Comparing a Regional, Subcontinental and Long-Range Lightning Location System over the Benelux and France

Dieter R. Poelman[1,*], Stéphane Pédeboy[2], Françoise Honoré[3], Graeme Anderson[4]

1. Royal Meteorological Institute, Brussels, Belgium
2. Météorage, Pau, France
3. Météo-France, Toulouse, France
4. United Kingdom Met Office, Exeter, United Kingdom

ABSTRACT: Increasing possibilities for using lightning data —for instance in monitoring and tracking applications— necessitate proper spatial and temporal mapping of lightning events. It is therefore of importance to assess the capabilities and limitations of a ground-based lightning network of interest to locate electromagnetic signals emitted by lightning discharges. In this paper data covering two storm seasons between May and September 2011 and 2012 are used to investigate in how far the spatial and temporal lightning observations of three different lightning location systems agree over an area covering the Benelux and France. Data from a regional network employing SAFIR sensors operated by the Royal Meteorological Institute of Belgium (RMI-BE), a subcontinental network operated by Météorage (MTRG), and the Met Office's long-range Arrival Time Difference network (ATDnet) are considered. It is found that the median location difference among corresponding strokes and flashes between ATDnet and MTRG is 1.9 km and 2.8 km, respectively, and increases by a factor of ~3 when comparing ATDnet and/or MTRG to SAFIR. Furthermore, lightning data are correlated in terms of relative detection efficiency, quantifying the number of detections that coincide between two different networks. The highest relative values are found amongst ATDnet and MTRG. In addition, a lower limit of ~25% of ATDnet's lightning flashes is of type inter/intracloud.

INTRODUCTION

Numerous lightning location systems (LLS) exist to date employing a variety of sensors and detection techniques, operating at very-low/low frequencies (VLF/LF) up to the very-high-frequencies (VHF). An LLS employs either sensors of a single type or a combination of different sensors. Depending on the operating sensors, angle and/or timing information is provided. This in its turn determines whether a (magnetic) direction finding (MDF), a time-of-arrival (TOA) technique, or a combination is used by the central processor to retrieve unambiguous solutions from the raw data.

The different national meteorological services (NMS) in Europe obtain lightning data via two

* Contact information: Dieter R. Poelman, Royal Meteorological Institute of Belgium, Brussels, Belgium, Email: dieter.poelman@meteo.be

different routes: either provided by their own network or purchased from the available commercial providers. This diversity makes it challenging to interchange information amongst each other. However, with the ongoing evolution of lightning detection possibilities, lightning data plays an ever-increasing role in, for instance, real-time storm monitoring and leads to the development of specific applications, such as automated storm tracking and nowcasting [Kohn et al. 2011].

Several techniques can be employed to investigate the performance of a network in terms of its detection efficiency (DE), location accuracy (LA), peak current estimate and classification of the observed lightning type, that is, negative versus positive and/or cloud-to-ground (CG) versus cloud-to-cloud (CC) signals. The most desirable way to do this is by using so-called ground-truth data. The latter can be gathered from direct hits to towers [Diendorfer 2010], measurements of rocket-triggered lightning [Jerauld et al. 2005; Nag et al. 2011] or via video and electric field (E-field) measurements [Biagi et al. 2007; Schulz et al. 2010; Poelman et al. 2013]. However, ground-truth observations are not readily available at all times.

Intercomparison studies between LLS within regions of overlapping coverage offer an additional way to analyze detections made by one network to another. The best way is to monitor the behavior over an extended period, spanning several thunderstorm seasons in order to remove potential biases due to, for example, sensor outages. Care must be taken to interpret the outcome as different networks make use of different processing algorithms and are unlikely to have similar detection efficiencies. Nevertheless, such studies can contribute to a more thorough understanding of the performance of a particular LLS.

In this paper, data from the NMS of Belgium, France and the United Kingdom are cross-correlated.

NETWORKS

Météorage

The French national lightning location system has been operated by Météorage (MTRG) since 1986. It detects low-frequency electromagnetic signals generated by CG lightning, as well as a fraction of large-amplitude CC discharges. Currently, data from the different sensors are processed simultaneously using Vaisala's Total Lightning Processor (TLP) set in the operational centers of Météorage and Météo-France in Pau and Toulouse, respectively, providing seamless extended observation coverage over Western Europe. The position of the sensors is plotted in Fig. 1.

Depending on the region of interest median LA values ranging from 440m to 600m and a stroke and flash DE of about 85% and 100%, respectively, are found based on video records [Schulz et al. 2010, Poelman et al. 2013].

In what follows, we denote with MTRG the dataset containing solely CG detections, whereas $MTRG^+$ is used as an extended dataset containing CG, as well as the observed large-amplitude CC discharges due to the capability of the LS7001 sensors.

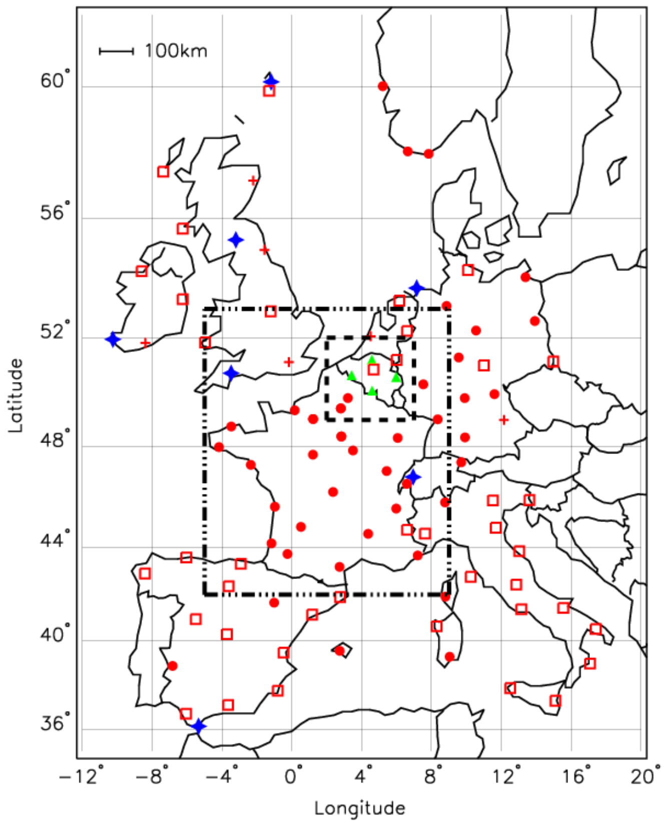

FIG. 1. Sensor positions for MTRG are plotted in red with a different symbol for different type of sensors. In addition, some sensors of ATDnet are plotted in blue, and the four SAFIR sensors are indicated as green triangles. The two research areas are indicated as well: dashed lines depict research area 1, whereas dash-dotted lines outline research area 2.

Met Office

The Met Office (UKMO) owns and operates since 1987 a long-range lightning location network called ATDnet, consisting currently out of 18 sensors deployed in Europe, Africa, the Indian Ocean and Caribbean and Asia. Eleven of these are currently used for operational processing, giving good coverage over all of Europe. The network exploits VLF radio pulses emitted by lightning, locating the sources by the timing of arrival when the peak energy of the emitted waveform arrives at each sensor site.

Performance estimates are calculated over the United Kingdom and Europe with a stroke DE up to 90% and a median LA of ~2-3 km [Keogh et al. 2006]. However, recent performance measurements, based on ground-truth data over Belgium [Poelman et al. 2013] indicate a stroke DE of 58%, flash DE of 88%, and a median random location uncertainty of 1 km. The location of the sensors in western Europe are plotted in Fig. 1.

Royal Meteorological Institute of Belgium

The Royal Meteorological Institute of Belgium (RMIB) has been operating an LLS since 1992. This network consists of four sensors of type SAFIR, see Fig. 1. The central processor uses an interferometric lightning location retrieval method in the VHF band to retrieve after triangulation the location of intracloud source points. In addition, the sensors are equipped with an E-field antenna detecting the LF return stroke signature, allowing the system to discriminate between CC and CG electrical signals on the basis of the rise and decay times of the observed waveform. Once an LF signal is detected, the CG stroke is assigned a location using the position of a time-correlated VHF signal. Even though the SAFIR network is a total lightning network, detecting both VHF and LF signals, we solely use in the course of this paper the LF part of the SAFIR data to compare signals from corresponding processes in the formation of a discharge w.r.t. the other VLF/LF networks.

The performance of SAFIR has been tested recently against ground-truth data using video and E-field measurements [Poelman et al. 2013], resulting in a median LA of 6 km and a stroke and flash DE of 70% and 93%, respectively, in Belgium.

DATA AND METHODOLOGY

Stroke data between May and September 2011 and 2012 are used for the analysis. When comparing flashes from different lightning networks, it is a necessity to have a common definition of a flash. Therefore, strokes detected by the different networks are grouped into flashes in a same manner to yield compatible flash data as follows. An individual stroke belongs to a particular flash if $\Delta t < 1$s and $\Delta r < 15$ km. In addition, an interstroke criterion $\Delta t_{\text{interstroke}} < 0.5$ s is used as well. If at least one signal in a flash is classified as CG, then we classify the flash as a CG flash, else it is classified as a CC flash. The position and peak current of the first return stroke are chosen as the position and peak current of the CG flash. In case of a CC flash, the mean of the different source point positions is used as the location of the CC flash.

Strokes and flashes are compared using the relative detection efficiency (RDE) concept to evaluate the relative performance of two different datasets by calculating the number of overlapping events registered by one system assuming the other as the truth, and vice versa. A stroke (/flash) is considered the same in two datasets when $\Delta t \leq 1$ms (/1 s) and $\Delta r \leq 15$ km. The longer adopted time window for flashes is inherent to the duration of a flash, being a combination of different strokes. Thus, consider two LLS A and B, with n_A and n_B as the number of detections by A and B, respectively, and $n_{A\cap B}$ as the number of detections simultaneously observed by both systems. Then, RDE(A out of B) = $n_{A\cap B}/n_B$.

DATA COMPARISON: RESEARCH AREA 1

We restrict the area of interest to latitude [49°N, 52°N] and longitude [2°E, 7°E]. This is an area of common overlap between the three lightning networks. Table 1 lists the total number of strokes and resulting flashes for each network over the period May-Sept 2011 and 2012. ATDnet detects more then SAFIR and MTRG, whereas MTRG$^+$ detects a similar quantity as ATDnet. A closer look at the

Table 1. Number of detections over research area 1 during May-September 2011 and 2012.

	Strokes	Flashes
MTRG	205024	114092
SAFIR	250856	140646
ATDnet	369628	264462
$MTRG^+$	393636	217020

temporal distributions of flashes detected by the individual networks, as plotted in Fig. 2, reveals that ATDnet outnumbers by far the detections of the other networks between 0300 and 2000 UTC, but is not the case at night. The latter can be partly understood since the propagation of VLF follows the earth-ionospheric waveguide. Hence, the diurnal variability of the height of the ionosphere introduces significant degradations in ATDnet's performance [Lynn 1977; Gaffard et al. 2008, Bennett et al. 2010]. Additionaly, one observes that the temporal distribution of $MTRG^+$ more closely follow the temporal

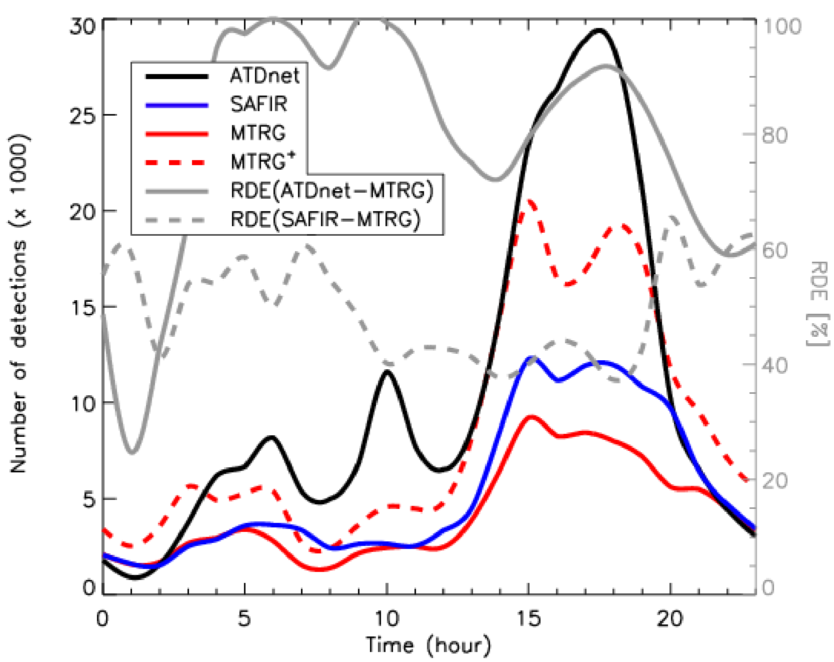

FIG. 2. Temporal distribution of the number of flashes detected by ATDnet (*black*), SAFIR (*blue*), MTRG (*red/solid*) and $MTRG^+$ (*red/dashed*) over research area 1 during May-Sept 2011 and 2012. In addition, the variation of the flash RDE (%) of ATDnet (*grey/solid*) and SAFIR (*grey/dashed*) w.r.t. MTRG is plotted as well.

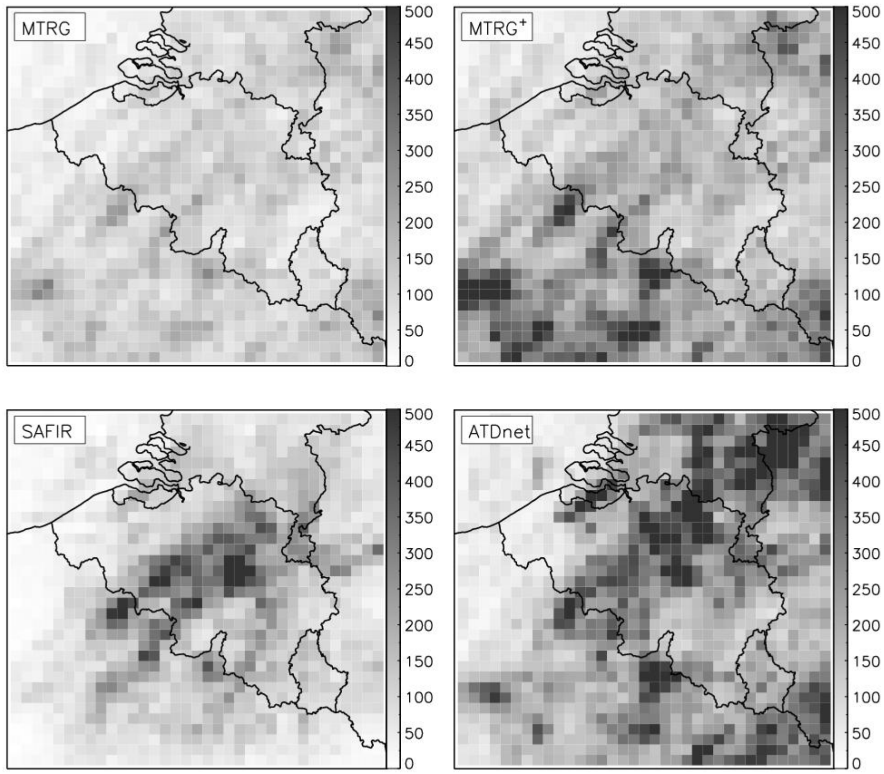

FIG. 3. Spatial distribution of the number of flashes detected by MTRG, MTRG$^+$, SAFIR and ATDnet over research area 1 during May-September 2011 and 2012. Color shading indicates the absolute number of flashes per 10 x 10 km^2. Note that all values above 500 are given the same shade.

distribution of ATDnet than MTRG. This could be an indication that a certain fraction of large amplitude CC discharges emitting sufficient VLF radiation are being picked up by ATDnet as well.

Fig. 3 plots flash density maps for MTRG, MTRG$^+$, SAFIR and ATDnet. Some differences are noticeable between these networks. It is seen that 1) in general, the spatial distribution differs among the networks; 2) detections by SAFIR seem to be biased towards the center of Belgium, probably because of an inhomogeneous detection efficiency, favoring detections over the domain within the four SAFIR sensors; and 3) detections by MTRG are more or less homogeneous. The increased density over the center of Belgium, as seen by SAFIR and ATDnet, is not being picked up by MTRG.

One could wonder what causes ATDnet to detect much more compared to, e.g., MTRG, resulting in an apparent different spatial behavior. First and foremost, note that the applied quality control settings within the individual central processors differ, whereby ATDnet accepts lightning detections with location errors a few factors larger then is allowed by MTRG. Secondly, a closer look into the raw sensor data of MTRG reveals that during a few days of severe thunderstorm activity during the 2011 storm season, several sensors were out of order for a short or longer time span around Belgium. Hence, due to these sensor outages, the performance of MTRG can be considered as substandard during the latter season. In addition, looking at the individual density maps for 2011 and 2012 (not shown here), the 2011 storm season dominates the total flash density map as presented in Fig. 3. It is thus likely that a combination of 1) applied quality control parameters, 2) sensor outages by MTRG and 3) CC signals being picked up by ATDnet can explain the observed differences between ATDnet and the other networks over this particular region and period.

Median spatial deviations for strokes and flashes between the different networks are given in Table 2. It is found that MTRG and ATDnet position overlapping detections closest to each other. The largest deviations are found when comparing SAFIR to the other networks.

RDE values are listed in Table 2. It is seen that 1) the lowest overall RDE values are found when comparing either ATDnet or MTRG against SAFIR. This is not surprising since the median LA of SAFIR is ~6 km, based on ground-truth observations [Poelman et al. 2013], diminishing the number of overlaps. 2) In general, the highest RDE values are found between MTRG and ATDnet, with for instance 80% of ATDnet's flashes overlapping MTRG flashes. 3) We find that MTRG recognizes 34% of the flashes out of ATDnet. This value increases respectively to 57% when considering $MTRG^{+}$ out of ATDnet.

TABLE 2. Relative detection efficiency and spatial deviation values belonging to research area 1.

	Stroke RDE [%]	Flash RDE [%]		Stroke RDE [%]	Flash RDE [%]	Median Stroke Deviation [km]	Median Flash Deviation [km]
MTRG out of SAFIR	28	37	SAFIR out of MTRG	34	46	6.5	7.1
MTRG out of ATDnet	26	34	ATDnet out of MTRG	47	80	1.9	2.8
ATDnet out of SAFIR	27	60	SAFIR out of ATDnet	18	32	6.7	7.5
$MTRG^{+}$ out of ATDnet	40	57	ATDnet out of $MTRG^{+}$	39	69	2.0	3.0

Thus, about 25% of the CC flashes detected by MTRG$^+$ have an overlap with ATDnet. In other words, a lower limit of ~25% of ATDnet's flashes are CC flashes; assuming a correct discrimination between CG and CG lightning in the MTRG$^+$ dataset. The value of this lower limit decreases to about 15% when strokes are considered.

In addition to the temporal distribution, we plot in Fig. 2 the variation of the RDE of ATDnet and SAFIR out of MTRG as a function of time. One observes that for SAFIR the RDE varies continuously with no clear trend during the course of the entire 24 h, whereas clearly the RDE for ATDnet is high during the day and drops at night.

DATA COMPARISON: RESEARCH AREA 2

In this section, we expand the region of interest to latitude [42°N, 53°N] and longitude [-5°W, 9°E]; an area covering Belgium, France, the Netherlands, South-England, West-Germany and North of Spain. In this way, potential local effects such as sensor outages are suppressed. Only MTRG, MTRG$^+$ and ATDnet are considered, since these networks alone can detect lightning activity over this larger area.

Table 3 lists the number of strokes and resulting flashes for ATDnet, MTRG and MTRG$^+$. The distribution of the number of detected flashes as a function of time for ATDnet, MTRG and MTRG$^+$ is plotted in Fig. 4. It is seen that ATDnet detects more during the day compared to MTRG, while a drop is noticed at night. However, MTRG$^+$ now has roughly the same distribution as ATDnet during the day.

Flash density maps for MTRG, MTRG$^+$ and ATDnet are presented in Fig. 5. It is seen that MTRG follows the same pattern as ATDnet, albeit with a lower detection rate. On the other hand, MTRG$^+$ detections are more densely spaced around the southwest of France and around the Paris region compared to MTRG. To quantify the ability of MTRG$^+$ to detect CC activity, the spatial distribution of the CC/CG flash ratio is presented as well in Fig. 5. It is seen that this ratio increases to values between

TABLE 3. Number of detections over research area 2 during May-September 2011 and 2012.

	Strokes	Flashes
MTRG	2317648	1205134
ATDnet	3377845	2403434
MTRG$^+$	4636339	2415182

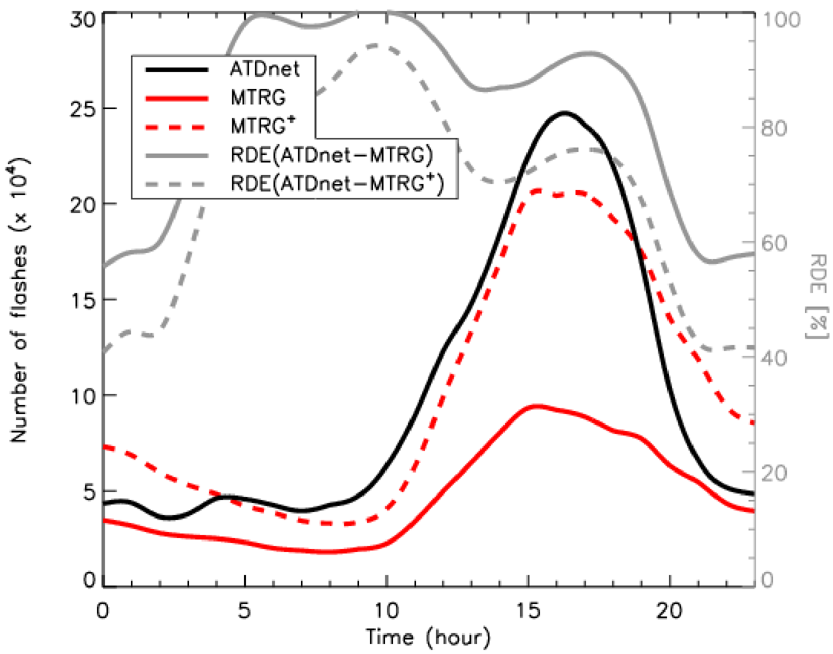

FIG. 4. Temporal distribution of the number of flashes detected over research area 2 during May-Sept 2011 and 2012 by ATDnet (*black*), MTRG (*red, solid*), and MTRG$^+$ (*red, dashed*). In addition, the RDE [%] of ATDnet w.r.t. MTRG (*grey/solid*) and MTRG$^+$ (*grey/dashed*) is plotted as a function of time.

2 and 4 mainly in the southwest of France and the region around Paris. This is not surprising, since short baselines between LS700x-type sensors at these particular regions leads to a better detection efficiency of intracloud lightning.

RDE values for strokes and flashes are listed in Table 4, together with the median spatial deviation between overlapping strokes and flashes. First, median spatial deviation values are comparable to the values found over research area 1. Second, MTRG recognizes 40% of ATDnet's flashes. This value increases to 66%, when comparing MTRG$^+$ out of ATDnet. This indicates that a certain fraction of CC signals are being picked up by ATDnet, assuming a correct discrimination by MTRG$^+$, and is similar to the value found over research area 1. Hence, we conclude that the majority of the flashes detected by ATDnet are CG flashes, mixed with a lower limit of ~25% CC flashes. On the stroke level, it is found that 18% of ATDnet's strokes are of type intracloud following a similar reasoning in the case of flashes —a value comparable to the 26% found comparing WWLLN strokes to the Los Alamos Sferic Array in Florida [Jacobson et al. 2006].

In addition to the temporal distributions in Fig. 4, we plot the variation of the RDE of ATDnet out of MTRG and MTRG$^+$. Again, the RDE is high during the day and drops at night —similar as over area 1.

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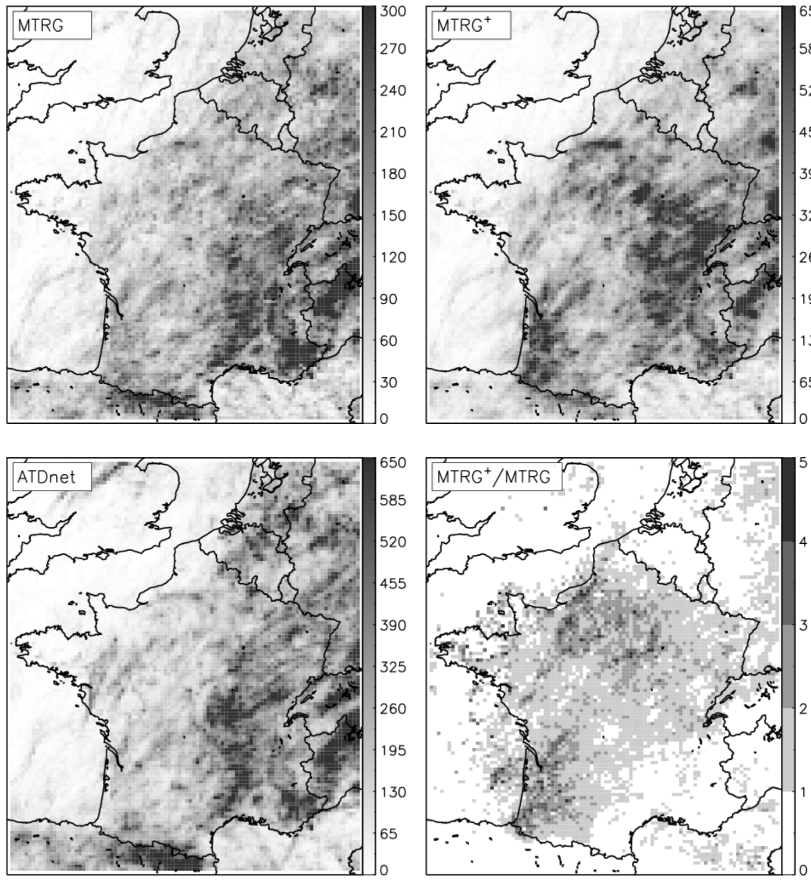

FIG. 5. Spatial distribution of the number of flashes detected by MTRG, MTRG$^+$, and ATDnet over research area 2 during May-Sept 2011 and 2012. The color shading indicates the absolute number of flashes per 10x10 km^2. Note the different gray scales in the plots. In addition, the CC/CG flash ratio of MTRG$^+$ is plotted as well.

CONCLUSIONS

In this paper three distinct lightning location systems covering Belgium during two storm seasons between May and September 2011 and 2012 are compared. Two research areas, different in size, are chosen to investigate the spatial and temporal variations. Sensor configuration, type of sensors used and the applied technology and quality control settings to process the data give rise to a variation in the number and location of detected lightning signals.

We find that ATDnet detects more lightning signals compared to the CG datasets of MTRG and SAFIR. However, MTRG$^+$, containing the total lightning detections by MTRG, follows more closely the temporal distribution of ATDnet. For the first time, an attempt has been made to quantify the fraction of CC signals that are being picked up by ATDnet. A lower limit of ~25% is found when flashes are considered. ATDnet's relative detection efficiency peaks during the day and exhibits a nocturnal drop. This is attributed to modal interferences and the increase of the effective ionospheric height due to a

TABLE 4. Relative detection efficiency and spatial deviation values belonging to research area 2

	Stroke RDE [%]	Flash RDE [%]		Stroke RDE [%]	Flash RDE [%]	Median Stroke Deviation [km]	Median Flash Deviation [km]
MTRG out of ATDnet	33	40	ATDnet out of MTRG	49	80	1.9	2.7
$MTRG^+$ out of ATDnet	51	66	ATDnet out of $MTRG^+$	37	66	2.0	2.8

reduction in photoionization from solar UV radiation. Nevertheless, when compared to MTRG we find a median spatial flash deviation of about 3 km and high RDE values.

A median spatial flash deviation of about 7 km of SAFIR referenced against MTRG and ATDnet is found. This is a factor of about two larger then what is found between MTRG and ATDnet. RDE values are lower compared to the ones between MTRG and ATDnet and could be due to the reduced LA of SAFIR. Opposed to ATDnet, the temporal RDE variations do not favor a specific moment during the day.

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