5% and 58.2%, respectively. It was also demonstrated that NLDN discharges were normally reported about 2 ms earlier than the correlated LIS groups. NLDN flashes with higher multiplicity appeared to have a higher chance to be correlated with LIS groups. It was also demonstrated that regular TRMM satellite yaw manoeuvres resulted in abrupt shifts in LIS group locations by approximately 5-10 km relative to the locations of correlated NLDN strokes.

1.5. Objectives of the present study

As a ground base long range network, ATDnet presents the potential to provide complementary data to the upcoming geostationary lightning sensors. It is therefore essential to further deepen our knowledge of the similarities and differences of ATDnet data and satellite base optical observations such as those carried out by LIS on TRMM. LIS used the same observing method as will be used by Geostationary Operational Environmental Satellite-R Series Geostationary Lightning Mapper (GOES-R GLM as described by Goodman et al., 2013) and the Meteosat Third Generation Lightning Imager (MTG-LI as described by Grandell et al., 2009). As such, LIS large dataset spanning from 1998 to 2014 provides an excellent opportunity to study ATDnet performance relatively to a satellite based optical lightning sensor.

The main objective of the present study is the evaluation of ATDnet performance against LIS. This study expands on the work carried out by the Met Office in 2011/12 (Collins et al. 2012), as well as the work carried out by the National Oceanic and Atmospheric Administration (NOAA) e.g. Rudlosky, 2014. The main emphasis of this comparison is to study the Atlantic Ocean area although the whole of the LIS coverage area is also investigated. The work is divided into smaller subsections that address different aspects of the main objective and are described below:

1. *Measuring ATDnet-relative DE over the LIS data domain i.e. 38°N to 38°S:* Earlier attempts to measure ATDnet DE relative to LIS have given contradictory results. Defer et al. (2005) compared 20 days worth of ATDnet and LIS data in the Mediterranean region during winter 2002-2003 and concluded that ATDnet detected 12% of 1671 LIS flashes during the study period. Collins et al. (2012) found that ATDnet detected only 0.01% of LIS groups and 1.4% of LIS flashes within their study domain (30°S-35°N and 50°W-50°E) during 1st to 7th May 2011. Later Scott D. Rudlosky (NOAA) used different methodology and got ATDnet DE values that exceeded the results of the earlier studies. Thus, ATDnet DE relative to LIS needs to be clarified on the basis of spatially and temporally extensive datasets.

2. *Examining the impact of LIS flash characteristics on ATDnet DE:* ATDnet is primarily designed to locate CG lightning return strokes whereas LIS has been described as an all lightning sensor capable of detecting CG and IC. Neither of

the systems directly discriminates between different types of lightning. However, LIS provides some flash characteristics that reflect the strength of flashes. Thus, it is possible to examine which LIS flash characteristics have a stronger impact on ATDnet DE.

3. *Comparing ATDnet performance in different regions*: It is known that ATDnet detects some lightning as far as the South Atlantic and South America. However, it is not known how ATDnet DE and LA compare between Europe and more distant regions. LIS is suitable for such comparisons as its DE is assumed to be spatially uniform over long time periods.

4. *Investigating individual storms with high and low ATDnet DE:* Case studies of individual storms characterised by remarkably high or low ATDnet-relative DE could give better understanding on ATDnet performance on the storm level. For example, storms with very low relative DE might be related to temporary reduction in ATDnet DE caused by sensor failures or data communication issues. On the other hand such storms might be dominated by weaker than usual flashes emitting weak sferics that remain below ATDnet detection threshold.

Chapter 2 of the report describes data and methods. Chapters 3 and 4 present the main results on the global and regional scale, respectively. Chapter 5 contains case studies and Chapter 6 lists some suggestions for future research. Chapter 7 concludes the report.

2. Data and methods

2.1. Description of the Data

2.1.1. ATDnet data

Like most of the ground based networks ATDnet monitors lightning activity within its spatial range continuously. Occasionally data from some sensors might be lost temporarily due to communication problems or hardware issues. Such problems are mostly solved quickly and their impact on the performance of the network is usually minor, (e.g. slight reduction of DE in some regions), with one exception during the study period relating to the loss of the Valentia sensor in Ireland (this sensor was out of service from spring 2012 to February 2015). Another notable change in the network during the study period occurred in February 2014 when the Manas outstation in Kyrgyzstan was permanently decommissioned.

The original ATDnet fix dataset is used in the present study. ATDnet fixes correspond to CG lightning return strokes or strong IC pulses. The date, time, location (latitude and longitude) and location error estimate of each fix is provided by the ATDnet central processing system. ATDnet reports fixes to 0.1-µs precision. The location error estimate contains the orientation and length of the major axis and the minor axis of an ellipse in which a fix is located with a 95% probability. No discrimination between IC and CG discharges is provided.

All ATDnet fixes are checked by the ATDnet quality control system against predefined location error and signal quality criteria and classified as “good” or “poor”. Only “good” fixes that pass the criteria are used in ATDnet data products. The present study uses only “good” fixes in order to reflect ATDnet-relative DE at the customer level. Furthermore, Enno et al. (2016b) demonstrated that only a small fraction of ATDnet fixes corresponding to genuine lightning discharges are wrongly rejected by the quality control system and classified as “poor”.

In the present study, ATDnet fixes are validated against LIS, and not vice versa, therefore it is not necessary to filter ATDnet fixes for LIS view times. Thus, the whole ATDnet and LIS datasets could be compared directly and LIS flash times and locations automatically filtered out all ATDnet fixes that might be linked to LIS flashes.

2.1.2. LIS data

LIS data availability is limited by LIS view times, i.e. the overpass times of the TRMM satellite that constitute only about 0.1% of the time. However, this provides sufficient observations to map long term lightning patterns accurately (Christian et al., 2003). The LIS flash database used for this study (i.e. 2008 - 2014) consist of approximately 9.9 million flashes.

LIS reports the time, location, and radiant energy of individual total lightning events (Christian et al., 1999b): Events are defined as single pixels that exceed the LIS background level during a single frame (1.8 ms). Events in adjacent pixels (i.e. with a side or corner touching) of the same frame are combined to form groups. A group centroid is geo-located for each group by spatially weighting the event locations by their radiance (Zhang et al., 2016). Groups that occur within 330 ms and 5.5 km are further combined into flashes using a weighted Euclidean distance method (Mach et al., 2007). A flash centroid is geo-located by all the included groups.

In the present study LIS flash data are used: this dataset contains the times and locations of flashes and additional flash characteristics derived from the number, area and brightness of involved events and groups. Flash time corresponds to the time of the first group and flash location is the location of the flash centroid. The additional eight flash characteristics used in the present study are summarized in Table 2.1.

Table 2.1. Summary description n of the LIS flash characteristics used in the present study.

Abbreviation	Description	Unit
DELTA	Duration of flash.	s
NG	Number of groups per flash.	-
NE	Number of events per flash.	-
RAD	Flash radiance.	J m^{-2} sr^{-1} μm^{-1}
AREA	Flash area.	km^2
MNEG	Maximum number of events per group.	-
MGA	Maximum group area.	km^2
MGRAD	Maximum group radiance.	J m^{-2} sr^{-1} μm^{-1}

2.2. Developing the comparison method

2.2.1. Examining the 2012 report

The existing reports and publications on ground based LLS and LIS comparisons were examined in the development phase of the optimal comparison method. Firstly, the ATDnet validation against LIS by Collins et al. (2012) was examined thoroughly in order to understand the reasons behind the very low ATDnet-relative DE reported by this study.

The investigation revealed that the general approach and methodology of the 2012 report were appropriate. The scripts used for the comparison were free of major issues. The main problem was the length of the study period (i.e. too short) combined with the large study area. The first five days of the 7-day study period were characterized by up to 2 times lower ATDnet-relative DE values in the study area than the average of April and May in 2011. As such, in the present study the study period is extended to 7 years worth of data during 2008-2014 to avoid any problems and biases that could arise from short study periods and small data samples.

The size of the study area also contributed to the very low ATDnet-relative DE as most of the lightning during the study period occurred in central Africa and South America, i.e. very far from ATDnet sensors. Meanwhile the lightning activity over the Mediterranean and the East Atlantic where ATDnet is expected to have higher DE was very low. As such, the present study divides global LIS field of view into 2° x 2° grid cells to highlight the spatial variability of ATDnet-relative DE. In addition, regional analyses are performed in smaller spatial domains at different distances from ATDnet sensors in Europe.

2.2.2. Selecting the main comparison method

Three different methods have been used in past studies to compare LIS and ground based lightning location networks:

- Group level method: compares LIS groups against ground-based LLS strokes.
- Flash level method: compares LIS flashes against a ground-based LLS flashes.
- Flash to stroke method: compares LIS flashes against ground-based LLS strokes.

The group level method assumes that every LIS group corresponds to a CG return stroke or a pulse of an IC discharge and that every stroke or pulse results in one LIS group. In reality this is not always true. It is possible that the optical signal of a return stroke is divided between two consecutive LIS frames and thus triggers two LIS groups. It might also happen that the intensity of the optical emission of a return stroke varies in space so much that it does not exceed the LIS event threshold for some pixels. In this case the same return stroke could result in two or more spatially-separated LIS groups. On occasion, it can happen that two or more coincident strokes are spatially so close to each other that they are reported as one group due to constraints in the spatial resolution of LIS.

The flash level method suffers from limitations caused by grouping strokes into flashes and groups into flashes. For example, the centroid of a spatially-extensive LIS flash might be far from the ground contact point of the first CG return stroke which is often reported as the flash location by ground based networks. Thus, there is a risk that important bits of spatial information are lost when strokes/LIS groups are combined into flashes.

The flash to stroke method presents a good compromise between the other two methods. Furthermore, this method has already demonstrated to be suitable for comparing ground based networks and LIS (Rudlosky and Shea 2013; Rudlosky 2014 and 2015). Therefore, the flash to stroke method is used in the present study. The locations of all groups in LIS flashes are taken into account so that an ATDnet fix far from the flash centroid but still within its spatial extent could be detected as ATDnet match. This method retains the times and locations of all strokes detected by ATDnet so that it is possible to estimate the number of detected strokes per LIS flash and how these strokes are distributed in time and space relative to the corresponding LIS flash.

2.2.3. Selecting the spatial and temporal criteria

In the present study, an ATDnet fix must adhere to following conditions to be considered a match with a LIS flash; the ATDnet fix must have occurred:

- within 25 km of any group in a LIS flash (i.e., furthest groups north, south, east and west)
- and within 330 ms before, during, or after a LIS flash.

These spatial and temporal match criteria were introduced by Rudlosky and Shea (2013) who examined several time and distance thresholds to determine the best matching criteria. The same thresholds were used again successfully in subsequent studies by Rudlosky (2014 and 2015) for similar flash to stroke comparisons. These criteria can be visualised on Fig. 2.1.

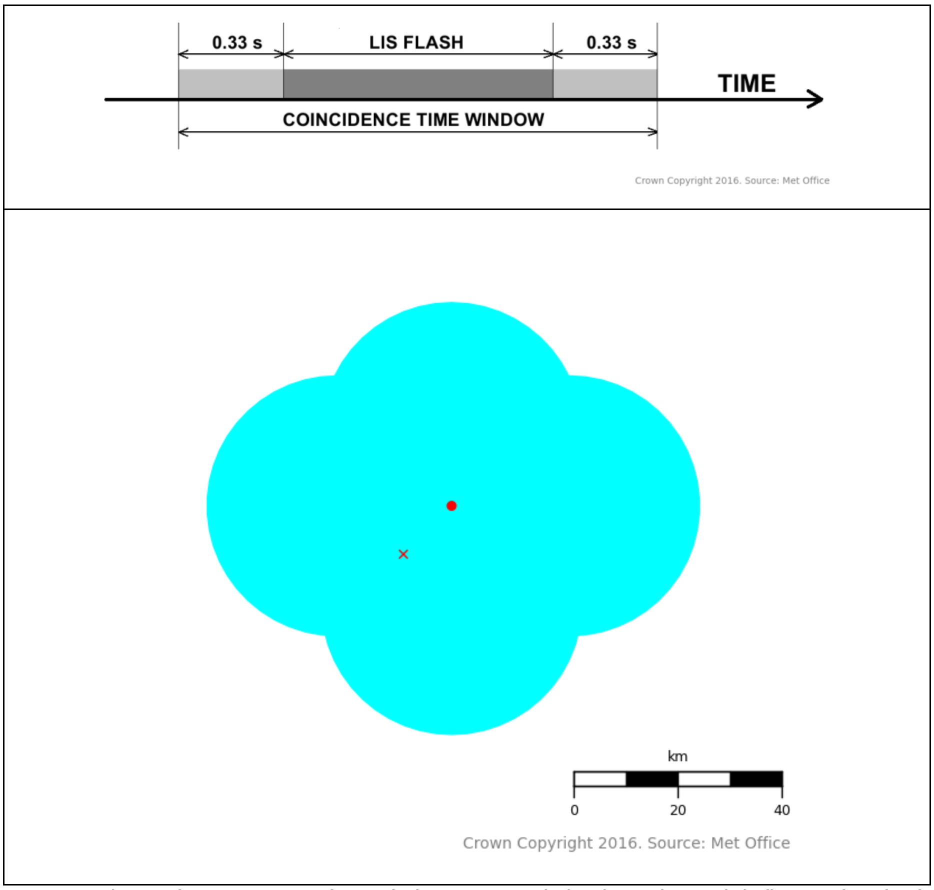

Figure 2.1. Schematic representation of the temporal (top) and spatial (bottom) criteria used for matching ATDnet fixes and LIS flashes. (top) Coincidence time window starts 0.33 s before LIS flash start and ends 0.33 s after LIS flash end. (bottom) A matched ATDnet fix must occur within 25 km of any group in a LIS flash (area in aqua). The red dot is the centroid of the LIS flash and the red cross marks the location of a matched ATDnet fix.

'ATDnet fixes with a matching LIS flash' are referred to as 'ATDnet-linked fixes' in the rest of the report. Similarly, 'LIS flashes with at least one matched ATDnet fix' are referred to as 'LIS-linked flashes'.

2.3. Refining the comparison method

The relatively broad spatial and temporal thresholds are expected to ensure that all matches are identified. However, additional caution was added to avoid double counting.

As such, three different nuances of the flash to group method were tested in the refinement process.

The simplest method (M_I) allows ‘many-to-many’ relationships between LIS flashes and ATDnet fixes, i.e. a LIS flash can have multiple linked ATDnet fixes and an ATDnet fix can be linked to multiple LIS flashes. This method resulted in the highest ATDnet-relative DE (Table 2.2) as the broad time and distance thresholds often allow a single ATDnet fix to be linked to more than one LIS flash. It is most likely to happen in intense storms that are characterised by frequent simultaneous or almost simultaneous LIS flashes in relatively limited space.

It is not scientifically sound to assume that a single ATDnet fix can be linked to more than one LIS flash even if multiple LIS flashes meet the used spatial and temporal thresholds. Instead, only one of the potentially linked LIS flashes can be the original source of the sferics received by ATDnet sensors and used to locate the ATDnet fix.

The second method (M_{II}) and the third method (M_{III}) prevent many-to-many relationships and allow only ‘1-to-many’ relationships between LIS flashes and ATDnet fixes. A LIS flash can have more than one linked ATDnet fix but an ATDnet fix can be linked only to one LIS flash. If more than one potentially linked LIS flash is found for an ATDnet fix then only one of those can be linked to the ATDnet fix. It is plausible to allow a LIS flash to be linked to multiple ATDnet fixes as ATDnet is designed to detect CG return strokes. Thus, LIS flashes that represent multistroke ground flashes are expected to have more than one linked ATDnet fix.

The M_{II} method uses spatial distance to select between LIS flashes that are potentially linked to the same ATDnet fix. For each such LIS flash the distance between its centroid and the corresponding ATDnet fix is computed. Only the LIS flash closest to the ATDnet fix is assumed to be linked to the ATDnet fix. The linked LIS flash is not flagged as used, thus it might be linked to other ATDnet fixes.

The tests of the M_{II} method revealed some problems that might lead to somewhat underestimated ATDnet-relative DE. Some potentially linked LIS flashes lost their linked ATDnet fixes to other LIS flashes that already had one or many linked ATDnet fixes and were counted as ATDnet misses. This indicated the need to flag LIS flashes once the first linked ATDnet fix is found. It was also suggested that the spatial proximity between the LIS flash centroid and ATDnet fixes might not be the best measure for determining linked flashes as the location uncertainties of ATDnet fixes and LIS flashes can be as large as tens of km-s.

The M_{III} method was designed to overcome the shortcomings of the M_{II} method. In case of multiple potentially-linked LIS flashes the times of ATDnet fixes and LIS flashes are used to determine the best match. For each potentially-linked LIS flash the time difference between its start and the time of the corresponding ATDnet fix is computed. The LIS flash closest in time to the ATDnet fix time is linked to the ATDnet fix. Such a method is assumed to perform better than M_{II} as the times of ATDnet fixes and LIS flashes are known much more precisely than their locations.

Once a linked ATDnet fix is found for a LIS flash, the M_{III} method flags the LIS flash as "used" and it can no longer be directly linked to another ATDnet fix. The flagged LIS flash can have another (secondary) linked ATDnet fix only if it is found that the ATDnet fix cannot be the first linked fix for any other LIS flash. This avoids the situation where potentially-linked LIS flashes lose their linked ATDnet fixes to other LIS flashes that already have one or many linked ATDnet fixes. Meanwhile the method retains all possible subsequent return stroke detections as a detected LIS flash can still have multiple linked ATDnet fixes.

The difference between the simplest M_I method and the most sophisticated M_{III} method are demonstrated in Fig. 2.2. It can be seen that, in this case, the M_I method often found more than one LIS-linked flash per ATDnet fix resulting in the total of 11 LIS-linked flashes for six ATDnet fixes. In contrast, the M_{III} method found one LIS-linked flash for each ATDnet fix.

The numbers of LIS-linked flashes computed by the three methods were compared. Numbers of LIS-linked flashes were counted in a 2°x2° grid. Later the grids were compared by computing linked flash ratios between different methods. The following formula was used for computing the linked flash ratios:

$$LFR\% = FC1 / FC2 * 100$$

where LFR is the linked flash ratio and FC1 and FC2 are the flash counts computed by using method 1 and method 2 respectively.

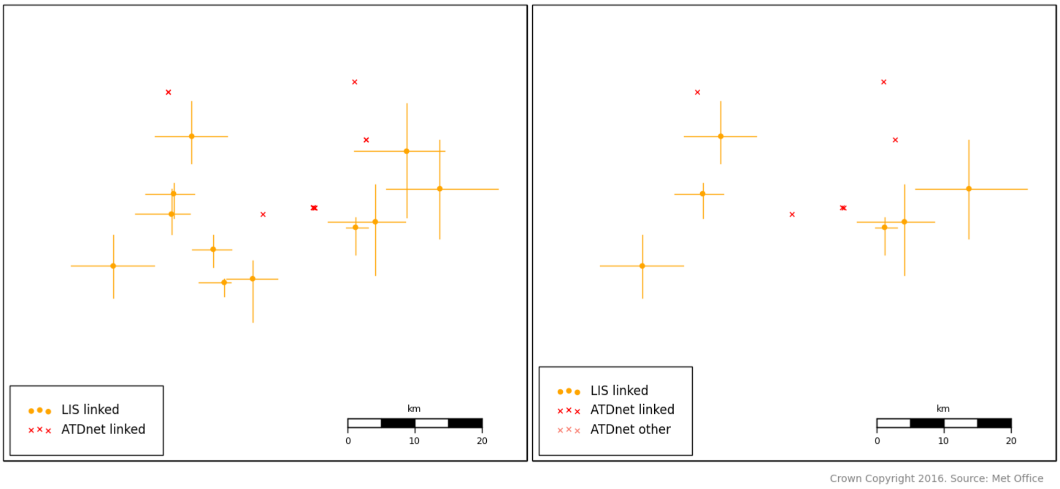

Figure 2.2. Linked LIS flashes and their corresponding ATDnet fixes computed by the M_I method (left) and the M_{III} method (right) for a relatively small and intense storm in Africa (approx. 12°N, 12°E) on 12th July 2014. The orange lines connect the centroids of LIS flashes and the furthest groups north, east, south and west. Note that there are six ATDnet fixes in each figures as two fixes in the centre of the figure almost overlap.

Linked-flash ratio maps for M_{II} and M_{III} relative to M_I are presented in Fig. 2.3. It can be seen that over most of the study area both M_{II} and M_{III} resulted in LFR of about 70-90% relative to M_I. It can also be seen that all over the study area the most sophisticated M_{III} method results in somewhat higher LFR than the M_{II} method.

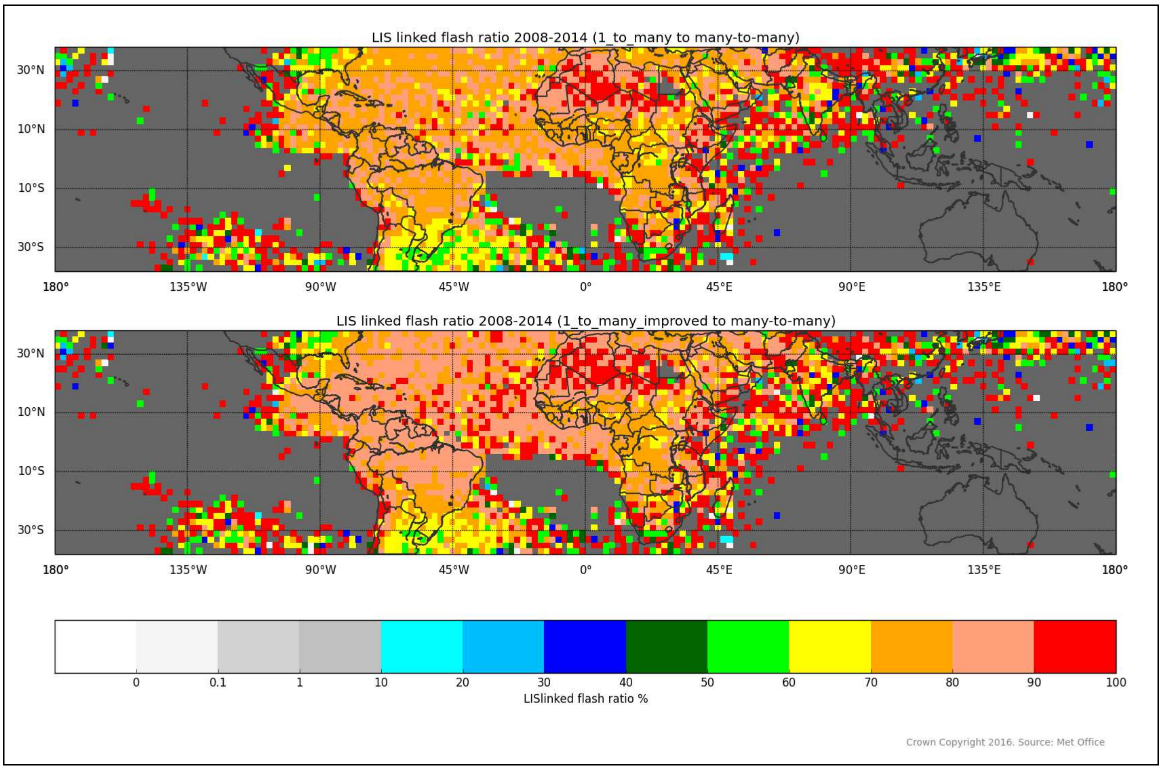

Figure 2.3. LIS 7-year average linked flash ratio for M_{II} (top) and M_{III} (bottom) method relative to M_I methods.

Globally the M_I method resulted in 297 893 LIS-linked flashes during the study period whereas M_{II} and M_{III} resulted in 224 977 and 235 593 linked flashes respectively. M_{II} resulted in 24.5% and M_{III} in 21.0% lower global number of linked flashes compared to the M_I method. It was decided that the M_{III} method is the most accurate and scientifically the most justified method for linking LIS flashes and ATDnet fixes. All the results presented hereafter are based on LIS flashes and ATDnet fixes linked by using the M_{III} method.

3. Global analysis

3.1. ATDnet-relative DE

The 7-year average ATDnet-relative DE map for the whole study area is represented in Fig. 3.1 in two different colour scales. The equal-interval colour scale highlights the spatial pattern of ATDnet-relative DE over areas with relatively high DE such as the Atlantic. The logarithmic colour scale is intended to reveal the spatial variations in ATDnet-relative DE over areas with lower DE like Africa and the Americas.

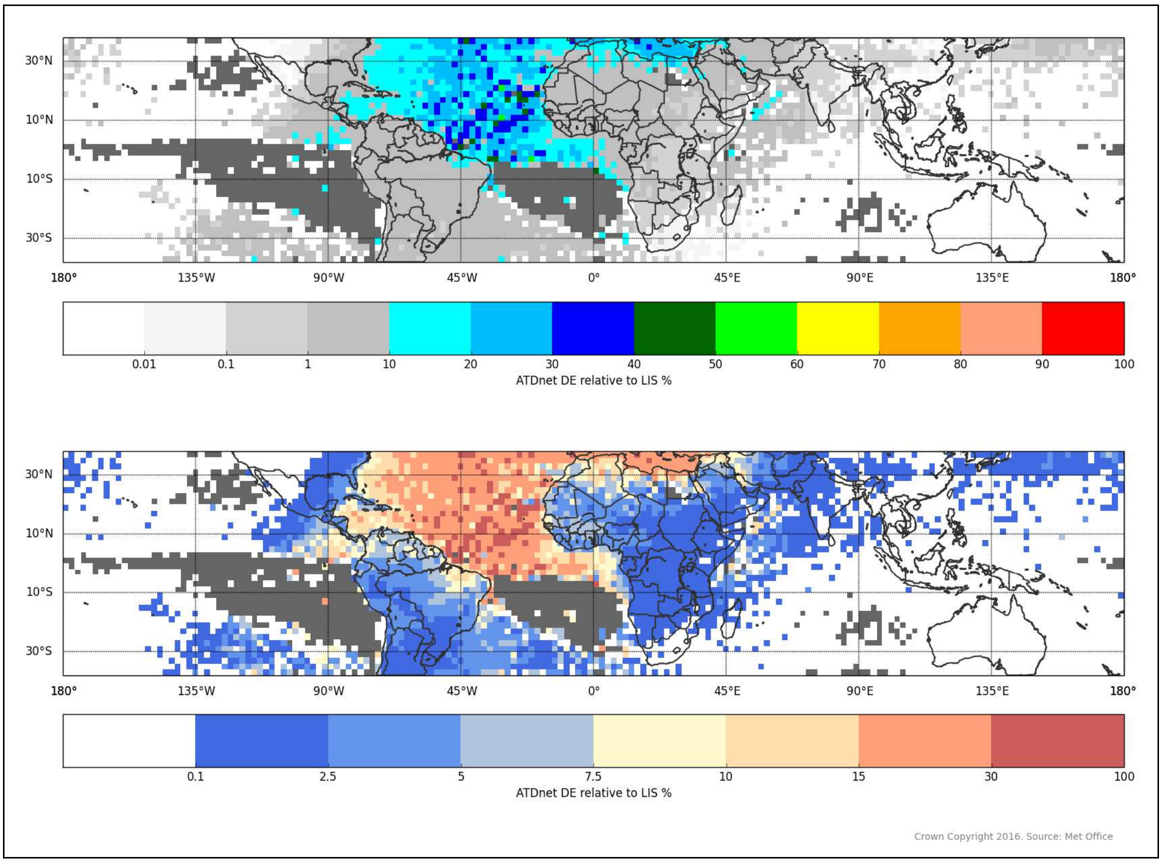

Figure 3.1. ATDnet DE relative to LIS in an equal interval (top) and logarithmic colour scale (bottom). Dark gray areas represent grid cells where ATDnet DE was not computed as there were less than 10 LIS flashes during the study period.

ATDnet performs best over the North Atlantic Ocean and the Mediterranean basin where it is capable of detecting approximately 20-30% of LIS flashes. Note that there are some grid cells with ATDnet-relative DE as high as 50-60% over the North Atlantic. More detailed examination reveals that such grid cells are characterized by very low total numbers of LIS flashes and thus they are not statistically representative. ATDnet-relative DE of around 10% is observed in the Caribbean Sea, northern Africa and the north eastern part of South America. ATDnet also detects some lightning in the rest of Africa and South America, the Middle East, Asia, the eastern seaboard of the US and the Gulf of Mexico. However, its relative DE remains below 10% in those areas and clearly decreases with increasing distance from the European continent due to the increasing length of propagation paths and the poorer location accuracy of the fixes located far away from the ATDnet perimeter.

A clear land and water contrast is visible with higher ATDnet-relative DE values over the Mediterranean basin and the Atlantic Ocean. This is very similar to the performance of WWLLN which is an ATDnet-like long range VLF lightning location system and detects lightning over the oceans approximately three times more efficiently than over land (Rudlosky and Shea 2013). Studies have shown that flashes over the oceans are generally stronger than over land (e.g. Said et al. 2013; Hutchins et al. 2013). Stronger flashes are likely to emit more powerful sferics which are easier to detect. Uniform propagation paths over salty ocean result in weaker waveform attenuation which further contributes to more efficient lightning detection.

3.2. Seasonal changes in ATDnet-relative DE

Seasonal ATDnet-relative DE maps (Fig. 3.2) were plotted to test the idea that ATDnet might be less sensitive to distant lightning in summer as lightning activity over the European continent generates much stronger sferics.

It can be seen that over most of the study area there is no clear seasonal cycle and ATDnet-relative DE values are fairly stable throughout the year. However, the northern part of South America has highest ATDnet-relative DE in winter and spring and lowest in summer. In contrast, exactly the opposite seems to happen over the Caribbean Sea. Thus, it is not clear whether the seasonal relative DE cycle in South America is related to lightning activity over Europe. Alternatively it may reflect changes in lightning properties or variation in the ionosphere characteristics between Europe and South America.

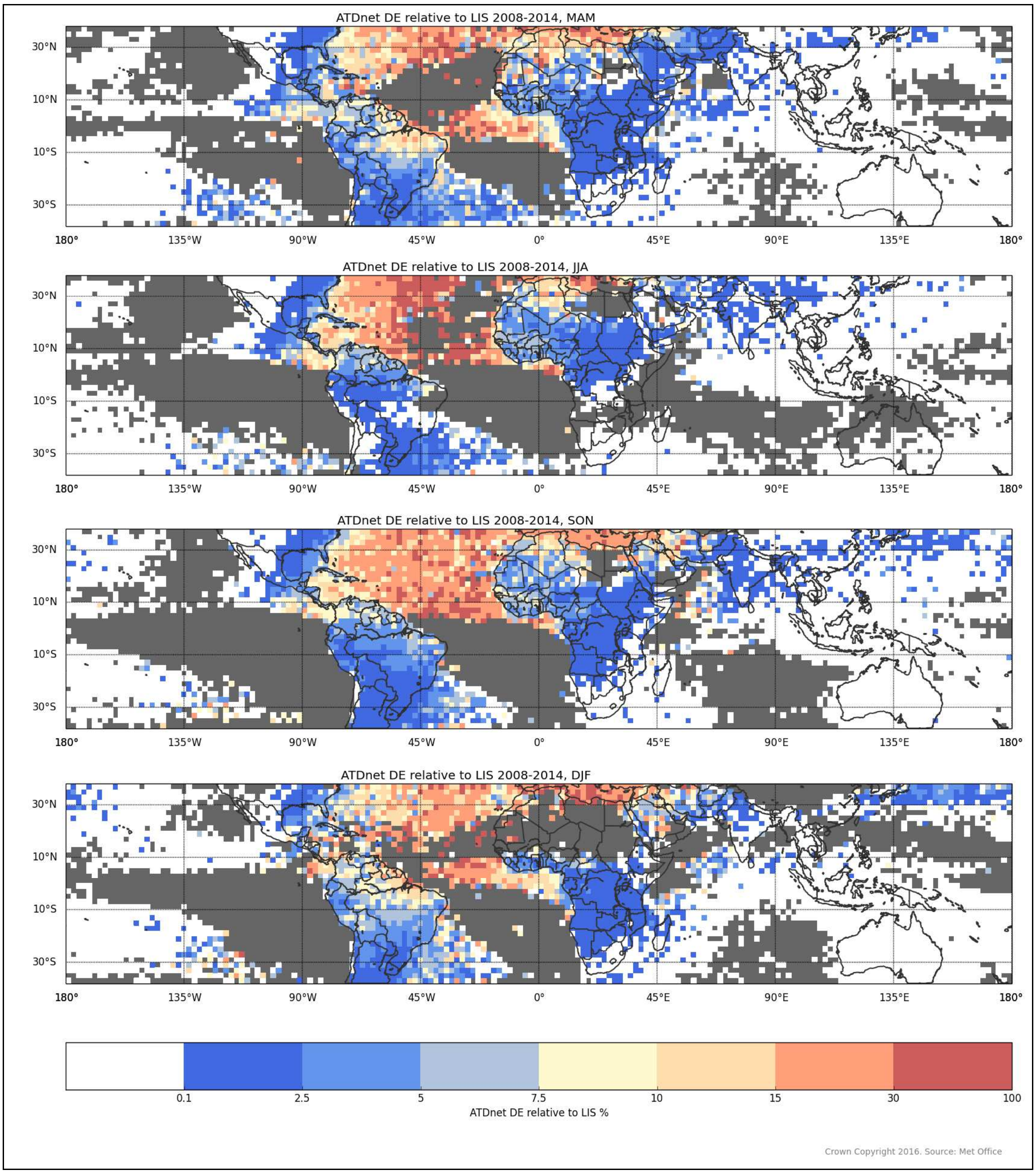

Figure 3.2. ATDnet DE relative to LIS in (1st - top) spring [March, April, May or MAM], (2nd from top) summer [June, July, August or JJA], (3rd) autumn [September, October, November or SON], and (4th - bottom) winter [December, January, February or DJF].

3.3. Inter-annual variability of ATDnet-relative DE

As shown in Figure 3.3, the annual total number of LIS flashes is quite stable between 1.3 and 1.5 x 10^6 flashes per year. ATDnet-relative DE is remarkably lower in 2008 when it is below 1.5%; during 2009-2011, it is around 2.3 to 2.4% whilst the last three years of the study period are characterized by the highest ATDnet-relative DE of around 2.7 to 2.8%.

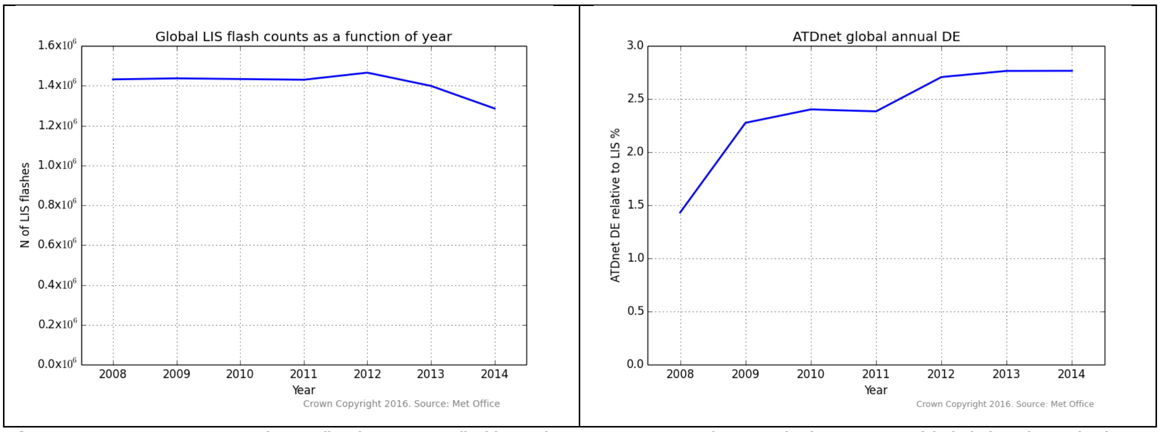

Figure 3.3. Annual LIS flash counts (left) and ATDnet annual DE relative to LIS (right) for the whole study area 2008-2014.

Further yearly ATDnet-relative DE maps are enclosed in Appendix 1; these show that lower ATDnet-relative DE values in 2008 are accentuated over South America. Over the following years, DE values over South America improves; this could be related to the change to ATDnet group velocity introduced at the beginning of 2009: before the change ATDnet suffered much larger northeast to southwest oriented location errors over South America. Thus, it is possible that many ATDnet fixes detected over South America during 2008 are not linked to any LIS flashes due to the large location errors.

3.4. LIS flash characteristics and ATDnet-relative DE

The impact of eight different LIS flash characteristics (Table 2.1) on ATDnet-relative DE was examined. Figures 3.4-3.11 represent LIS flash histograms and ATDnet-relative DE graphs for all the LIS flash characteristics. Note that different bin sizes are used for different characteristics. Maximum value of the y-axis is the same for all relative DE plots (25%) to enable cross-comparison.

All the LIS histograms exhibit strongly right skewed distributions with their standard deviation usually greater than their mean. All the histogram plots are truncated below the maximum value of the particular characteristic considered in order to better show the low end of the distribution where the sample size is largest. For all the ATDnet-relative DE plots, a threshold of 100-flash minimum per bin is used to avoid unreliable results caused by small samples. However, it is still clearly visible that the relative DE data gets increasingly noisier with the diminishing number of LIS flashes as is the case towards higher values of the x-axis.

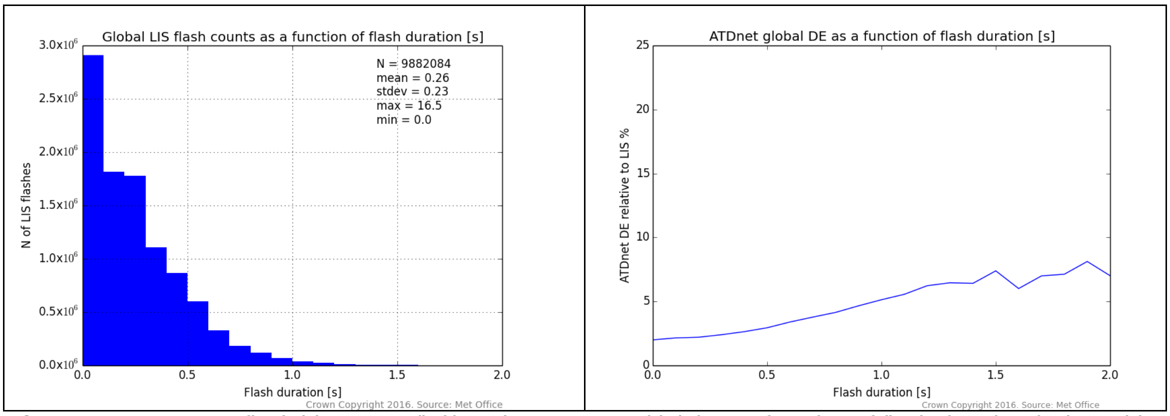

Figure 3.4. LIS flash histogram (left) and ATDnet DE (right) as a function of flash duration (using a bin size of 0.1).

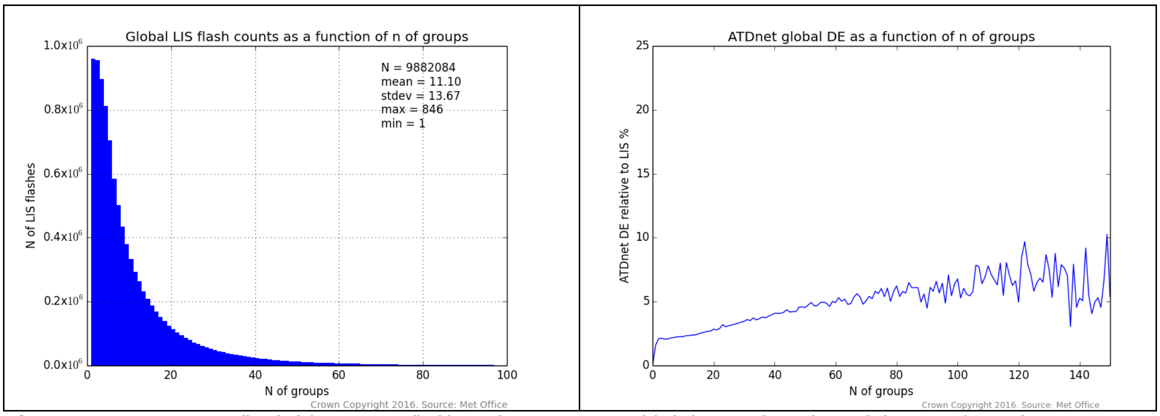

Figure 3.5. LIS flash histogram (left) and ATDnet DE (right) as a function of the number of groups per LIS flash (using a bin size of 1).

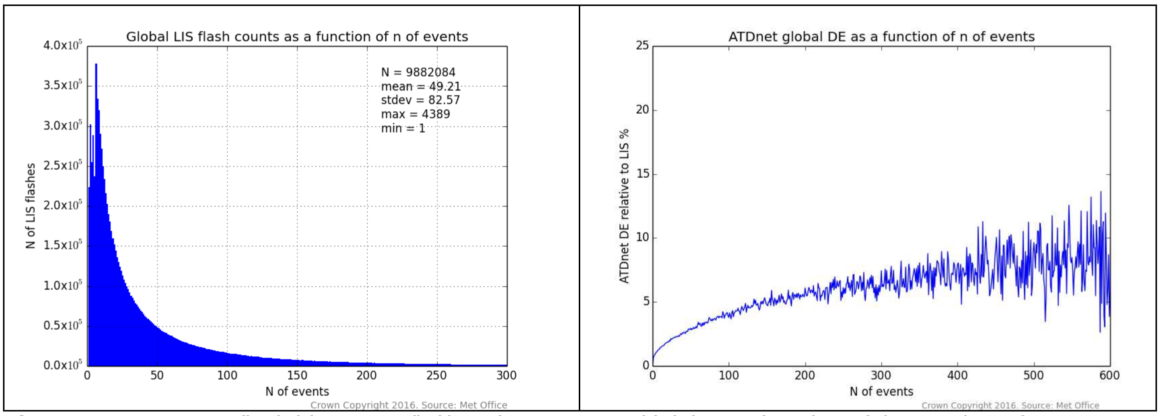

Figure 3.6. LIS flash histogram (left) and ATDnet DE (right) as a function of the number of events per LIS flash (using a bin size of 1).

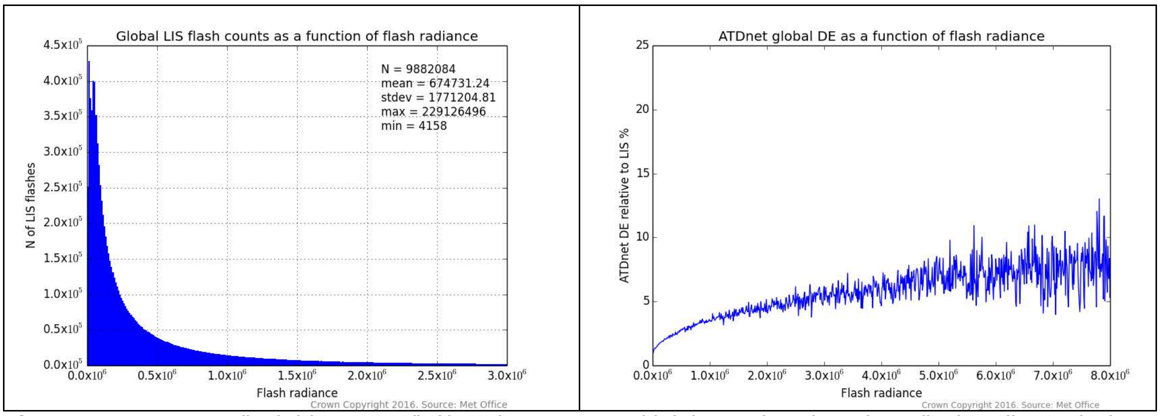

Figure 3.7. LIS flash histogram (left) and ATDnet DE (right) as a function of LIS flash radiance (using a bin size of 10 000).

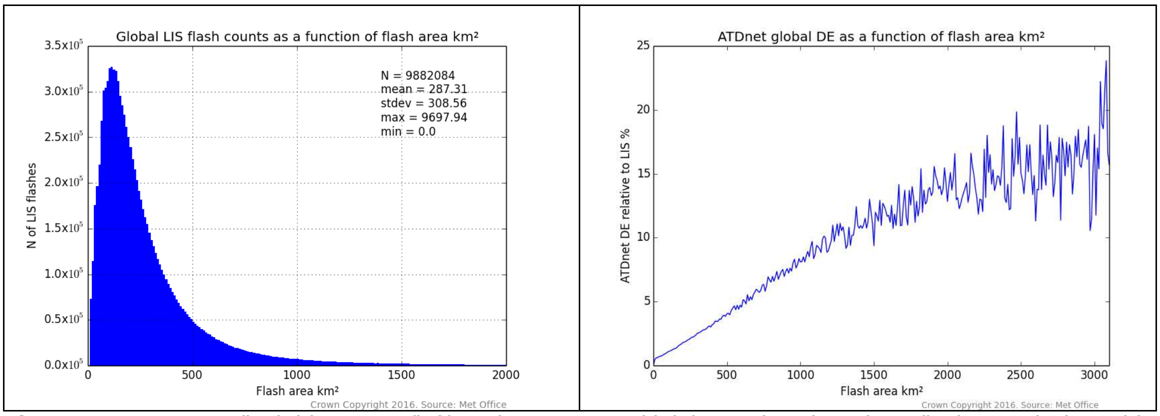

Figure 3.8. LIS flash histogram (left) and ATDnet DE (right) as a function of LIS flash area (using a bin size of 10).

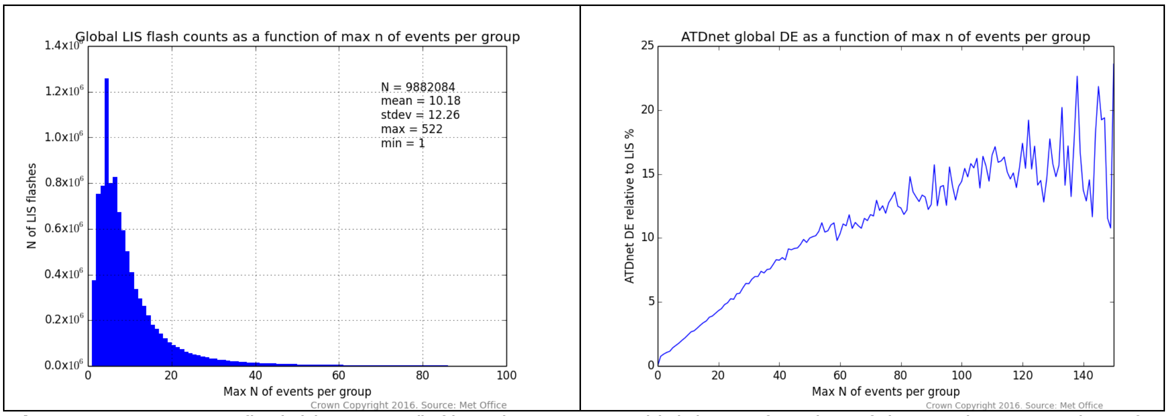

Figure 3.9. LIS flash histogram (left) and ATDnet DE (right) as a function of the maximum number of events per group (using a bin size of 1).

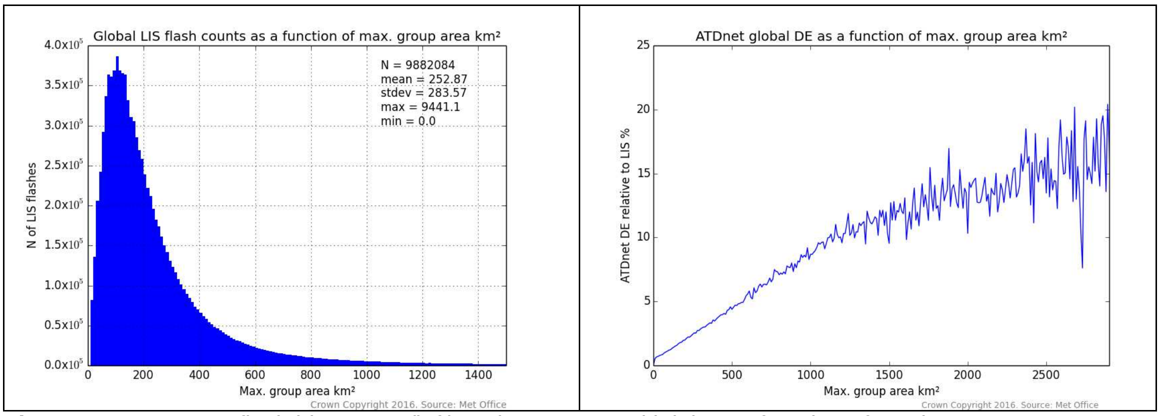

Figure 3.10. LIS flash histogram (left) and ATDnet DE (right) as a function of maximum group area (using a bin size of 10).

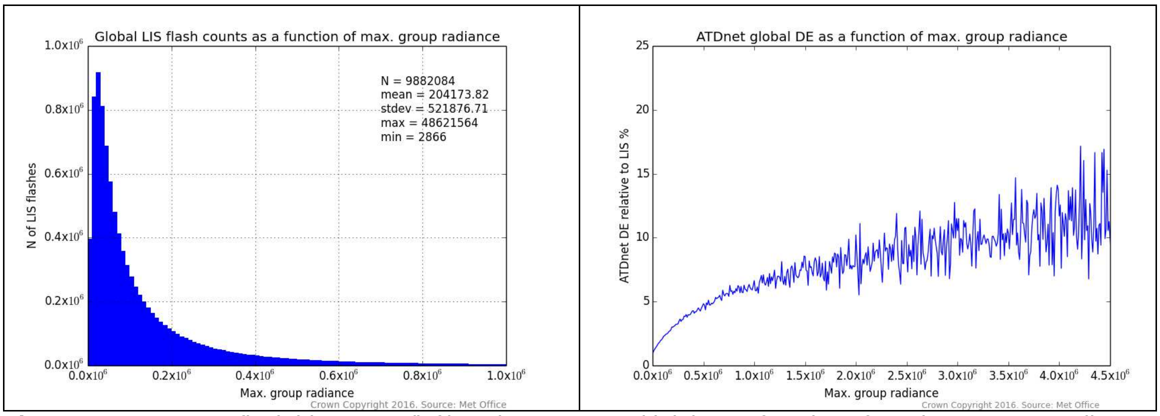

Figure 3.11. LIS flash histogram (left) and ATDnet DE (right) as a function of maximum group radiance (using a bin size of 10 000).

The results revealed a positive relationship between the values of all the LIS characteristics and ATDnet-relative DE, i.e. brighter flashes with larger area, longer duration and greater number of groups and events were generally detected more frequently by ATDnet. It was found that flash area, maximum group area and maximum number of events per group had stronger impact on ATDnet-relative DE. ATDnet-relative DE values of 15-20% correspond to high values of those flash characteristics. In contrast flash duration, the number of groups and events per flash as well as flash radiance and maximum group radiance had a smaller impact on ATDnet-relative DE which was only 5-10% even if the values of those parameters were high.

These findings are in line with the observation that maximum group area (MGA) and maximum number of events per group (MNEG) are the two LIS flash characteristics most suitable for discriminating between CGs and ICs (Koshak 2010). Thus, it can be assumed that the fraction of CG increases towards higher values of MNEG and MGA and so does the ATDnet-relative DE because the system is designed to locate CG return strokes. Large group and flash size might also compensate for ATDnet location errors.

The overall logarithmic shape of the DE graphs is likely related to the fact the global LIS dataset was used whereas ATDnet is a regional LLS. Thus, there are areas outside the range of ATDnet where even the strongest flashes are unlikely to be detected. It might also indicate that the method of matching LIS flashes and ATDnet fixes does not find all potential pairs, e.g. the search radius of 25 km might be too small compared to ATDnet location errors in some parts of the study area.

The characteristics of LIS-linked and LIS-not-linked flashes are compared (Table 3.1). Results show that the mean values of all eight LIS flash characteristics are significantly lower for not-linked flashes (P<<0.01). P values are computed by using the two-sided Welch's t-test (Welch 1947), which does not assume equal population variance.

Table 3.1. The mean values and variances of the studied LIS flash characteristics for LIS-linked and LIS not linked flashes.

	LIS-linked (N=235593)		LIS not linked (N=9646491)		P
	average	variance	average	variance	
DELTA	0.31	0.080	0.25	0.054	0.00
NG	14.9	348.1	11.0	182.7	0.00
NE	93.7	16985.8	48.1	6520.3	0.00
RAD	1524608.3	1.03E+13	653975.0	2.94E+12	0.00
AREA	560.0	319502.3	280.7	87869.2	0.00
MNEG	20.2	540.0	9.9	138.3	0.00
MGA	490.6	275459.5	247.1	74232.3	0.00
MGRAD	495075.7	1.15E+12	197069.2	2.49E+11	0.00

3.5. Number of ATDnet fixes per detected LIS flash

There are 235 593 linked LIS flashes and 288 663 linked ATDnet fixes in the study area during 2008-2014. The average number of ATDnet fixes per detected LIS flash is 1.23. Nearly 85% of the LIS flashes have only one linked ATDnet fix and approximately 10% have two linked fixes (Fig. 3.12). Approximately 0.65% of all linked LIS flashes (4002 flashes) have more than four linked ATDnet fixes.

The spatial distribution of the number of ATDnet fixes per LIS-linked flash is shown in the Fig. 3.13. Note that a threshold of 10 LIS-linked flashes per grid cell was applied and all cells with less than 10 flashes are shown in gray.

There are clearly more ATDnet fixes per detected LIS flash over water than over land which is similar to higher ATDnet-relative DE over the Atlantic Ocean and the Mediterranean basin (Fig. 3.1). This is likely related to the same factors that lead to higher DE in those areas. As flashes over the oceans are stronger it can be expected that they have more return strokes and thus higher probability of triggering multiple ATDnet fixes. Higher air conductivity over salty water increases the probability that sferics from subsequent weaker return strokes are still detectable at great distances.

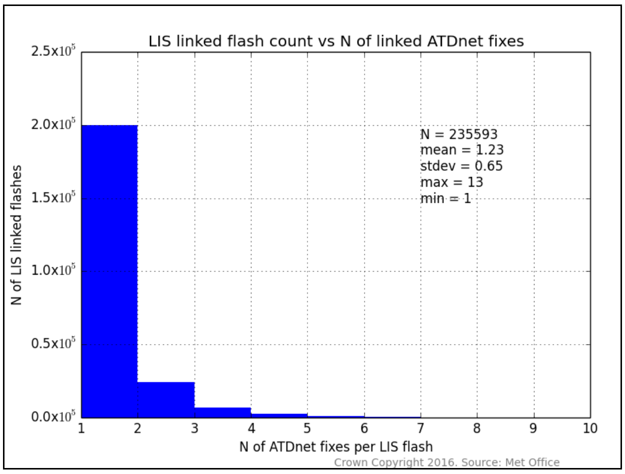

Figure 3.12. Distribution of detected LIS flashes as a function of the number of linked ATDnet fixes per flash.

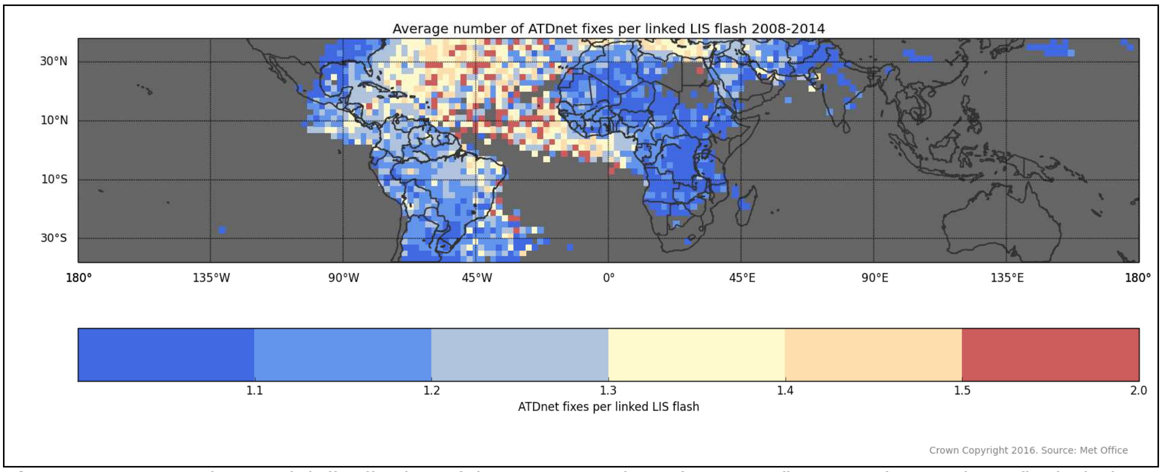

Figure 3.13. The spatial distribution of the mean number of ATDnet fixes per detected LIS flash during 2008-2014.

3.6. Time distribution of linked ATDnet fixes

Times of linked ATDnet fixes are compared with the start times of the corresponding LIS flashes. The results reveal that the majority of linked ATDnet fixes occur close to the start time of the corresponding LIS flash (Fig. 3.14). Furthermore, 56.7% of all ATDnet-linked fixes are concentrated in the -0.1 to 0.1 sec time window from LIS flash start time. The analysis with 1 ms time bins shows that the maximum in the distribution of ATDnet-linked fixes is located at 1-2 ms before LIS flash start time and that 25.5% of all ATDnet-linked fixes occur within 3 ms before LIS flash start time.

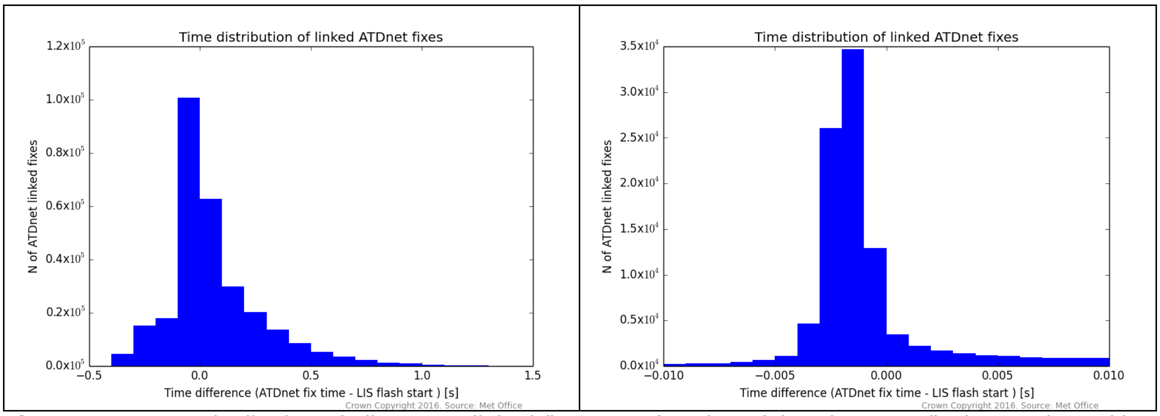

Figure 3.14. Distribution of all ATDnet-linked fixes as a function of time from LIS flash start time with a bin size of 0.1 s (left) and the same zoomed for the time window of -0.01 to 0.01 s from LIS flash start time with a bin size of 1 ms (right). Note the different y-axis extent of the two subplots.

The time distribution of first and secondary ATDnet-linked fixes within the LIS flash duration are shown and compared in Table 3.2. Both distributions appear to peak at 1-2 ms before their corresponding LIS flash start time using a timing bin size of 1 ms.

Table 3.2. Characteristics of time distribution of all, first and subsequent ATDnet-linked fixes.

	All	First	Secondary
Total N	288663	235593	53070
% before LIS flash start	48.0	51.1	34.0
% after LIS flash start	52.0	48.9	66.0
Max. time bin (bin size = 1 ms)	-1...-2 ms	-1...-2 ms	-1...-2 ms
% in 3 ms before LIS flash start	25.5	27.4	17.1
% in 3 ms after LIS flash start	2.6	2.8	1.6

Figure 3.15 shows both distributions using a coarser timing bin size of 100 ms: this figure reveals that the timing of the secondary ATDnet-linked fixes is more prominent within 100 ms after LIS flash start time than within 100 ms before LIS flash start time. It can be also seen that slightly more than half of all first ATDnet-linked fixes occur before the start of the LIS flash as opposed to only about third for the secondary ATDnet-linked fixes (Table 3.2). Further detailed examination show that there is a small subsidiary maximum in the frequency of secondary ATDnet-linked fixes at approximately 40-60 ms after LIS flash start.

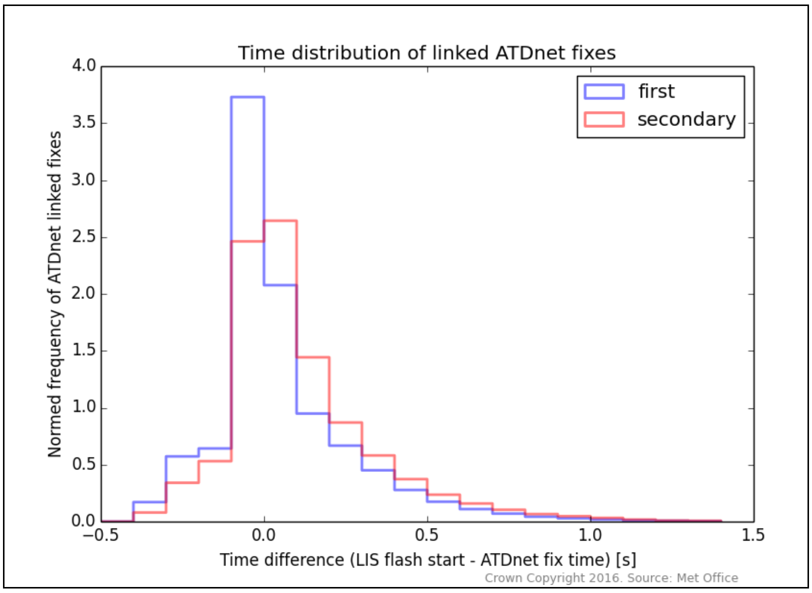

Figure 3.15. Normalised frequencies of first and secondary ATDnet-linked fixes as a function of time from the beginning of LIS flashes (bin size = 100 ms).

Those findings imply that a LIS flash start time often corresponds to the detection of an initial breakdown. An initial breakdown is a powerful process within clouds at the beginning of IC and CG (Nag et al. 2009) and thus its optical emission should be detected by LIS. Furthermore, ATDnet was demonstrated to be sensitive to initial breakdown sferics (Enno et al. 2016a).

The fact that ATDnet fixes often precede LIS flashes by 1-2 ms is very interesting although there is no general consensus on the reason of this time delay. A similar time delay between strokes detected by ground based LLS and the start of the LIS flash was previously reported by Franklin (2013) and Zhang et al. (2016).

The differences in the distribution of first and secondary ATDnet-linked fixes are relatively small and do not give much information. It can be assumed that higher fraction of secondary fixes correspond to cloud-to-ground return strokes which develop after the initial breakdown. However, there is also a remarkable fraction of secondary ATDnet-linked fixes detected within a few ms before LIS flash start. In such cases it is interesting why there is at least one ATDnet fix even earlier. It is possible that the earlier ATDnet fix is wrongly linked to the particular LIS flash in those cases or that LIS has missed the actual start of the flash for some reason.

4. Regional analysis

4.1. Regional characteristics of ATDnet-relative DE

LIS and ATDnet observations are compared over five regions (details given in Table 4.1 and Fig. 4.1). These regions were selected for their location at different distances from ATDnet sensors.

Table 4.1. Characteristics of areas used in regional analysis.

	Latitude	Longitude	LIS-linked	LIS total	ATDnet DE
Mediterranean [MED]	38°N - 30°N	8°W - 36°E	29558	171769	17.2
East Atlantic [EAT]	38°N - 0°N	48°W - 18°W	11885	52846	22.5
West Atlantic [WAT]	38°N - 12°N	76°W - 48°W	26489	203209	13.0
South Atlantic [SAT]	0°S - 38°S	36°W - 10°E	2892	56384	5.1
South America [SAM]	6°N - 16°S	78°W - 40°W	36287	744570	4.9

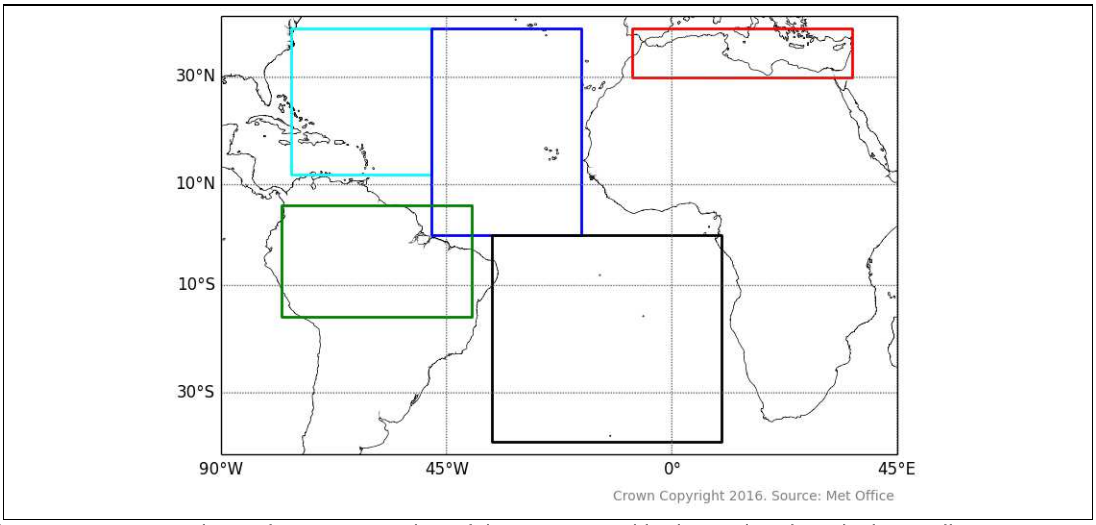

Figure 4.1. Schematic representation of the areas used in the regional analysis: Mediterranean Basin or MED (red), East Atlantic Ocean or EAT (blue), West Atlantic Ocean or WAT (aqua), South Atlantic Ocean or SAT (black), and South American or SAM (green).

The East Atlantic Oceanic region is characterized by the highest ATDnet-relative DE of 22.5% whereas ATDnet only detected approximately 5% of LIS flashes over the most distant regions, such as the South America and the South Atlantic Ocean. The most surprising finding is that ATDnet-relative DE in the MED region is approximately 5% lower than in the EAT region although the MED region is closer to ATDnet sensors in Europe. More detailed examination reveals that the difference is most likely related to the presence of large land areas of northern Africa in the western part of the study area.

On the basis of LIS statistics published by Beirle et al. (2014) there is an abrupt change in LIS flash properties along the southern coast of the Mediterranean with much weaker flashes and probably greater fraction of IC over northern Africa.

To check this assumption, the MED region is divided into a western and an eastern part along 10°E so that the western part is mostly land whereas the eastern part is mostly sea. The total number of LIS flashes during the study period is 85 265 in the western part and 86 504 in the eastern part of the region. ATDnet-relative DE is only 11.9% in the western part but 22.4% in the eastern part of the area. Given that the eastern part of the MED region also encompasses some land and that the northern part of the Mediterranean basin could not be studied due to LIS limitations it can be assumed that over the Mediterranean Sea ATDnet performs slightly better than over the East Atlantic Ocean. However, as the MED is the smallest region in this study, it was decided to preserve the original bounds given in Table 4.1 throughout the rest of the study. Nevertheless, its unique land/sea relative DE contrast is considered where relevant.

The number of LIS flashes per year and ATDnet-relative DE percentage values per year are shown in Fig. 4.2 for each of the regions selected for this study. South America is by far the most active region with approximately 100 thousand LIS flashes annually. The West Atlantic Ocean and the Mediterranean Basin both have around 20-30 thousand LIS flashes annually whereas the East Atlantic Ocean and the South Atlantic Ocean have approximately 10 thousand LIS flashes annually over the study period.

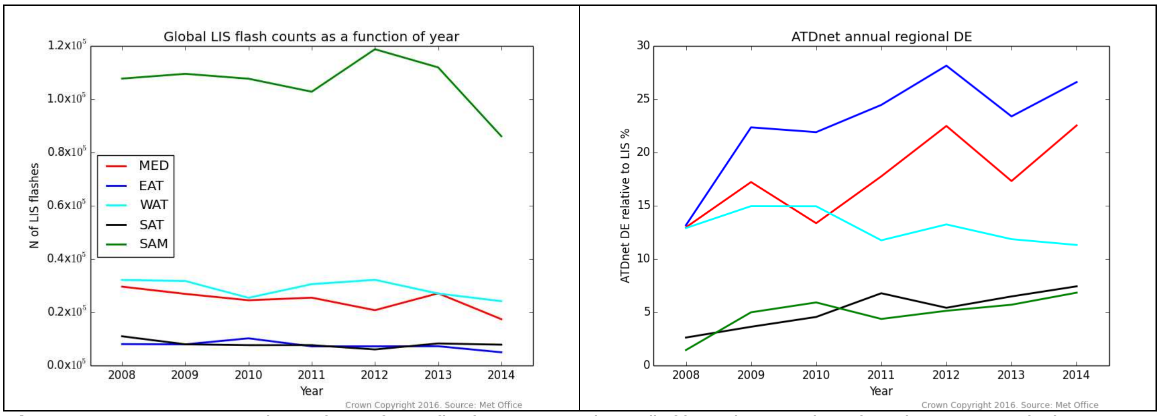

Figure 4.2. Annual number of LIS flashes per regions (left) and annual regional ATDnet-relative DE (right).

ATDnet-relative DE shows gradual increase throughout the study period in four out of the five regions, with the exception of the West Atlantic Ocean where ATDnet-relative DE slightly decreases towards the end of the study period. This unexpected behaviour could be related to the fact that one of the westernmost ATDnet sensors in Valentia, Ireland, was out of order from 2012 to 2015. It is likely that Valentia is one of the most important contributors to ATDnet detections near the western edge of the ATDnet spatial range and thus its outage is expected to result in decreased DE in those areas.

Figure 4.3 shows ATDnet regional relative DE as a function of different LIS flash properties. In all the studied regions, flash area, maximum group area and maximum number of events per group are the LIS flash characteristics with the highest impact on ATDnet-relative DE. It can be seen that in MED, EAT and WAT regions 35-45% of LIS flashes with a large maximum number of events per group are detected by ATDnet. Even as far as South America ATDnet is capable of detecting 25-35% of such flashes. This is in line with the finding by Bennett et al. (2010) that ATDnet-relative DE for return strokes with high peak current does not differ significantly between Finland and Brazil.

It is interesting that weaker flashes in the MED region are detected less efficiently than weak flashes in the EAT regions whereas the difference diminishes towards strong LIS flashes. The difference might be due to the fact that propagation paths between northern Africa and ATDnet sensors are mostly over land and thus characterized by higher attenuation. Similarly, LIS flashes in the oceanic SAT region are detected slightly more efficiently than LIS flashes in the continental SAM region.

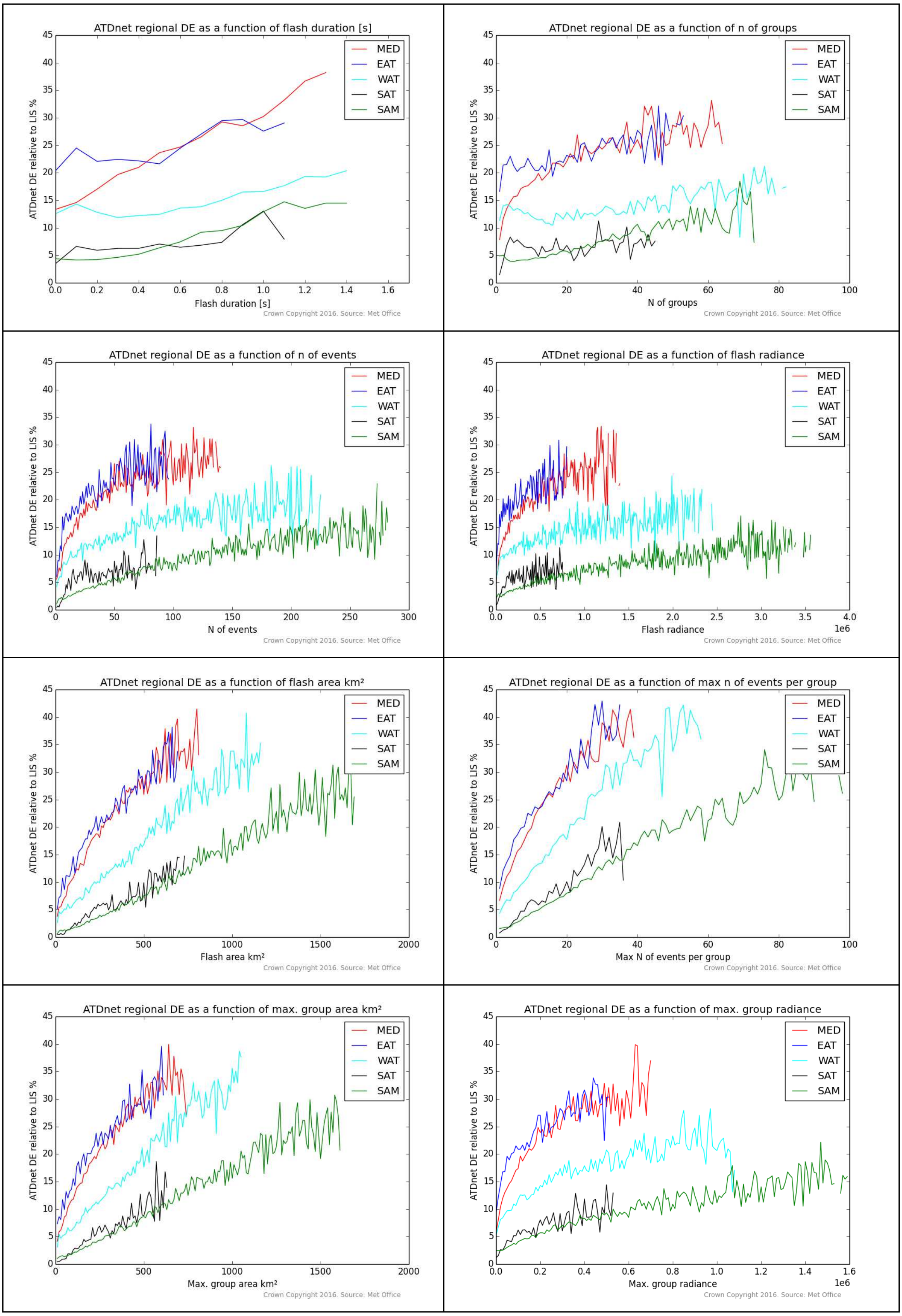

Figure 4.3. ATDnet regional relative DE as a function of different LIS flash properties. Note that a 100 LIS flashes per bin threshold was used in DE calculations.

4.2. Diurnal changes in ATDnet DE

Diurnal changes in ATDnet-relative DE are studied in all the five regions. Firstly, the diurnal distribution of all LIS flashes is examined (Fig. 4.4).

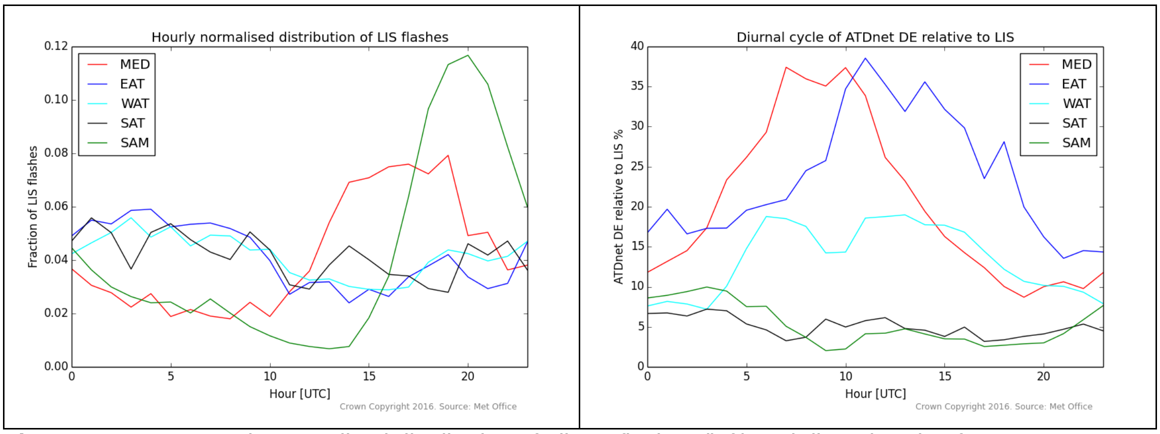

Figure 4.4. Hourly normalised distribution of all LIS flashes (left) and diurnal cycle of ATDnet DE relative to LIS (right).

The strongest diurnal cycle emerge over South America which is in line with the fact that it is the only major land region in the study. An afternoon peak is also clearly visible in the Mediterranean basin because the region encompasses significant land areas in northern Africa. The three regions over the Atlantic Ocean show no remarkable diurnal cycle in LIS flash frequency. The weak maximum between 00 and 10 UTC is probably related to the fact that LIS itself detects lightning more efficiently at night.

All five regions show diurnal changes in ATDnet-relative DE (Fig. 4.4). There are remarkable differences in the temporal behaviour of ATDnet-relative DE in individual regions. The three closest regions to ATDnet sensors (MED, EAT and WAT) all exhibit a night-time minimum with the lowest relative DE approximately between 18 and 05 UTC. This might be attributable to modal interference that results in distorted waveforms and makes waveform correlation harder for the ATDnet central processing. It should also be taken into account that LIS DE is estimated to be about 20% higher at night (Boccippio et al. 2002). Flashes with weaker optical signal detected by LIS only in darkness are likely to have lower peak currents and weaker sferics making them harder to detect for ATDnet. The highest ATDnet-relative DE in the three closest regions generally occurs during daytime when the impact of modal interference is much smaller and LIS DE is lower. However, the Mediterranean region shows somewhat different maximum.

Over the Mediterranean region ATDnet-relative DE increases during local morning hours but starts to decrease around 10 UTC. This is likely related to the changes in the diurnal fraction of stronger flashes over the Mediterranean Sea and weaker flashes over northern Africa. This is confirmed by the observation that lightning activity in the MED region is dominated by flashes over the sea during night and morning hours. The situation changes at around 12 UTC where the MED region becomes dominated by lightning over northern Africa for the rest of the afternoon. As flashes over northern Africa are weaker it can be expected that they have adverse effect on ATDnet-relative DE. Note that high lightning activity over northern Africa occurs mainly in summer. It can be demonstrated that the corresponding odd behaviour of ATDnet diurnal relative DE graph is characteristic to summer and not present in winter (Fig. 4.5).

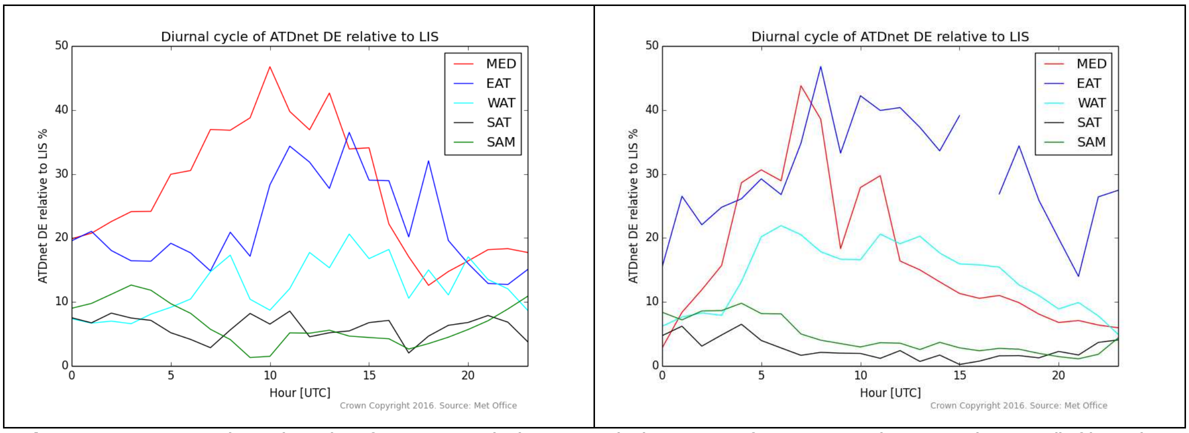

Figure 4.5. Diurnal cycle of ATDnet-relative DE relative to LIS from November to February (left) and May to August (right). Note that the interruption in the May to August graph for EAT is due to there being fewer than a 100 flashes per time bin.

5. Case studies

5.1. Selection of cases

Firstly, daily numbers of linked and all LIS flashes and ATDnet-relative DEs were computed for all regions. Secondly all days were sorted into descending order of daily total number of LIS flashes by region. Interesting days were then selected visually from days with high total number of LIS flashes as their DE values are statistically more reliable. Several days with very low DE emerged in 2008; these were avoided for case studies as they were likely related to the latest major ATDnet upgrade that happened around that time. It is likely that some of the ATDnet outstations were temporarily out of service and the exact times of such outages are unknown. Thus, low DE cases in 2008 are most certainly not representative of the current ATDnet system.

Cases were selected so that the closest and the most distant regions are both represented. Storms were also selected based on their overall spatial pattern (i.e. approximately similar to one another) in order to avoid DE differences due to storms at different distances from ATDnet sensors. Two cases with remarkably high and two cases with remarkably low ATDnet-relative DE were chosen from both the MED and EAT regions. In addition one case with high and one with low ATDnet-relative DE was selected from the SAT and SAM regions.

5.2. The Mediterranean Basin region

For the first case study, 23rd July 2012 and 18th April 2010 are compared (Fig. 5.1 and Table 5.1). Both days had 685 LIS flashes from which ATDnet detected 33.4% and 3.9% of these LIS flashes, on each respective day. For the second case study, 26th October 2008 and 24th October 2010 are compared (Fig. 5.2 and Table 5.1). The days had 488 and 483 LIS flashes in the MED region, respectively. The corresponding ATDnet DE values are 54.5% and 3.5%.

In both cases the most successfully detected storms by ATDnet were characterized by longer and brighter LIS flashes. In addition, the most successfully detected storm also had many more groups and events per flash during the second study. Conversely, the maximum number of events per group was higher in the least successfully detected storms for both case studies. The same is true for the flash and group area (AREA and

MGA) metrics in the first case study. It can also be seen that LIS always observed the least successfully detected storms at night whereas the most successfully detected storms are observed during daytime overpasses.

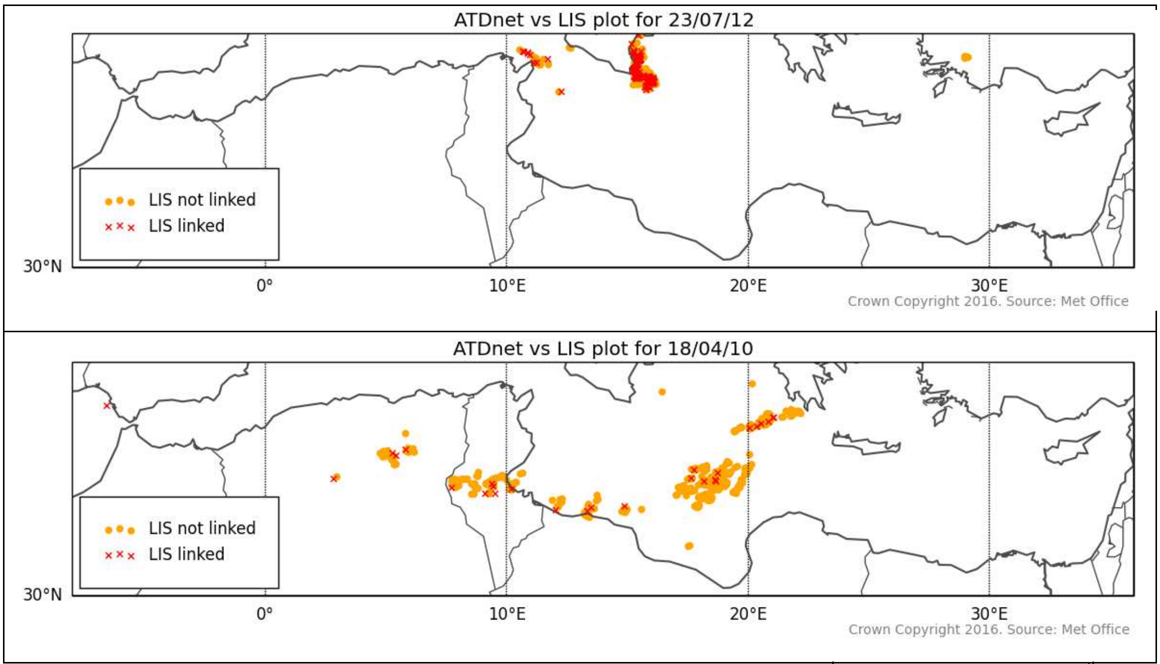

Figure 5.1. LIS-linked and not linked flashes in the MED region on 23rd July 2012 (top) and 18th April 2010 (bottom).

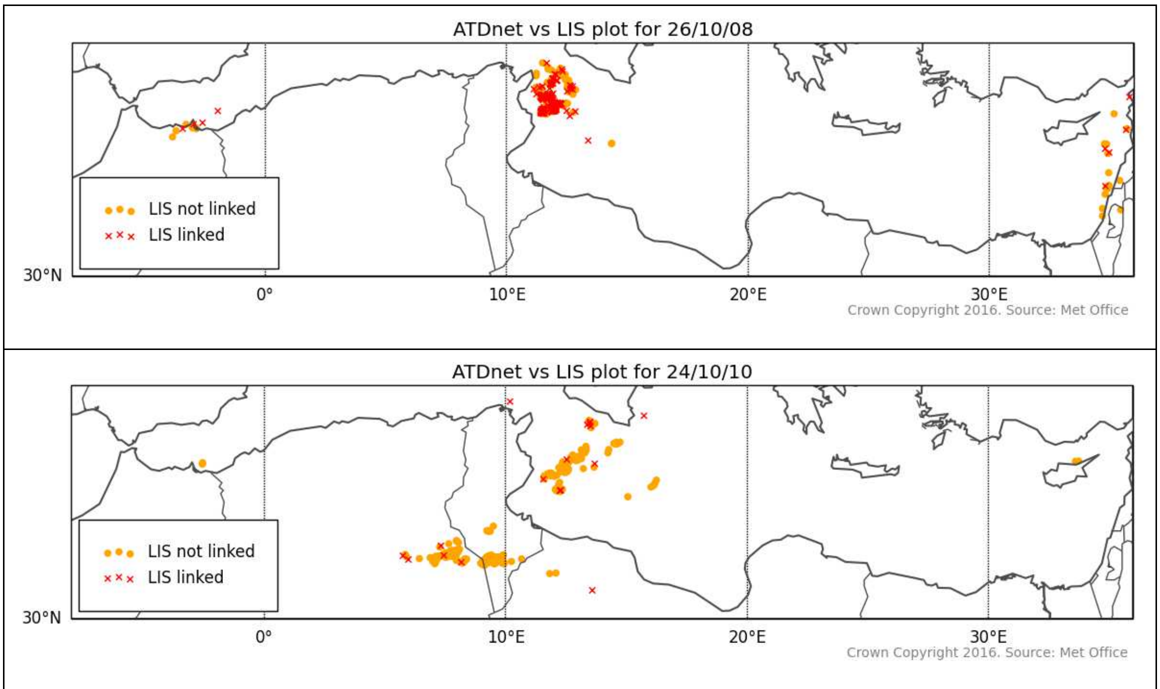

Figure 5.2. LIS-linked and not linked flashes in the MED region on 26th October 2008 (top) and 24th October 2010 (bottom).

Table 5.1. Details of the case studies in the MED region. Average values of LIS flash characteristics and statistical significance of the differences between compared cases (P) are given.

	Case study 1			Case study 2		
	23/07/2012	18/04/2010	P	26/10/2008	24/10/2010	P
N of LIS flashes	685	685		488	483	
ATDnet DE	33.4%	3.9%		54.5%	3.5%	
LIS overpass times	11:41-11:43 13:19-13:21	00:28-00:32 21:58-22:00 23:36-23:38		07:53-07:55 09:30-09:32	00:49-00:52 02:26-02:29 22:17-22:19 23:54-23:57	
DELTA	0.40	0.27	0.00	0.50	0.24	0.00
NG	13.93	11.01	0.01	27.35	9.16	0.00
NE	32.85	43.78	0.00	83.80	40.76	0.00
RAD	660886.36	389099.64	0.00	1539348.75	409900.08	0.00
AREA	192.32	220.91	0.00	282.93	265.87	0.24
MNEG	4.65	8.51	0.00	7.55	9.06	0.00
MGA	156.26	185.91	0.00	213.42	234.55	0.07
MGRAD	148482.25	108103.53	0.00	258806.79	113263.94	0.00

There were no known ATDnet hardware or software issues that could account for the low relative DE observed on 18th April 2010 and 24th October 2010.

5.3. The East Atlantic Ocean region

For the first case study, 11th March 2009 and 2nd December 2010 were compared (Fig. 5.3, Table 5.2). The first day had 252 and the second day had 234 LIS flashes with the corresponding ATDnet-relative DE values of 38.1% and 9.8%, respectively. For the second study, 26th August and 7th December 2010 were compared (Fig. 5.4 and Table 5.2). Both days had 113 LIS flashes in the EAT region but ATDnet detected 62.8% of LIS flashes on 26th August and only 6.2% LIS flashes on 7th December 2010.

For the first case study, the flash radiance parameters (RAD and MGRAD) were significantly higher in the storm with higher ATDnet-relative DE. For the second case study, all flash characteristics showed significantly higher values in the storm that was most successfully detected by ATDnet. It can be seen that flashes on 26th August 2010 had more than twice as many groups and events as the flashes detected on 7th December 2010. In both cases the storm with higher ATDnet-relative DE involved only or mostly LIS daytime overpasses whereas the flashes of the least successfully detected storm were mostly observed during local night-time.

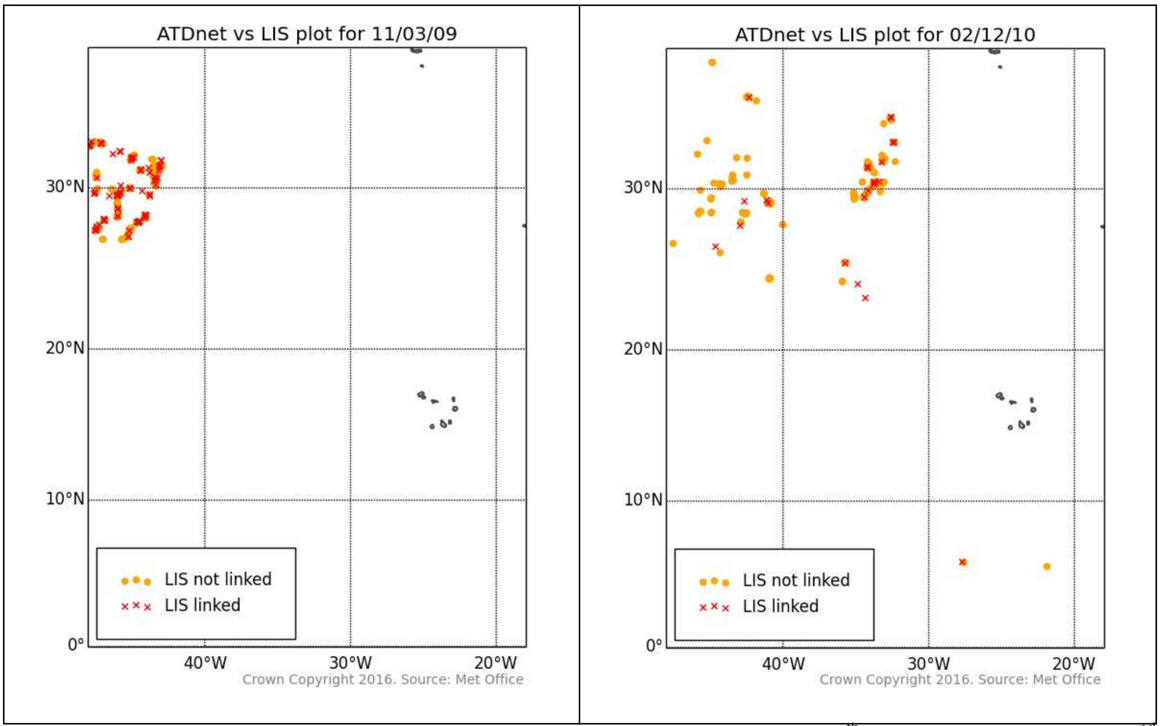

Figure 5.3. LIS-linked and not linked flashes in the EAT region on 11th March 2009 (left) and 2nd December 2010 (right).

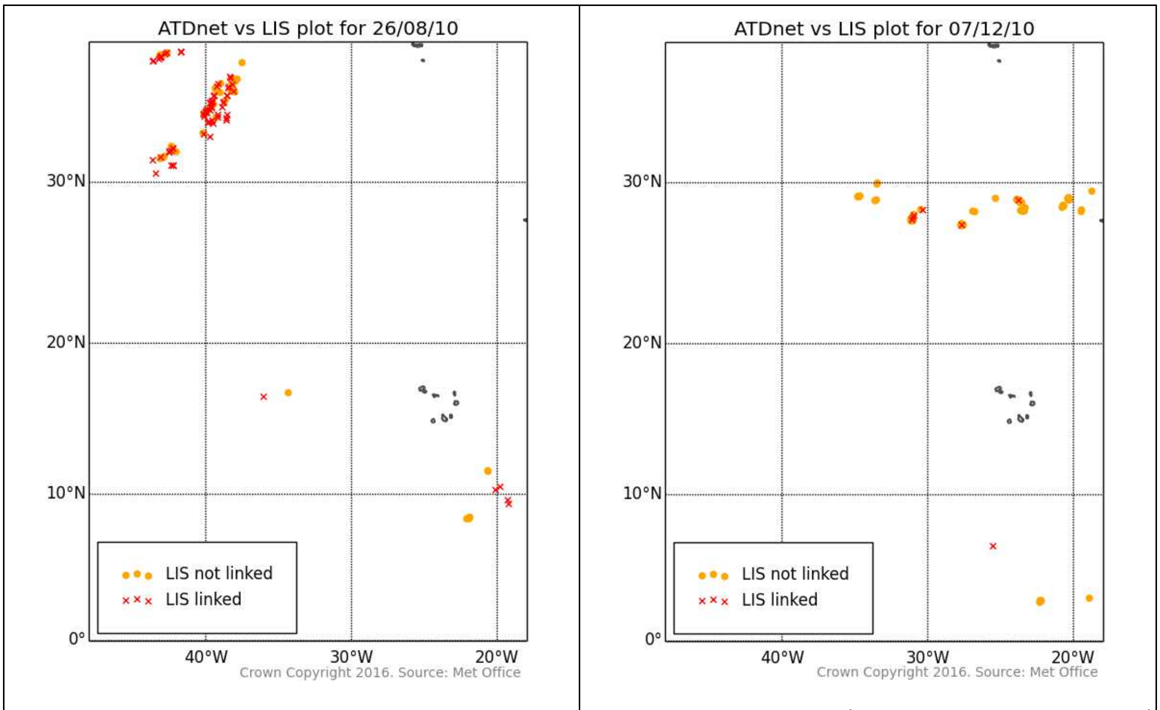

Figure 5.4. LIS-linked and not linked flashes in the EAT region on 26th August 2010 (left) and 7th December 2010 (right).

Table 5.2. Details of the case studies in the EAT region. Average values of LIS flash characteristics and statistical significance of the differences between compared cases (P) are given.

	Case study 1			Case study 2		
	11/03/2009	02/12/2010	P	26/08/2010	07/12/2010	P
N of LIS flashes	252	234		113	113	
ATDnet DE	38.1%	9.8%		62.8%	6.2%	
LIS overpass times	12:54-12:57 16:10-16:12 17:48-17:50	05:30-05:34 08:46-08:50 10:24-10:27		07:46-07:48 09:24-09:26 11:02-11:04	00:56-00:57 02:32-02:33 05:51-05:53 07:27-07:28	
DELTA	0.27	0.25	0.21	0.37	0.22	0.00
NG	16.46	14.80	0.21	31.86	14.00	0.00
NE	51.27	60.18	0.13	159.68	48.20	0.00
RAD	966306.46	699601.79	0.02	2346982.72	649310.18	0.00
AREA	252.45	290.28	0.02	538.24	261.59	0.00
MNEG	8.36	9.76	0.03	16.90	7.71	0.00
MGA	211.71	251.91	0.01	423.45	229.36	0.00
MGRAD	239721.58	178885.33	0.04	380563.31	154332.73	0.00

ATDnet technical reports suggest that on both days with low relative DE all stations in the ATDnet network were affected by a powerful interfering signal which suddenly appeared at 15.1 kHz. This signal drastically reduced ATDnet sensitivity. The signal emerged at around 09:00 UTC on 2nd December 2010; it was successfully mitigated by implementing a notch filter within the following 20 minutes or so. As such, it is not completely clear if this interference affected ATDnet performance during the 08:46-08:50 LIS overpass. ATDnet detected 3.8% of LIS flashes during the 05:30-05:34 overpass and 10.7% of LIS flashes during the 08:46-08:50 and the 10:24-10:27 overpasses. On 7th December 2010 the interference emerged again but only after LIS overpasses at around 8 UTC and thus is not expected to account for ATDnet low relative DE.

5.4. South America and the South Atlantic Ocean regions

In South America region, the 4th November 2009 (881 LIS flashes, ATDnet-relative DE 10.0%) and the 3rd September 2011 (859 LIS flashes, ATDnet-relative DE 0.5%) were compared (Fig. 5.5 and Table 5.3). In the SAM case study, all LIS flash characteristics showed significantly higher values in the storm that was most successfully detected by ATDnet. Both LIS overpasses occurred during daytime in most of the SAM region and while it was night-time in Europe. No ATDnet hardware or software issues that could explain the low relative DE on 3rd September 2011 were found.

In the South Atlantic Ocean region, the 12th December 2012 (128 LIS flashes, ATDnet-relative DE 11.7%) and the 6th June 2009 (129 LIS flashes, ATDnet-relative DE 2.3%) were compared (Fig. 5.6 and Table 5.3). In the SAT case study, LIS flash duration, number of events and maximum number of events per group were significantly higher in the storm with higher ATDnet-relative DE. Note that the averages of all other flash characteristics were also higher for the storm with higher relative DE but the differences were not statistically significant at P = 0.05 level. The LIS overpasses on 12th December 2012 occurred during night-time in the storm location and in Europe. On 6th June 2009 the sun had already risen over Europe during all LIS overpasses but it was still night/dawn at the storm location. No ATDnet hardware or software issues that could explain the low relative DE on 6th June 2009 were found.

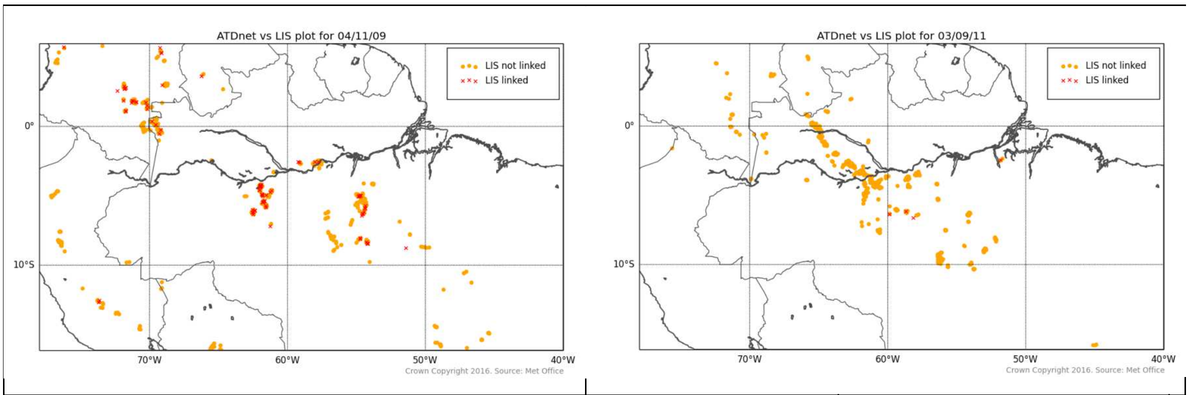

Figure 5.5. LIS-linked and not linked flashes in the SAM region on 4th November 2009 (left) and 3rd September 2011 (right).

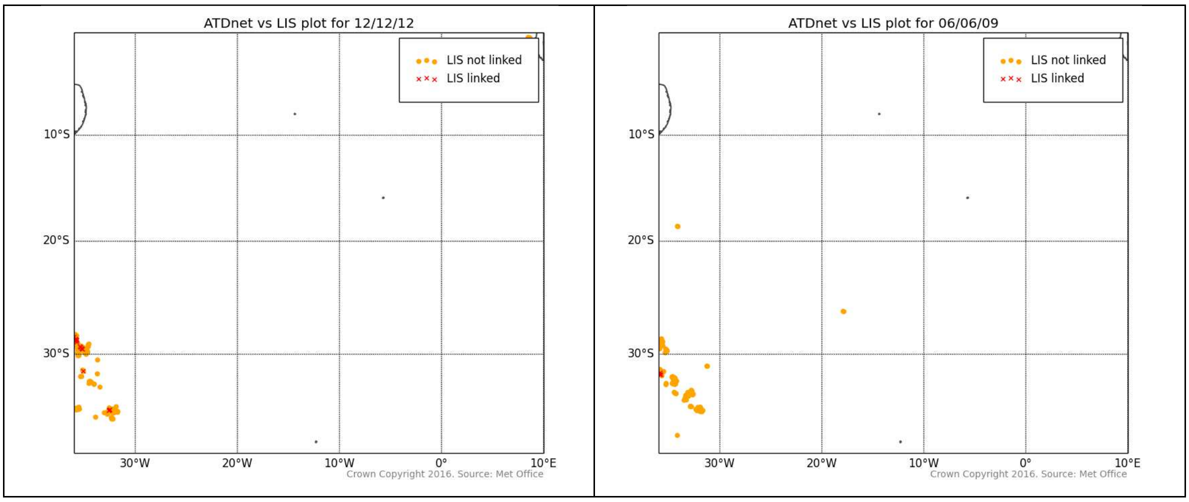

Figure 5.6. LIS-linked and not linked flashes in the SAT region on 12/12/2012 (left) and 06/06/2009 (right).

Table 5.3. Details of the case studies in the SAM and SAT regions. Average values of LIS flash characteristics and statistical significance of the differences between compared cases (P) are given.

	Case study 1 (SAM)			Case study 2 (SAT)		
	04/11/2009	03/09/2011	P	12/12/2012	06/06/2009	P
N of LIS flashes	881	859		128	129	
ATDnet DE	10.0%	0.5%		11.7%	2.3%	
LIS overpass times	21:54-22:04	19:34-19:41		01:14-01:16 02:52-02:54	04:27-04:29 06:05-06:06 07:43-07:44 09:20-09:21	
DELTA	0.29	0.26	0.00	0.19	0.11	0.01
NG	11.24	9.06	0.00	12.34	8.16	0.10
NE	59.59	34.31	0.00	61.65	28.98	0.02
RAD	675363.59	515694.89	0.01	875356.05	375397.99	0.07
AREA	383.94	214.13	0.00	274.93	223.75	0.16
MNEG	12.64	8.32	0.00	10.34	6.57	0.01
MGA	317.21	184.19	0.00	241.05	203.59	0.25
MGRAD	254685.16	167733.06	0.00	231530.38	140414.86	0.27

5.5. Summary of the case studies

The results of the case studies generally support the idea that storms with stronger LIS flashes are more efficiently detected by ATDnet. However, only two case studies reveal significantly higher values of all 8 flash characteristics in the storm with high ATDnet-relative DE (Table 5.4).

Table 5.4. Comparison of all case studies. Cases with the average value of LIS flash characteristics significantly higher for the storm with high ATDnet-relative DE are designated with the "+" sign and cases with the opposite are designated with the "-"sign. P = 0.05 was used as a threshold for statistical significance.

	MED		EAT		SAM	SAT
	CS1	CS2	CS1	CS2		
DELTA	+	+		+	+	+
NG	+	+		+	+	
NE	-	+		+	+	+
RAD	+	+	+	+	+	
AREA	-		-	+	+	
MNEG	-	-	-	+	+	+
MGA	-		-	+	+	
MGRAD	+	+	+	+	+	

In all the six cases, flashes in the most successfully detected storms have higher average radiance and maximum group radiance (though the difference is not statistically significant for the storm in the SAT region). Interestingly there are two cases where the flash and group area parameters (AREA, MGA) and three cases where the maximum number of events per group (MNEG) are significantly higher for the least successfully detected storms. This seems to contradict the previous findings that indicated positive relationship between AREA, MNEG, MGA and ATDnet-relative DE. There are two possible explanations:

- Firstly, the MED and EAT are the closest regions to ATDnet sensors which are characterized by relatively small ATDnet location errors. Thus, it is less likely that smaller LIS flashes are counted as undetected simply because of large location errors of their corresponding ATDnet fixes.
- Secondly, and probably more importantly, there are other factors with stronger impact on ATDnet-relative DE than flash characteristics. All the three studies are characterised by a daytime storm with high ATDnet-relative DE and a nighttime storm with low relative DE. It is known that better signal propagation conditions during daytime lead to better ATDnet DE. It is also likely that LIS higher DE at night further contributed to the lower relative DE of ATDnet whereas LIS lower daytime DE further contributed to the higher ATDnet-relative DE. It might also be that the lower average flash and group area and maximum number of events per group for the daytime storms that were better detected by ATDnet are related to LIS limitations in daytime detection. Weaker events are more likely to remain undetected by LIS in daylight and this is expected to lead to somewhat smaller group/flash area and maximum number of events per group.

6. Future research

The present study covers several important aspects of ATDnet performance against LIS. There are, however, additional research questions for further studies. Here is a summary of those questions. Note that the list is not exhaustive.

1. *What is the LIS DE relative to ATDnet and how does it compared to ATDnet DE relative to LIS*? ATDnet data has to be filtered for LIS view times for such a study. This comparison would show how much ATDnet could add value to satellite observation if used in combination with a satellite based optical sensor.

2. *What is the ATDnet-relative DE relative to LIS as a function of the maximum allowed distance between LIS flashes and ATDnet fixes in a distant areas such as central Africa and South America?* In the present study, an ATDnet fix had to be located within 25 km from LIS flash groups to be linked to the flash. However, it is likely that not all the ATDnet fixes corresponding to LIS flashes meet this criterion. This problem is expected to affect especially distant regions with large ATDnet location errors such as central and southern Africa and South America. Experimenting with different distance thresholds in such areas would give an estimation of the size of the fraction of ATDnet fixes with large location errors.

3. *Can satellite data be used as a quality measure of the ATDnet quality control system?* In the present study linked fixes were searched only against ATDnet fixes classified as “good fix” by ATDnet quality control system. However, the study could be repeated with all ATDnet fixes, including those classified as “poor” and removed from ATDnet data products. Such a study would reveal the fraction of genuine fixes linked to LIS flashes that are wrongly classified as ATDnet poor fixes. It should be possible to study the spatial distribution of such fixes. Moreover, this approach could be used in the future for continuous monitoring of the performance of the ATDnet quality control system. For example, hourly or daily fractions of ATDnet fixes rejected by the quality control system but linked to flashes detected by geostationary imagers could be computed. It might also work as a post processing poor fix rescue procedure so that every poor fix is compared against satellite data and the linked ones are “rescued” and reclassified into good fix dataset.

4. *Can the frequency of linked ATDnet fixes be studies as a function of direction and distance of the corresponding LIS flashes in different regions?* Such a study might shed some new light into ATDnet location accuracy and error estimations. It would be possible to compare the real distances between linked ATDnet fixes and LIS flashes with the predictions of the theoretical LA model.

Conclusions

ATDnet flash detection efficiency (DE) relative to the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) was evaluated. LIS used the same observing principles as will be used by GOES-R Geostationary Lightning Mapper and MTG Lightning Imager. Thus, the results of the present study could be used for planning complementary studies and data products.

The study has proven that ATDnet is capable of detecting lightning not only in and around Europe but also over the whole tropical Atlantic and also in most of Africa, South America and the eastern seaboard of the US. Although ATDnet-relative DE decreases with the increasing distance from Europe the system is still expected to be able to locate all significant storms over the abovementioned areas.

ATDnet-relative DE values were found to be 20-30% over the Mediterranean and the East Atlantic and decrease to 5% in distant regions such as South America and the South Atlantic. These values might seem relatively low at first but they should be interpreted in the right context together with the capabilities and limitations of LIS and ATDnet.

Firstly, LIS is an all lightning sensor whereas ATDnet is designed to locate cloud-to-ground lightning return strokes. It is generally known that cloud lightning (IC) is much more frequent than cloud-to-ground lightning (CG) and constitutes around 75-80% of total lightning in the world (Rakov and Uman 2003). It has been suggested that the IC fraction is even higher than that in certain regions especially in tropics (e.g. Pinto et al., 2007). In addition, some studies indicate that LIS might be slightly more sensitive to cloud lightning (Ushio et al. 1999; Thomas et al. 2000) which means that the fraction of cloud flashes in the LIS dataset might be even higher than the global IC:CG ratio.

Secondly it has to be taken into account that virtually all the LIS data domain lies outside ATDnet perimeter. Thus, the ATDnet-relative DE values represented here are expected to be significantly lower than ATDnet-relative DE in Europe. On the other hand it is remarkable that ATDnet is capable of detecting a significant proportion of stronger flashes even as far from Europe as South America and the South Atlantic. It is also encouraging that ATDnet is more efficient over the oceans where the lightning data availability is currently very limited.

ATDnet-relative DE was demonstrated to vary significantly from storm to storm as a function of LIS flash properties and time of day. This highlights the potential benefits of complementary ATDnet and geostationary lightning imager data products. For example, ATDnet performs better during the day when optical lightning detection from space might be somewhat less efficient.

The findings of the present study encourage further steps towards collaboration and/or synergies with geostationary lightning imager's data. The first opportunity will be with GOES-R GLM due to be launched in November 2016. The results of the present study indicate that ATDnet detects a significant number of lightning discharges within the GOES-R footprint in South America for a comparative study with GOES-R. Similar studies over Europe could also provide valuable new information once LIS on the International Space Station (ISS) become operational some time in 2017.

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Appendix A1: Annual ATDnet DE maps 2008-2014

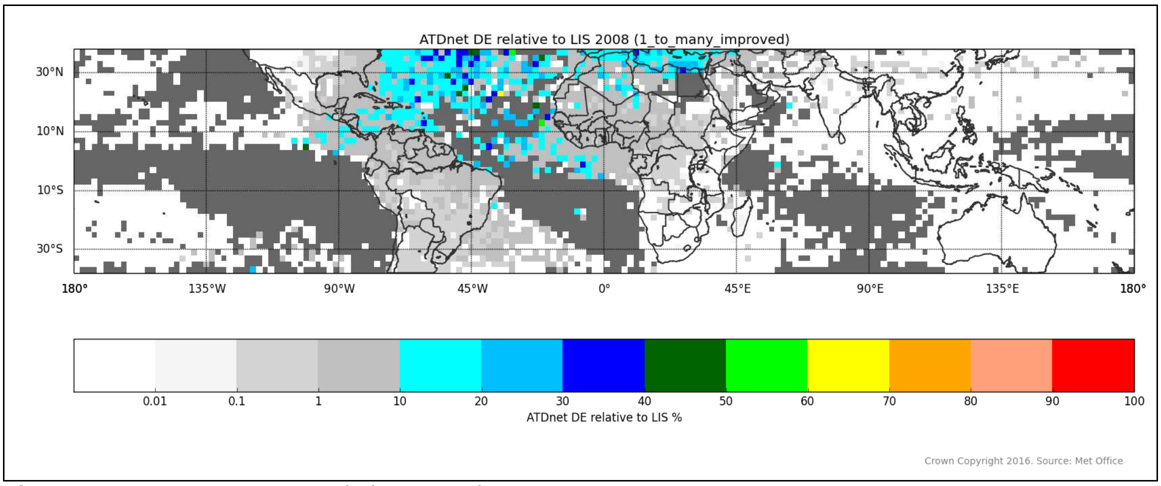

Figure A1.1. ATDnet DE relative to LIS in 2008.

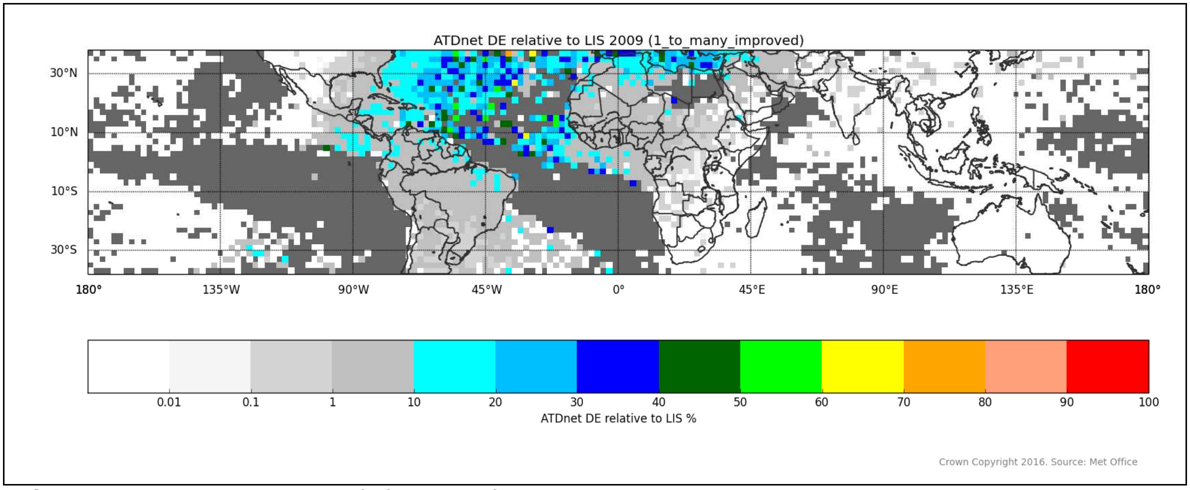

Figure A1.2. ATDnet DE relative to LIS in 2009.

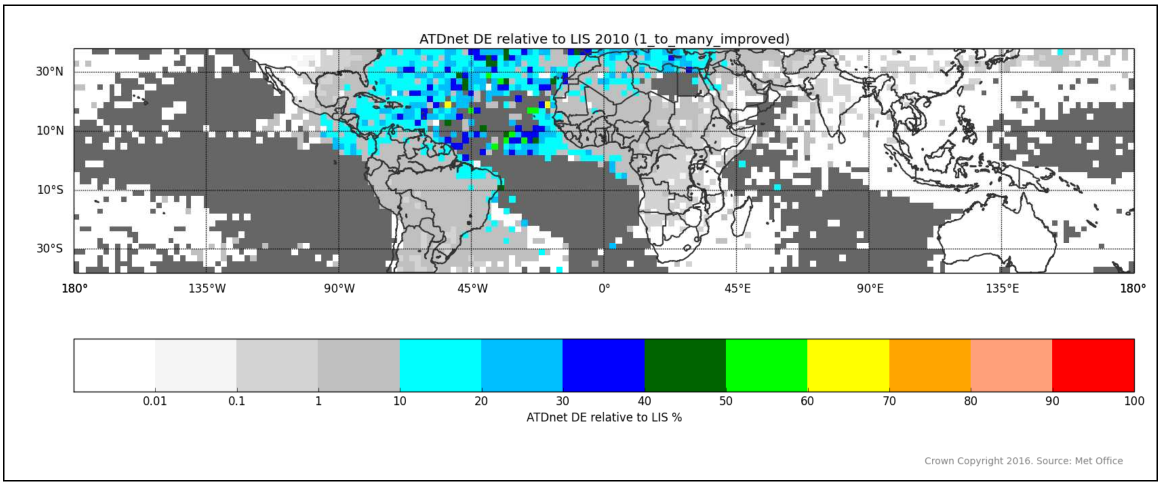

Figure A1.3. ATDnet DE relative to LIS in 2010.

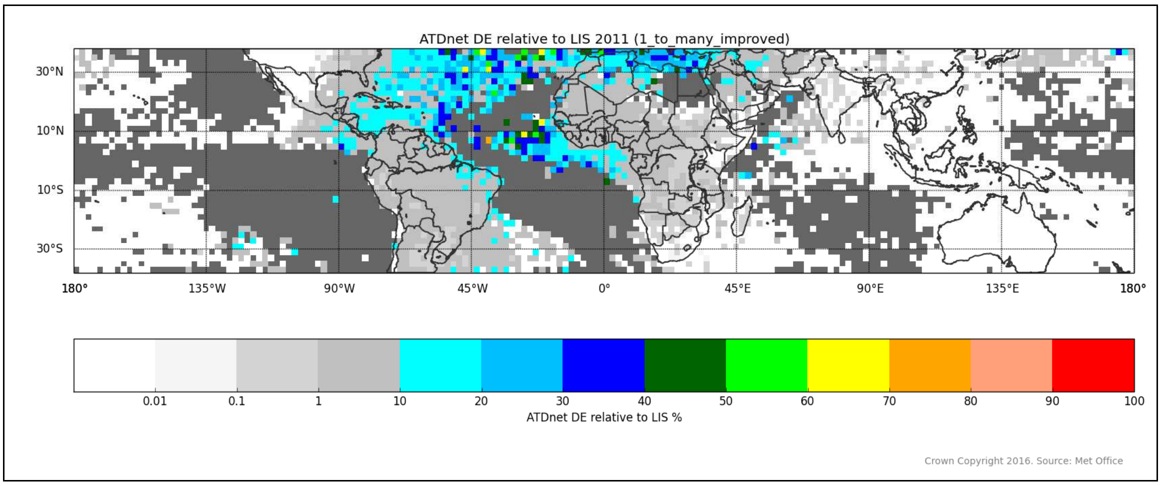

Figure A1.4. ATDnet DE relative to LIS in 2011.

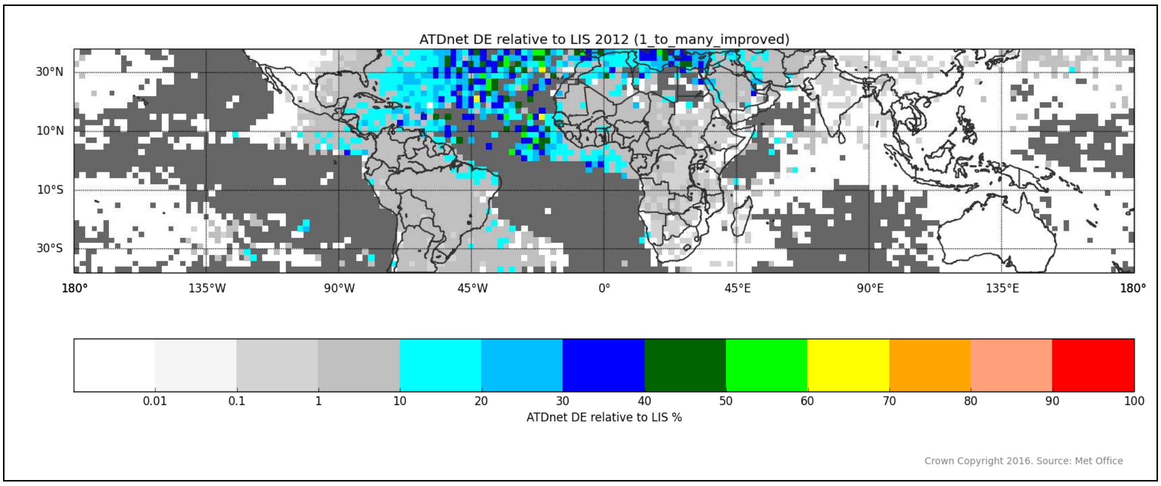

Figure A1.5. ATDnet DE relative to LIS in 2012.

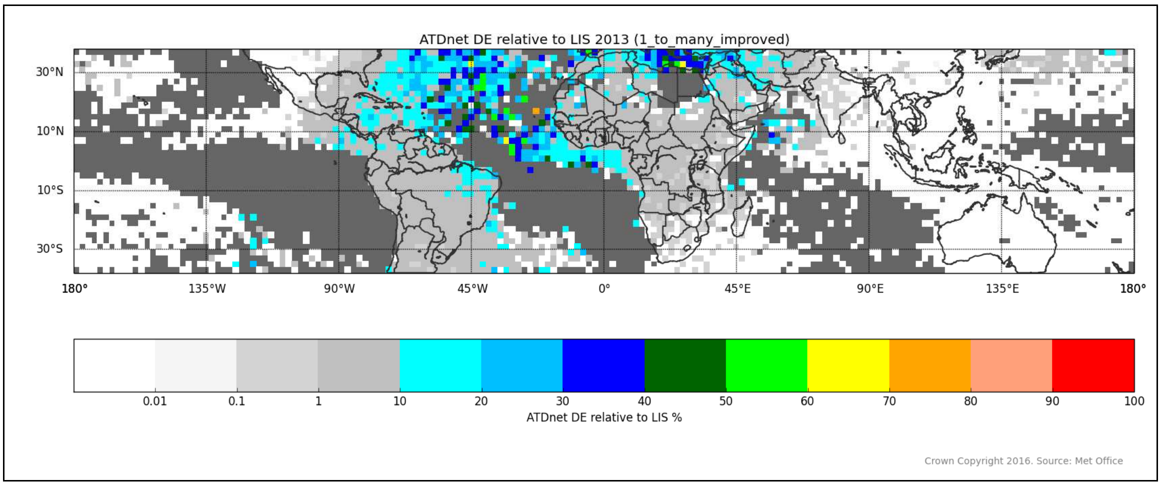

Figure A1.6. ATDnet DE relative to LIS in 2013.

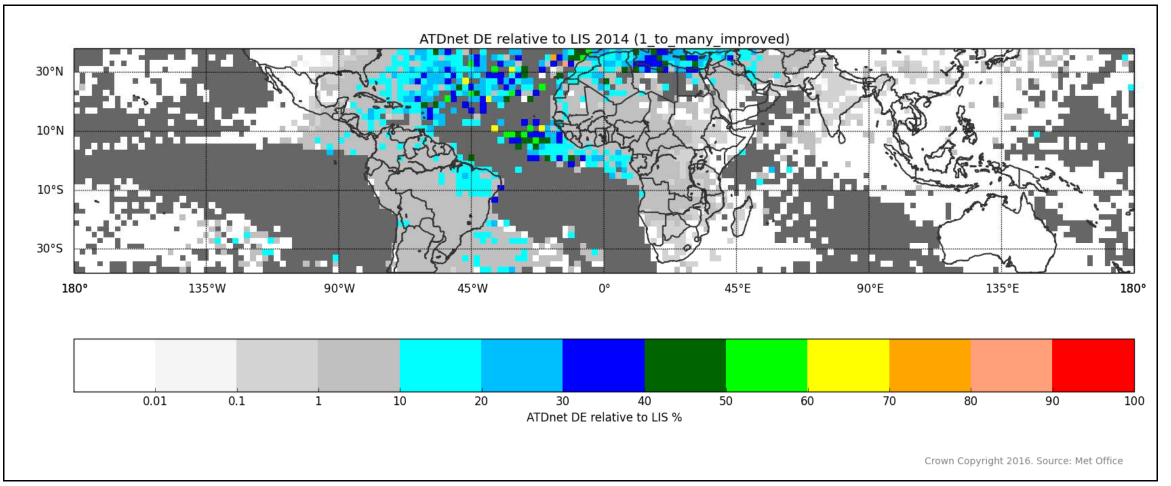

Figure A1.7. ATDnet DE relative to LIS in 2014.

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