Detection of atmospheric lightning activity with ground-based radiofrequency receivers – establishment and initial results

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Understanding atmospheric lightning flashes and their occurrences is one of the most important aspects of the Earth's climate science. Real-time lightning data have profound importance in climate science, air-quality research and atmospheric nitrogen budget, apart from lightning being one of the major natural disasters. Keeping these in view, a lightning detection sensor (LDS) network has been established at six locations in India, viz. Kolkata, Ranchi, Raipur, Bhubaneswar, Nagpur and Visakhapatnam. Preliminary analysis of the data suggests that it is possible to detect the phenomenon and identify vulnerable zones of lightning activity. We analysed the Kolkata, Ranchi and Visakhapatnam data during June–July 2017 to identify the areas with major impact by cloud-to-ground lightning events and also see if a warning can be provided based on single-sensor data. Status of the ongoing development in LDS network is discussed here based on the current understanding of existing lightning detection networks.

Keywords: Cloud-to-ground events, lighting detection, natural hazards, radiofrequency sensors.

UNDERSTANDING lightning physics and future scenarios of lightning strokes and flashes is an important feature of the Earth's climate science[1]. At present our ability to predict future climate changes in the global lightning activity is limited because it depends on a better understanding of the climate system, including the impact of anthropogenic activities and the influence of external factors such as solar activity on lightning.

Lightning data and their usage in operational weather forecasting have shown phenomenal improvements in extreme events[2]. Further, identifying the hot spots of lightning occurrences and early detection of lightning strikes are required to mitigate the loss of life[3]. The lightning strokes produce NO_x which is immediately transferred to the ground and has important consequences in surface ozone chemistry[4]. In recent times, it is well understood that lightning activity is an indicator of weather and climate change[5]. Romps *et al.*[6] have shown that a rise in surface temperature can enhance the occurrences of lighting activity. The global warming becoming prominent in the Antarctica region further supports the above[7]. Of importance to this is the fact that lightning and cumulus activity are the source of atmospheric perturbations known as gravity waves, which are important coupling agents across different atmospheric regions[8,9]. In short, characterization of lightning activity is important for the lower atmosphere and disaster management, and also to resolve some of the least understood features in the upper atmosphere.

In terms of spaceborne exploration, the lightning imaging sensor (LIS) on-board the tropical rainfall measuring mission (TRMM), provided snapshot information and helped in characterizing the occurrences of lightning. At present, a GOES-R mission is launched to cover the American Subcontinent sector using the GLM sensor. However, for exact monitoring with temporal characteristics and societal applications such as identification of potential danger zones and now-casting, only ground-based VHF/UHF receivers have been found useful since more than a decade. Using this method, few countries such as USA, Brazil, Poland, Finland and Japan have established a dense network of long-range lightning detection sensors. In the Indian sector, India Meteorological Department (IMD), New Delhi through the Indian Institute of Tropical Meteorology (IITM), Pune has initiated such a network.

The present study showcases the installations carried out by the National Remote Sensing Centre (NRSC), Indian Space Research Organisation towards a nation-wide network, characterizing the cloud-to-ground lightning (CG) occurrences over specific regions and the learnings so far. We also present a method of identifying potential danger/vulnerable zones using single-sensor data and possible further planned improvements.

The lightning detection sensor (LDS) used in this study is (Boltek-LD-350) Canada[1]. The receiver antenna is omni-directional which detects frequency ranging from 50 to 500 kHz. This corresponds to wavelengths of 6000–600 m, i.e. the electromagnetic processes occurring at scale size of 0.3–3 km are captured by LDS which is highly suitable to detect the cumulus processes, including lightning which arises due to thunder clouds. This antenna has interface with a global positioning system (GPS) antenna for accurate time stamping of the signal received. This tuned with the sky wave oscillation caused by the sferics which are GPS-referenced provides the range of lighting occurrences. The waveform received is in the form of '$A.\cos(wt + \varphi)$', which provides amplitude A, frequency w and phase φ information. Through correlated frequency and phase differences, the range is estimated.

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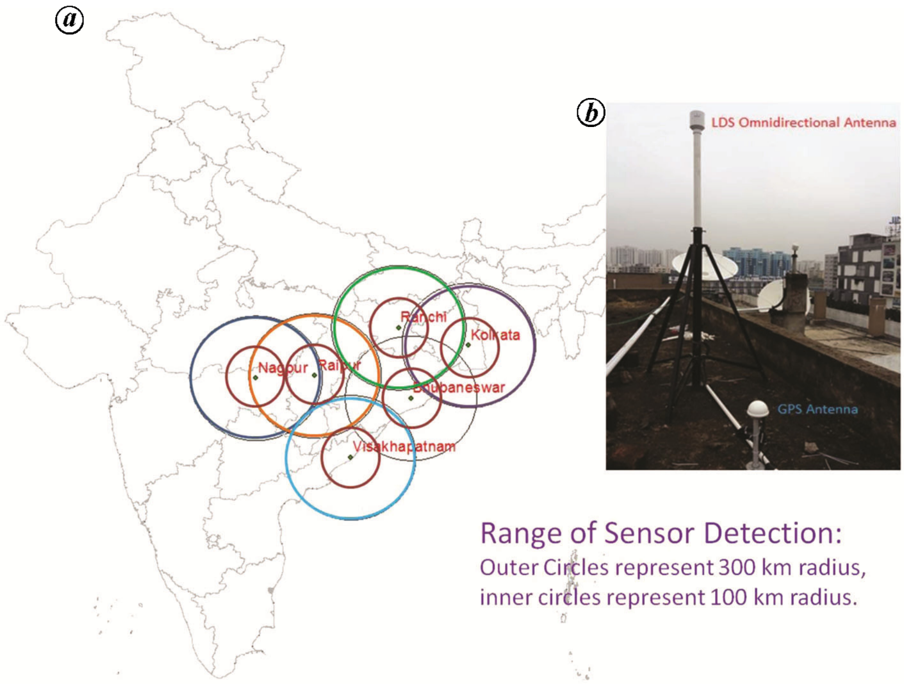

Figure 1. ***a***, Map of India showing the existing lightning detection sensors (LDS) and their radius of detection. ***b***, A typical LDS set-up.

This LDS also uses gated magnetic direction finder to estimate the direction of lightning occurrences.

Note that individual sensors used in the present study have magnetic direction finders. The LDS antenna uses the characteristics of lightning waveforms which estimates the distance of CG return strokes from the sensor. Because this is a single-point lightning detection system, multiple strikes originating from a thunderstorm at a specific distance get averaged out over the sampling window. So essentially the geographical location of individual strike discharges will not be accurate with a single-point lightning sensor, while the location of storm cells in most cases is good enough to provide early warning of approaching dangerous weather. We also utilize the natural noise produced by a thunderstorm to better estimate distances to close storms. This noise is simply weak but frequent in cloud discharges that are not detected by the sensor at ranges over 30–50 km. The noise will increase in strength the closer a storm moves to a sensor. Together, we feed accurate locations of the sensor installation which enables the geolocation of lightning strike occurrences with precision better than 0.02°. A typical installation of the LDS is shown in Figure 1 along with those at six locations. As the calibration of individual sensors remains a difficult task, we opted for validating our data with ground-truth measurements (newspapers, observers' inputs and other sources), which have been elaborated by Taori *et al.*[10]. It should be mentioned here that though IMD and IITM have started a network, the sensitivity of the sensors is different. While the IMD/IITM sensors work in 1 Hz to 12 MHz frequency range; the NRSC sensors work in the frequency range of 1 Hz to 30 MHz, apart from their functional differences arising due to different makes. The differences in frequency range emphasize the scale sizes of electromagnetic waves to be in a wider range in the sensor used in the NRSC LDS network.

The LDS antenna is operated using the NexStorm software and data are transferred to the connected PC. The raw data transferred show the time, range, bearing angle, strike rate per minute and type of lightning with polarity and number of flashes. Though data are collected every second, a text file is created every 5 min summarizing the occurrences. However, for the identified lightning cluster, it provides an average position. This introduces a position inaccuracy ranging from 20 m to 5 km depending on the velocity of the cluster. In one summary file, there can be as high as 20 clusters. The obtained data have been plotted over the geographical information system (GIS). Figure 2 shows a sample data based on the sensor located at Kolkata, overlaid on the GIS. Noteworthy is that in spite of due care, there may still be the signature of radial biases which can be addressed through our modified lightning detection network, which relies on a combination of LD-350 sensors and LRX sensors. The CG lightning flashes are shown as filled circles. The colour indicates CG flash occurrences, with more number representing the phenomenon to be more severe. Note that the number of flashes is not calibrated; hence, it is considered to be in relative units instead of an absolute number. The CG flash occurrences and spatial accuracy are elaborated elsewhere[9].

We analysed the uninterrupted LDS data collected during June–July 2017 from the sensors located at Kolkata, Ranchi and Visakhapatnam. The CG flashes recorded using Kolkata sensor data are plotted in Figure 3 for June (left panel) and July (right panel) 2017. We can see that South 24 Parganas, Barddhaman, Howrah, Kolkata and North 24 Parganas are the most affected areas in June. Also noteworthy is that 5–25 June 2017 was the duration when CG lighting occurrences were frequent. In July, South 24 Parganas and Barddhaman were the most affected areas. The CG lighting occurrences were frequent during 10 to 24 July 2017.

Figure 4 shows the data collected by the sensor located at Ranchi for June and July 2017. The data reveal 4–16 June and 26–30 June 2017 to be the durations when CG lightning occurrences were frequent. Ranchi, Khunti and West Singhbhum are found to be the most vulnerable districts among these covered by this sensor. In July, Ranchi and Lohardaga are found to be the most affected areas with 4–30 July being the duration of frequent lightning occurrences.

The LDS located at Visakhapatnam also reveals similar pattern of lighting occurrences (Figure 5). During 6–16 June 2017 the CG occurrences were frequent, as also during 18–30 July 2017. In June 2017, Visakhapatnam, Vizainagaram and East Godawari districts were vulnerable, while in July 2017 only Visakhapatnam was the most affected district among those covered by the LDS sensor.

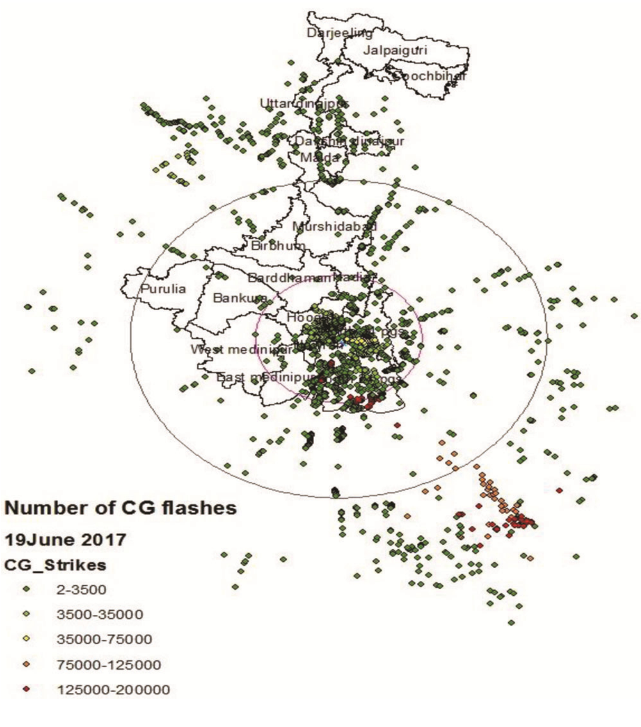

Figure 2. Number of cloud-to-ground (CG) lightning flashes as recorded by the LDS in Kolkata. Inner and outer circles represent 100 and 300 km radius respectively.

The post-analysis of data with geospatial information can provide statistics of the lightning occurrences at the district level with position and temporal accuracy as discussed above. With respect to the societal implications, warnings about vulnerable areas in timesscales less than 2 h are important.

It is possible to forecast the likelihood of intense lightning activity but it is impossible to predict actual strikes since lightning occurrences are so widespread, frequent and random. There are two ways to address the issue of identifying vulnerable areas. One is to club all sensor data and perform time-of-arrival method on the super dataset, while in the other case, apply the time-of-arrival method on single-sensor data. As first method (while it is more accurate) depends on simultaneous multiple sensor data, we showcase our method on second method for identifying and warning the potential vulnerable zones.

Important to emphasize is that the processes related to cloud electrification have still not been completely understood; hence physics-based methods often fail. We have developed a methodology which can provide lightning alerts using data-mining techniques by the process of unsupervised learning. The available lightning flash data and information are used to predict possible future strikes. This is because lightning flashes originate when charge polarization starts, while the strikes occur when it reaches the ground. Every flash need not result in a strike; however, more number of flashes does indicate the occurrence of a strike. The methodology basically adopts cluster analysis and understanding the evolution of such clusters over time to predict the future scenario. Lightning strike data from the past 1 h to time $t = 0$ are used to achieve this. The cluster selection is based on the maximum number of CG occurrences and based on the last 1 h of data, only those points are selected which have more than 80% of CG occurrences. The available lightning strike locations are geo-located, which makes it easier to visualize these clusters on a map. These lightning flash locations serve as datapoints to partition them into a small number of clusters. As an example, suppose there are x number of datapoints, these are divided into k number of clusters. The algorithm starts with initial estimates of k centroids, which are first assumed to be 20 in number and then they converge down to a few. This routine runs for about 2 h for examining the validity and the number of centroids, before it starts assessing the future scenario ($T + 30$ min, $T + 45$ min). For example, when the distance between a group is less than 4 km (at about 100 km range), they are considered to be part of the same group with a centroid. Each centroid defines one of the clusters. Then each datapoint is assigned to k centroids based on the Euclidean distance between the two clusters. If c_i is a collection of centroids

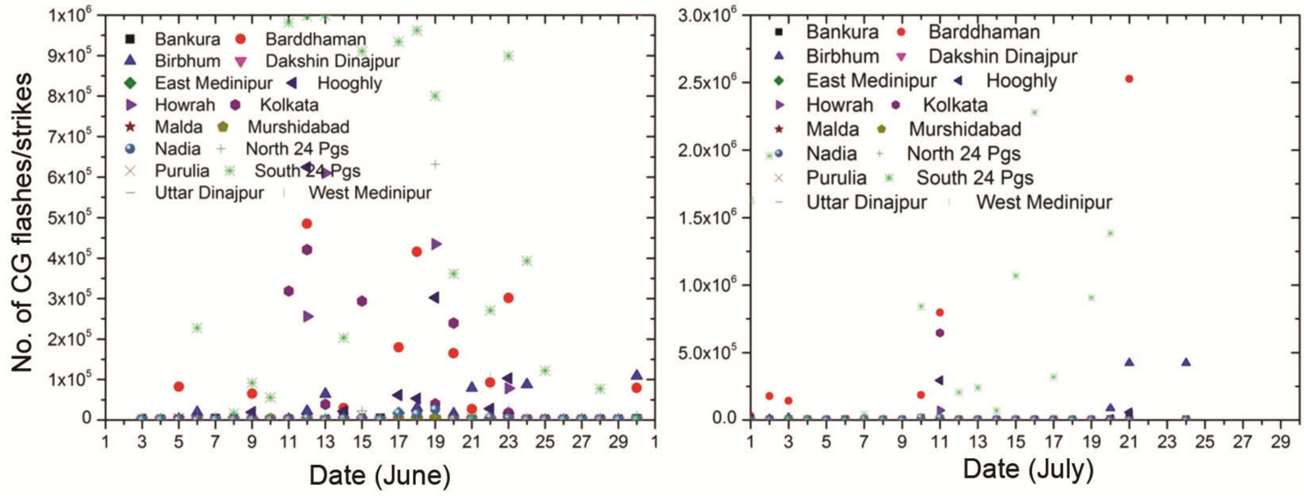

Figure 3. District-wise statistics on the number of CG lightning flashes that occurred in West Bengal as detected by the LDS in Kolkata.

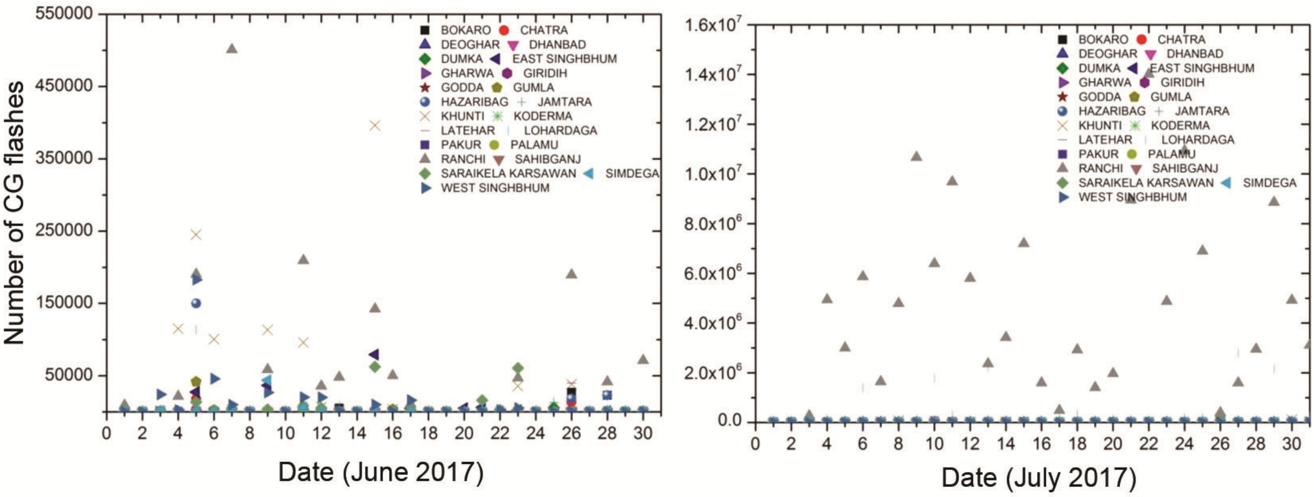

Figure 4. District-wise statistics on the number of CG lightning flashes that occurred in Jharkhand as detected the LDS in Ranchi.

in set C, then each datapoint x is assigned to a cluster based on

$$\arg\min_{c_i \in C} \operatorname{dist}(C_i, x)^2, \tag{1}$$

where $\operatorname{dist}(c_i, x)$ is the standard Euclidian distance. Let us assign S_i to datapoints of the ith cluster. Now the centroids are recalculated using the mean of all data assigned to the centroid of that cluster.

$$c_i = \frac{1}{|S_i|} \sum_{x_i \in S_i} x_i. \tag{2}$$

The algorithm reiterates the above-mentioned steps until the datapoints do not change clusters, or the sum of distances is minimized or until the maximum specified iterations is reached. These cluster centroids can give us an understanding of the general direction of movement of the cluster. The velocity of these clusters is calculated by taking into account the lightning flash data from the past 2 h and observing the movement in this given time using cluster centroids available at every 5 min intervals. This is required to obtain the stabilized velocity vector of the cluster movement. It is based on the present data and may also be reduced to 1 h once a denser network of sensors is established. The velocity vector is thus obtained using the movement of cluster centroids by cross-correlating them. Using this speed and direction, the future positions of these centroids are computed.

This early-warning system provides potential danger-zone information together with the severity of the CG strikes. For this, the number of flashes at a particular location every 5 min is used. Every 5 min incoming data are included in the velocity estimate and the velocity vector is changed with the time of reference continuously. As

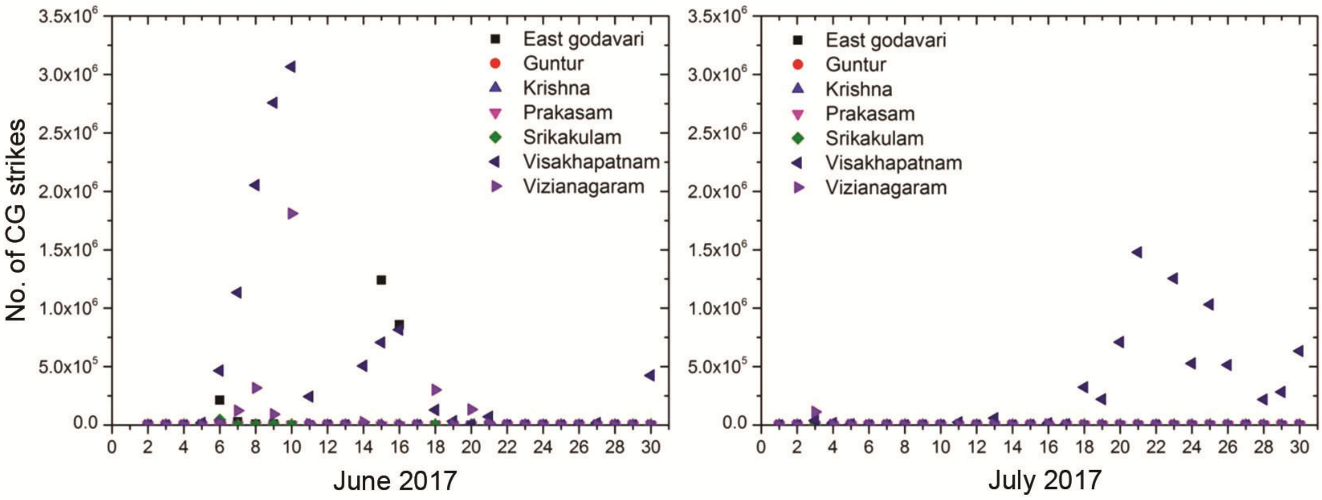

Figure 5. District-wise statistics on the number of CG lightning flashes that occurred in Andhra Pradesh as detected by the LDS in Visakhapatnam.

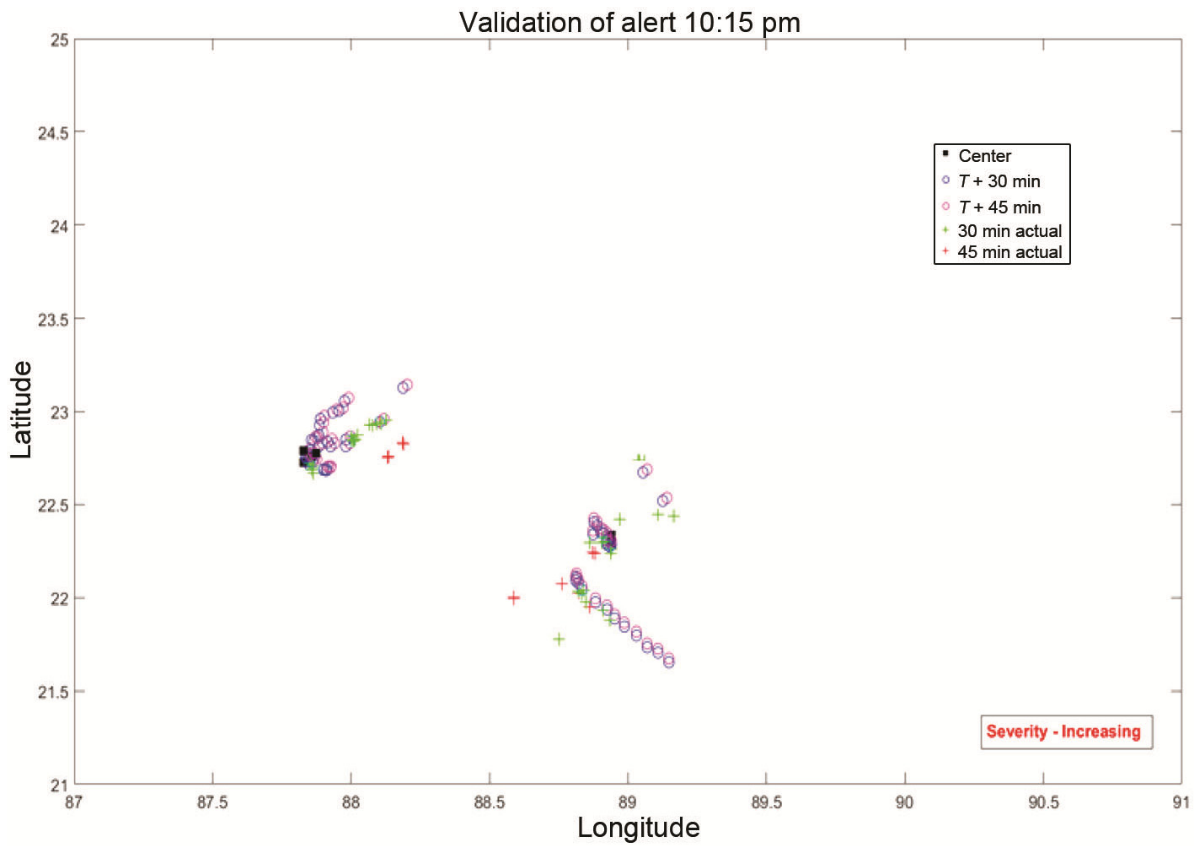

Figure 6. Sample performance of the methodology applied on LDS data from Kolkata. Black squares show the number of clusters and their movement. The identification of clusters at 30 and 45 min in advance is shown as blue and purple coloured open circles respectively. The actual occurrences as noted by the real data are shown as green squares. The warning is given at 10 : 15 pm, while the actual occurrences are laid down at 10 : 45 and 11 : 00 pm.

this algorithm may overestimate possible CG strike locations, a cut-off has been computed based on regression from multiple outputs. Any datapoint where the number of strikes is less than 10% of the mean strikes of a cluster in a given hour, using which the velocity is computed, will be removed. This has improved the accuracy for possible strike locations. Also, based on whether the number of flashes in a given hour is increasing or decreasing an alert system has been set-up, which will notify the observer if the strikes are getting severe or not. This information is based on the slope of CG flash occurrences. When the occurrences are increasing, the slope is more than 1 indicating that severity of CG strikes will increase.

Once the above processing starts, every 5 min data are integrated in the computation and at every 5 min interval, an estimate of vulnerable locations is made. This makes the computation dynamic and the warning system takes care of real-time movement of clusters and variability of thunder-cloud processes occurring within the clouds. Figure 6 shows a sample performance of this methodology applied on the Kolkata LDS data. This warning method is based on CG lightning flash data only. We noted nominal improvements when total lightning data is used. However, more effective warning can be obtained when the real time lightning data are fed in the weather forecasting models such as WRF-Elect. This may not only increase the lead time, but also the discontinuities occurring due to data gaps in spatial as well as temporal domain. With the real-time trend of occurrences, it would be possible to predict whether severity of lightning occurrences is increasing or decreasing (as shown in the right bottom corner of Figure 6).

Based on the errors, artefacts and limitations of geo-locating the lightning occurrences, NRSC has planned an expansion of the LDS network with a combination of LD-350 and LRX sensors. The long-range LRX sensors work on time-of-arrival algorithm where correlated lightning flashes are determined based on GPS-stamped waveforms. High accuracy of LD-350 sensors at near range can be used for estimation after removal of noise and artefacts. As far as the nationwide coverage is concerned, overlapping area of sensor range analysis suggests that about 64 sensors (having range >300 km) could provide nationwide uninterrupted monitoring of the atmospheric lightning phenomenon. Initial results obtained from these sensors reveal good number of lightning occurrences over the Indian Ocean correlated with INSAT-3D maps of cyclonic activity, highlighting the capability of the LD-350 and LRX sensors (not discussed here). Further, now casting shall be based on a combination of information on model and cluster analysis as shown in this study.

In summary, atmospheric lightning activity is being regularly recorded with the help of radiofrequency sensors installed by NRSC at six locations. The vulnerable zones can also be classified depending on the number of CG lightning flashes. It is also possible to provide a warning of lighting occurrences 30–45 min in advance. However, cross-validation of data and sufficient statistics are required for providing classification of vulnerable areas, while warning about the lightning occurrences requires data feed of such occurrences into the model apart from a cluster analysis-based system.

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