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First results on severe storms prediction based on the French national Lightning Locating System

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***Abstract* - Severe storms exhibit a common pattern consisting in a rapid increase of the total lightning rate (i.e. Cloud-to-Ground and Cloud-to-Cloud flashes) few to tenths of minutes in advance to heavy precipitation, hail or tornado. This “lightning jump” is an interesting feature for now-casting weather applications since it can help predicting severe weather occurrence with a sufficient lead time in most cases [Williams et al, 1999; Murphy and Demetriades 2005; Schultz et al, 2009].**

Several algorithms have been developed to monitor lightning rate trends and detect the onset of the lightning jump on the basis of VFH lightning data [Gatlin and Goodman 2010]. Out of those algorithms, the “2σ configuration” has been statically validated on various thunderstorm types and is likely to be the most effective to use for operational usage [Schultz et al. 2014].

Météorage has design and developed a cell identification method using the DBSCAN algorithm [Ester et al. 1996] to cluster VLF/LF total lightning data consisting in Cloud-to-Ground and Cloud-to-Cloud flashes collected by the French National Lightning Locating System. In this algorithm so called STORM, every individual cell is then tracked and its characteristics (eg. position, direction of propagation, speed, area and number of flashes) are monitored all long the lifecycle. The analysis of the evolution of the total lightning flash rate by the “2σ configuration” lightning jump algorithm helps predicting severe weather occurrences and triggering warning messages.

This study aimed at determining the overall performances of STORM by comparing computed lightning cell and severe weather alerts against ground truth hail observations. This dataset consists of 248 valid hail reports collect in 2014 across France by the ANELFA, the national association for hail risk prevention [Dessens et al 2006]. Preliminary results show a clear seasonal dependency since winter storms are less likely to be detected by STORM because they produce few lightning. However, they are encouraging since a Probability of Detection of 80% is obtained for severe hailstorms producing hailstones with a diameter equal to or greater than 2.5cm. In addition, the mean Warning Lead Time is found to be about 15 min and reach 18 min for severe thunderstorms. Those results being consistent with those from similar studies [Schultz et al. 2009] it turns out the usage of VLF/LF lightning data are relevant for severe storms tracking and alerts.

Further work shall be carried out to optimize STORM settings in order the cell identification algorithm is improved. Comparison of VLF/LF lightning cells with radar and Lightning Mapping Array should help in tuning the overall performances and better understanding strengths and weaknesses of such a tool.

Keywords—lightning data; severe storms; hail prevention; clustering algorithm; lightning jump

INTRODUCTION

Severe storms exhibit a common pattern consisting in a rapid increase of the total lightning rate (ie. Cloud-to-Ground and Cloud-to-Cloud flashes) few to tenths of minutes in advance to heavy precipitation, hail or tornado. Several authors studying the non-inductive charging mechanism have demonstrated this phenomenon, so called “lightning jump”, is related to the presence of a strong vertical updraft that drives the production of hydrometeors, increases the number of collisions between ascending ice crystals and descending graupels providing a way to separate electrical charges in the cloud [Deierling and Petersen 2008]. This process of charge separation is thought to be responsible for the conventional thunderstorm dipole structure that generates a strong vertical electric field between the upper positive and lower negative areas. When the electric becomes too high a preliminary breakdown may occur resulting in several electrical processes leading to a lightning flash. The frequency at which lightning produce reflects the strength of the updraft and its capacity to generate and enhance electrical charges in the cloud. In some cases, the rate suddenly increases before a severe weather (heavy rain, hail or tornado) occur. This “lightning jump” phenomenon becomes then an interesting feature for now-casting weather applications since it can help predicting severe weather occurrence with a sufficient lead time most cases [Williams et al, 1999; Murphy and Demetriades 2005].

Météorage, the French National Lightning Locating System (LLS) operator, has developed a “Severe Thunderstorm Observation and Reporting Method” (STORM) aiming at detecting dangerous storms and preventing severe weather based on VLF/LF total lightning data made of Cloud-To-Ground (CG) flashes and Cloud-To-Cloud discharges (CC).

In this study, the performances of STORM are tested against hail ground truth data collected in 2014 across France by the ANELFA, a French association for hail prevention [Dessens et al 2006]. At first, consistency and efficiency of the electrical cells tracking algorithm are estimated thanks to the correlation of temporal and spatial proximities between lightning cells and their related hail reports. Secondly, warning lead times are analyzed to assess the relevancy of alerts issued by the lightning jump algorithm.

THE STORM ALGORITHM

The STORM algorithm relies on two main functions which are the tracking of the lightning cells and the monitoring of lightning jumps. It is periodically run on the most recent minutes (5 minutes in this study, but might be more frequent) of lightning activity to identify active thunderstorms. Results are then correlated to those obtained from the prior run in order to either create a new lightning cell or update the status of already existing ones. Then, every individual living cell is tracked and its characteristics (eg. position of the barycenter, direction of propagation, speed, area and number of flashes per minute) are monitored and stored in a dedicated database all long the lifecycle of the cell.

Once a cell is identified, the evolution of its lightning flash rate is analyzed to detect whether or not a lightning jump is currently happening. In this case, a severity flag is triggered in order downstream applications are aware that severe weather is going to produce in the vicinity of this particular cell. On the opposite, when the severe cell is about to collapse and its lightning flash rate is decreasing the severity flag is switched off.

Météorage made the technical choice to adapt available tried-and-tested algorithms developed for others similar applications. The advantage is they are well documented and discussed by recognized experts either in statistics or lightning physics. The two main functions of STORM and its corresponding algorithms are presented in more details in the next section.

A. Lightning cells identification

Lightning cells identification based on lightning data consists of grouping lightning flashes in an area representing the electrical active core of a thunderstorm. These flashes when they are consistent are all related to the region where the vertical updraft generates electrical charges. Interesting to note, this area is limited most often time for isolated or multi-cellular systems but might expand when a charged stratiform region tends to generate distant lightning flashes like in supercell storms. Grouping consistent lightning flashes can be achieved thanks to data clustering methods. On a short period of few minutes of lightning observation, only the separation distance between flashes must be considered to form consistent groups.

Out of all the existing clustering methods (e.g. DENCLUE, CLIQUE, MAFIA, BIRCH, CURE, GBC, Chamelon…) Météorage has chosen the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. It relies on the "Nearby Neighbors Search" technique to group points together according to their separation distance and a given local density of points [Ester et al. 1996]. Individuals that do not match those two parameters are considered as outliers.

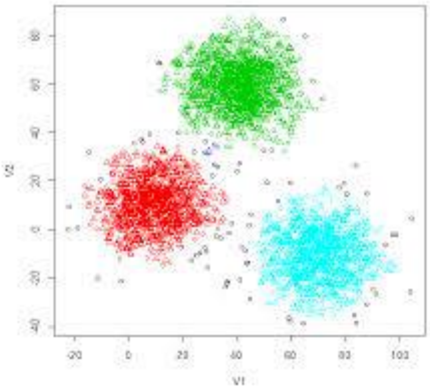

Fig 1. Example of three clusters determined with the DBSCAN algorithm (in grey are outliers).

The choice for DBSCAN was driven by its ability to handle large datasets that is relevant when considering STORM to work at a continental scale. In addition, this algorithm is also robust to outliers that is of great interest as some poor quality flash locations may pollute from time to time the lightning dataset. Finally, it is simple to parametrize as it uses only two parameters that are the local density and the maximum separation distance between two individuals. The setting of those parameters is crucial to achieve relevant cells identification. They were manually tuned on several school-cases thunderstorms for whose radar data were available. Of course, the values of these parameters are highly dependent on LLS performance (i.e. detection efficiency and location accuracy) and the type of thunderstorm being observed.

An intrinsic limitation of DBSCAN is the difficulty to accurately cluster groups of data exhibiting too much different density. This could potentially affect STORM in some situations when lightning cells at different stage of development coexist like in multi-cellular thunderstorms.

B. Cells severity assessment

After each run, the potential severity of living lightning cells is monitored based on the evolution of their individual lightning rate. Here again, several algorithms have been developed by different researchers to monitor lightning rate trends and detect the onset of the lightning jump exclusively, according to our knowledge, on the basis of VFH lightning data [Gatlin and Goodman 2010]. Out of these algorithms, the "2σ configuration" has been statically validated on various thunderstorm types and is likely to be the most effective to use for operational early warning usage [Schultz et al. 2009]. This algorithm considers the evolution of the total lightning rate as counts in one-minute intervals. The goal is to detect the onset of the lightning jump as soon as it occurs in order to issue warning messages with the bigger lead time possible. For this purpose, the flash counts difference between intervals T_0 and T_{-1} is compared to the standard deviation of the prior four intervals flash counts differences. When this value exceeds two times the standard deviation and the mean flash rate computed on the last five one-minute intervals is greater than one flash, then an alert is triggered and a "severe status" countdown of 25 minutes is started. This counter is reset each time a new jump is detected. The lightning cell remains in a "severe status" mode as long as the cell is alive or its counter is not equal to zero.

DATA USED IN THE STUDY

A. *The lightning dataset*

The French National LLS uses the most recent Vaisala's technology namely 20 LS7002 sensors dispatched across France to which are added about 60 foreign sensors (IMPACT and LS700X) belonging to neighboring national LLS partners. Two redundant Total Lightning Processors (TLP) collect and process the sensors row data in realtime. The resulting localized lightning data are continuously stored in a database, making them available for downstream applications. A recent quality control based on high speed video camera records collected during 2015 has shown Météorage's LLS detection efficiency (DE) is 97% for flashes and 94% for strokes. These results are in perfect agreement with those obtained in South-East France and more generally in Europe after similar studies based on the EUropean Cooperation LIghtning Detection (EUCLID) network which uses Météorage's data [Schulz et al, 2014; 2015]. The location accuracy is estimated around 110m based on video analysis of flashes exhibiting multi-strokes ground strike points. The cloud-to-cloud detection efficiency (DE_{CC}) is estimated to be in a range of 30 to 50% [Pédeboy et al, 2014] depending on the type of thunderstorm (Isolated storm, multi-cellular or supercell).

With such performance, it is expected the VLF/LF lightning dataset is complete enough to produce relevant cells identification and efficient severe weather alerts.

B. *Hail ground truth dataset*

The ANELFA is a nonprofit association that has started in 1951 to mitigate the risk associated with hailfalls based on vortex ground generators seeding silver iodide in thunderclouds [Dessens, 2007]. In order to estimate the efficiency of this technique several tens of passive hailpads are disseminated across fifteen departments in France (see figure 2).

A hailpad is made of a 30x40x3 cm polystyrene sensitive plate with a layer of white exterior paint to prevent spoilage due to weather and solar radiation. It is installed on a mast at a height of 1.5 m above ground [Farnell, 2009]. Begin date and time of hailfalls are manually determined by local volunteer being members of the association who send knocked hailpads to the ANELFA scientific research center for treatment. From the analysis of marks being made on the sensitive plate it is possible to determine the number, the maximum diameter, the cumulative mass and the kinematic energy of hailstones. If this very simple and cheap technique gives very nice results on hail physical parameters, it must be noted the dating of observations is subject to errors because it is made by human observers that are not always present when a hailstorm happens.

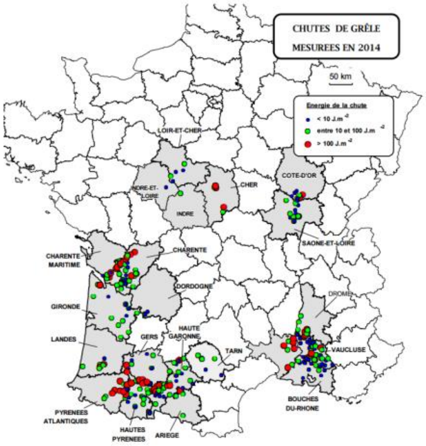

Fig 2. Members of ANELFA (in grey) and distribution of hail reports in 2014 as a function of hailfalls kinematic energy.

The hail dataset being considered in this study consists of a total of 337 reports which were registered during 73 days between January and November 2014. More than 70% of observations were made between May and July with a peak in June (34%) that is consistent with hailstorms climatology in France. The maximum hailstone diameter observed ranges from 5 to 37 mm, the mean value being 12 mm. It must be noted that only less than 5% (15) of the observations reported hailstones with a diameter greater than one inch (25 mm) that is a common admitted threshold value to qualify a severe hailstorm. Half of them occurred during the same episode on the 28th of June in the South-West France.

This one-year hail dataset is quite interesting as it encompasses observations related to different types of hail storms in several regions of France occurring during different seasons. Therefore, is interesting to test STORM performance against this complete dataset and check the sensitivity of the severe weather algorithm in respect to seasonal and regional parameters.

RESULTS AND COMMENTS

Because hail reports rely on human observers it is necessary to filter out those that are mistimed because they may affect the overall result in term of lightning cell correlation consistency and lead time warning calculation. Hail observations that do not exhibit lightning evidence within a time window of -/+ 10 minutes in respect to the hailfall dating and in a maximum range of 25 km from the hailpad location are removed. Météorage's LLS uptime is higher than 99.99% so it is unlikely a thunderstorm can be missed by the system. Therefore, using lightning data to filter out poor quality observations is expected to be relevant.

After filtering, a total of 248 reports were considered as a dataset of valid hail observations. A one-year lightning data reprocessing was carried out with STORM to compute corresponding lightning cells. Then, both cells and hail dataset were correlated on the same criteria basis, separation distance and time window, as presented here below in order to associate cells with their corresponding hail reports.

A. *Hail observation without an associated cell*

The result of the correlation analysis shows 103 (41%) hail observations are not associated with any lightning cell despite lightning flashes were recorded in their vicinity. A detailed review of these particular cases revealed several causes for this lack of correlation.

1) Seasonal dependency:

It is known that some thunderstorms tend to produce very few lightning particularly during winter time because the convection process is weak. On the graph below (see fig. 3), monthly distribution of both correlated (red) and non-correlated (blue) hail reports shows a clear seasonal dependency. Most of the uncorrelated hail reports were observed between January to May that correspond to winter and beginning of spring in France. The row of figures above the bars represent the total number of monthly observations being processed.

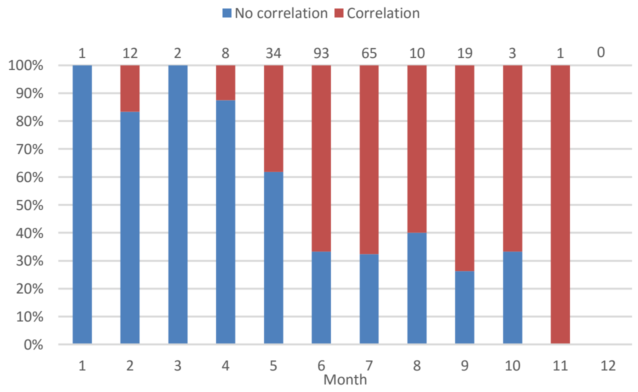

Fig 3. Monthly distribution of the correlated and non-correlated cells

This result confirms the lack of lightning data characterizing winter thunderstorms affects the cell identification process. This is not surprising as DBSCAN uses a threshold on the local density that is likely to not be reached when only few lightning produce.

On the graph below (fig. 4) one can see the evolution of the percentile 75th for hailstone diameters as a function of months. The upper row of figures represents the monthly number of hail observations involved in the statistics computation.

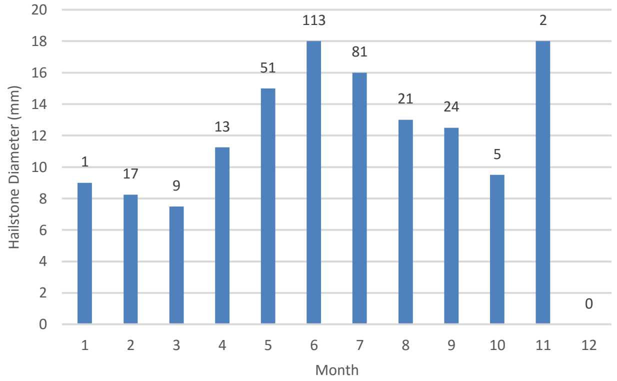

Fig 4. Monthly distribution of hailstones diameter

A clear trend shows that hailstones being produced during winter hailstorms are statically smaller than in summer time. It is expected the resulting damages on the ground are of less importance. This result tends to mitigate the poor results of STORM on winter hail data implying operational services might not suffer too much from this lack of cell detection and warning.

2) DBSCAN parameters

It can be noticed on fig. 3 that about 30% of hail reports are not correlated with electrical cells during spring and autumn periods. The lack of convection cannot be the reason explaining this result. A detailed review of these uncorrelated summer cases shows the local density criteria used to group lightning data is too strict. As a result, a storm cell may be split if at a given moment it exhibits a weaker flash rate during its lifecycle in the way the local density threshold criteria is no more fulfilled. As a result, STORM will shorten the active cell life. When the flash rate and the local density increases again then a new cell is created.

B. *Hail observation with an associated cell*

A review of the 145 correlated reports shows some of them match with more than one electrical cell. This mainly happens when multi-cellular storms are passing through hailpads resulting in a bunch of several potential candidates being correlated. Because of their proximity, storm cells in such systems fit the correlation criteria used in this study. In these specific cases, the closest cell in distance exhibiting the minimum time difference is selected as responsible for hail.

1) Consistency of the lightning cell correlation

A total of 82 different lightning cells were correlated with 145 hail reports among which 19 (22%) exhibit more than one single hail observation. Interesting to note the time correlation between cells and hail reports fit very well as 86% of the observation dataset is correlated within -/+5 minutes and nearly 70% hail and cell dating match perfectly with no time difference. In addition, the median separation distance between cells barycenter and hailpad locations is about 10 km that is in the order of magnitude of a typical storm cell. According to the very good match between both dataset, it is expected very few or none miscorrelated cells are likely to pollute the severe warning alert performances analysis.

As an example, figure 5 shows an example of two lightning cells identified by STORM on the 9th of June 2014 at night in the South-West France. Both cells are moving in parallel at a similar speed and at distance of 40 km. The total path length corresponding to 3 hours of observation is about 300 km. observed during One can see the very nice match between cell data and hailfalls recorded by the ANELFA. Interesting to note the northern cell splits in two between Niort and Poitiers.

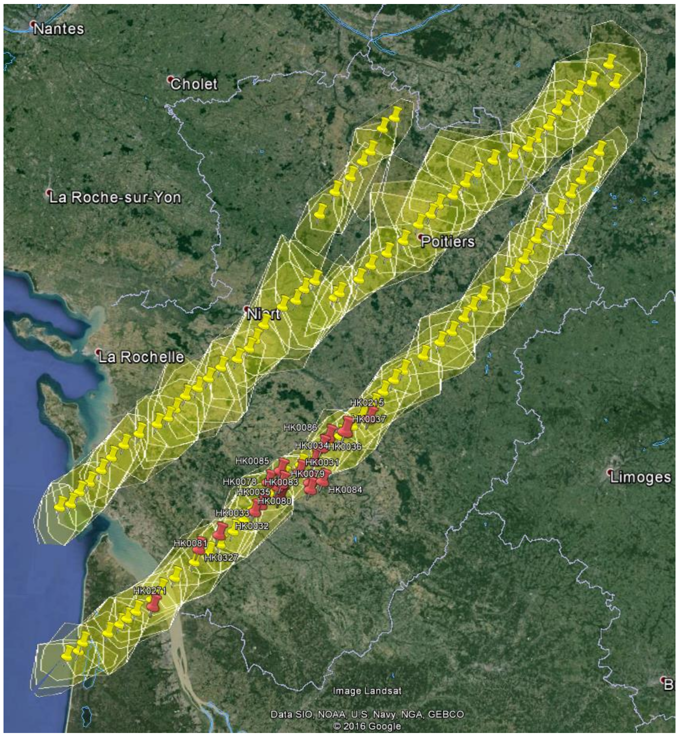

Fig 5. Lightning cells computed by STORM between 00:00 and 03:00 UTC on the 9th of June 2014 in South-West France. Lightning cells are materialized by their barycenter (yellow pins) and contours (yellow areas). Hailfalls locations are represented by red pins.

2) *Severe warning alerts analysis*

Out of the 82 hail correlated cells, 19 exhibit no lightning jump. Most of them occurred during the hailstorm period so no seasonal effect can explain this result. Indeed, the convective character of thunderstorms seems to be proved as the 75th percentile of hailstone diameter is about 16 mm. A case by case analysis shows the corresponding cells lasted 19 min in average with a standard deviation of 4 min. These durations seem relatively short to produce severe weather whereas the comparison with the mean duration of correlated cells in which a lightning jump was detected is 38 minutes. This result might be related to the clustering algorithm settings but must be further investigated in a future work.

Finally, this is an overall dataset of 63 severe cells associated with 120 hail reports that is available to assess performance of the severe weather detection algorithm. Assuming that all 145 hail reports are related to a severe cell that should have produced a lightning jump, STORM reaches a Probability of Detection (POD) is 82%. Interesting to note, the same parameter increases to 89% and 100% for cells exhibiting hailstones respectively larger than 20 mm and 25 mm in diameter. Note this computation is done on a reduced dataset that do not take into account cases where STORM failed to identify a lightning cell with hail reports. If these cases are considered, and again the assumption that all 248 hail reports should have led to the identification of a cell, then the POD drops down to 48%, then 60% and 80% respectively for cells producing hailstones larger than 20 mm and 25mm.

The warning lead time is defined as the period between the time an alarm is triggered by the lightning jump algorithm and the time of hail observation. Figure 6 shows a quite large distribution of warning lead times ranging from 0 to 60 min. This results from the wide varieties of thunderstorm types being considered in this study occurring in different seasons and terrain conditions. Nevertheless, the mean lead time computed is about 15 min increasing to 18 min when only cells producing hailstones of a diameter greater or equal to 25 mm are taken into account.

Assuming a 10 min delay is sufficient enough to deliver an efficient severe weather warning for most of operational applications, then STORM is successful to release relevant warning messages in 63% of all cases.

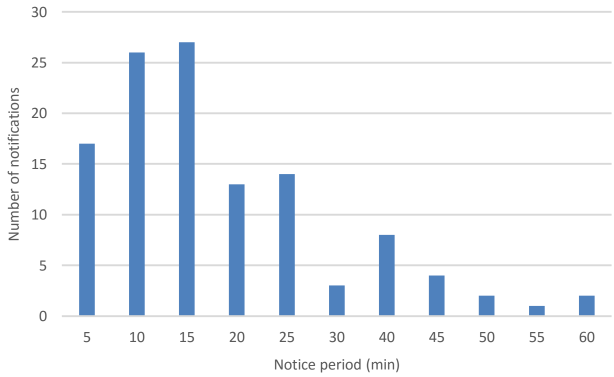

Fig 6. Distribution of the notice period computed as a function of duration in minutes.

DISCUSSION

The capability to reproduce realistic storm cells as they actually produce in nature directly depends on performances in term of detection efficiency and location accuracy of the lightning locating system being used. The same remark must be done regarding the “severe weather” assessment based on the lightning jump as the increase of the flash rate in a severe storm is mainly driven by CC [Williams et al, 1999] and only relying on CG flashes is not relevant [Soula et al, 2004; Schultz 2011]. These statements might be a point when considering VLF/LF systems mainly because of the limited CC discharges detection efficiency compared to VHF systems. Indeed, most of studies found in literature are based on LMA data [Rison et al, 1999] that are known to detect nearly 100% of the total lightning flashes occurring in a thunderstorm. Using a less comprehensive lightning dataset (i.e. VLF/LF lightning data) to build an efficient lightning cell identification and lightning jump detection tool is a challenging project that requires a clear validation.

The methodology chosen for this study consists of identifying severe cells based on hail observations reported by human observers. If these reports can be considered as ground truth data, it turns out the dating is subject to errors. Big dating errors can easily be filtered but in some cases small dating errors may produce cells misclassification and affect the overall result. Nevertheless, this simple method is considered to be relevant as a preliminary study of STORM performance, but no doubts future works should compare STORM alerts with severe weather observations based on radar data or VLF/LF lightning cell with LMA data.

The POD depends on the type of storm as there is a clear relation between POD and size of hailstones. This result is interesting and tends to validate the assumption stating all hail observations reported by ANELFA should have led to the identification of a lightning cell is not true in all cases. Indeed, observations reporting small sized hailstones are in general not correlated with a lightning cell because they are likely to produce few lightning. Furthermore, mistimed reports might also affect the calculation of the POD, so these POD values are expected to be conservative.

The capability of STORM to detect severe weather is not only depending on the lightning jump algorithm settings but relies also on the lightning cell identification. Of course, thunderstorms producing few lightning are not likely to be detected that is somehow not a limitation of STORM but clearly a physical drawback for LLS. However, putting apart these special cases, a particular attention shall be applied to the lightning data clustering settings in order it do not to split a real storm preventing so the detection of a jump in the flash rate, nor to merge several cells together otherwise false alarms might be issued. It must be noted, the False Alarm Rate (FAR) parameter has not been assessed in this study but it remains an objective in a future work.

The performance of STORM in term of POD and warning lead time obtained in this study are encouraging as they are consistent with those that can be found in literature (Schultz et al, 2009). Indeed, these author who have extensively studied several lightning jump algorithms claim the POD for a “2σ configuration” is 89% and the mean lead time is 20 minutes to be respectively compared to our 80% and 15 minutes. Important to note, their results are based on LMA data so they can be seen as a reference in comparison to STORM performances. Thus, the first result obtained in this study demonstrate the relevancy of using VLF/LF lightning in lightning cell identification and lightning jump detection.

CONCLUSION

Météorage has developed a storm cell identification and tracking algorithm, so called STORM, based on total lightning VLF/LF lightning data. Coupled with a “2σ configuration” lightning jump algorithm it is capable to monitor and detect a sudden increase in the total flash rate and trigger severe weather alerts.

This study, consisting in comparing computed lightning cells against 248 hail reports collected by the ANELFA during 2014 across France, led to some noticeable preliminary results.

First, the use of VLF/LF lightning data to identify and track thunderstorms is relevant since a POD of 80% is found when considering storms producing severe hail (hailstones with a diameter equal to or greater than 25mm), the same parameter dropping down to 48% on the overall dataset. However, this latter result must be mitigated because it is expected to be conservative. Indeed, it is very likely to be affected both by mistimed hail reports that prevent STORM to identify a given cell as well as hailstorms producing few lightning. To support this latter statement, a clear seasonal dependency was found showing the winter or early spring hailstorms are less detected by STORM than those occurring in rest of the year. Second, the mean warning lead time observed is 15 min on the overall dataset but increases up to 18 min when only severe storms are considered.

These first results are consistent with those of similar studies that can be found in literature (Schultz et al, 2009). They are encouraging since an optimization in the settings of the local density clustering parameter might result in an improvement in lightning cell identification.

Finally, further work must be carried out to extend the validation of STORM performances against radar and LMA data in order to better understand the relation between VLF/LF lightning cell and other physical thunderstorm parameters.

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