GIS enabled thunderstorm forecasting system for one of the world's hotspot region for severe thunderstorms

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Abstract

The eastern parts of India, Bangladesh, and the North Eastern Region (NER) of India are among the world's most active areas for thunderstorms and lightning, resulting in substantial human and livestock casualties annually. Lightning strikes cause over 500 fatalities in India and approximately 300 in Bangladesh each year, alongside significant property damage and loss of wildlife, such as the death of 18 elephants in Assam in 2021. To mitigate the devastating effects, this study developed a pilot-scale forecasting system for lightning and thunderstorms over the NER of India, leveraging space-based platforms, ground-based detectors, and numerical models. Data sources included the WWLLN (World Wide Lightning Location Network), India's national lightning detection network, Doppler Weather Radar (DWR), and satellite data from INSAT 3D/3DS. The WRF-ELEC model was employed for forecasting, assimilating lightning data via nudging techniques, and achieving forecasts with up to 75% accuracy for lead times of up to four hours. A GIS-based system was used to track convective systems and predict impacted areas at a village level with a one-hour lead time. This system integrates lightning detection, satellite imagery, and DWR data, enabling the identification of affected populations and land use, thereby aiding in disaster preparedness and mitigation. The study demonstrates the potential of integrating earth observation data, in-situ measurements, and numerical models to provide location-specific and time-sensitive lightning forecasts. Coupled with awareness campaigns on safety measures during lightning, this approach offers a robust mechanism to reduce casualties and property damage. Scaling this system beyond the pilot region could significantly enhance disaster risk reduction in other lightning-prone regions.

Keywords: Thunderstorm, NER of India, WRF-ELEC

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1. Introduction

Meteorological disasters associated with strong convective cloud systems are typically lightning, gusty wind, flash flood, cloud burst, hails, and tornadoes. Of these, lightning is one of the major disasters that damage property and life in India and worldwide (Ghosh et al., 2023). The eastern India, Bangladesh, and western parts of the North Eastern Region (NER) of India are one of the severe thunderstorm and lightning hotspots across the globe (Srivastava et al., 2023). There are several other hotspots of lightning, but this region, due to high density of population, is severely impacted by lightning. There are more than 500 deaths within the Indian part of this hotspot alone. Approximately 300 people die in Bangladesh as well by lightning strike every year. In addition, a large number of cattle, particularly cows, goats, sheep, and other domestic animal also die because of lightning strikes. In 2021, 18 elephants died in a single lightning strike in Assam, India. Thunderstorm strikes also damages electrical appliances very often, cause fire (both forest fires and fires to residential properties), and the wind associated with the thunderstorm uproot trees, poles, and cause severe damage to residential properties. Lightning has been identified as the natural disaster that kills highest number of human every year in India. This has brought significant attention of policy makers and meteorologists alike, to look for ways to reduce risk from lightning disaster.

There are several initiatives by different agencies to develop ways to mitigate the damage from thunderstorm disaster. Forecasting is envisaged as one of the most effective ways to save life and properties from such disaster. The lightning in a Thunderstorm is the major damaging component and is also most dynamic. The impact of lightning is very localized but fatal. However, with little care, very precious life can be saved from lighting strikes. It has been seen in India that most of the life lost by lightning strikes are those who normally works in the open field, like the farmers. As thunderstorm over the eastern and north eastern India is a short lived phenomenon, these farmers can be saved by providing a timely alert on impending thunderstorm event. This study has therefore been taken up to provide a location and time specific warning on thunderstorm using data from space based platform, radars, lightning detectors, and numerical model over the NE region of India on pilot scale. The same could be extended over the entire hotspot region based on success in the pilot level. Figure 1 provides a spatial distribution of lightning over the India and the surrounding region that was obtained using the 15 years (1998 – 2013) data from the Lightning Imaging Sensor (LIS) on-board the TRMM (Tropical Rainfall Measuring Mission) satellite for the pre-monsoon season (March-April-May).

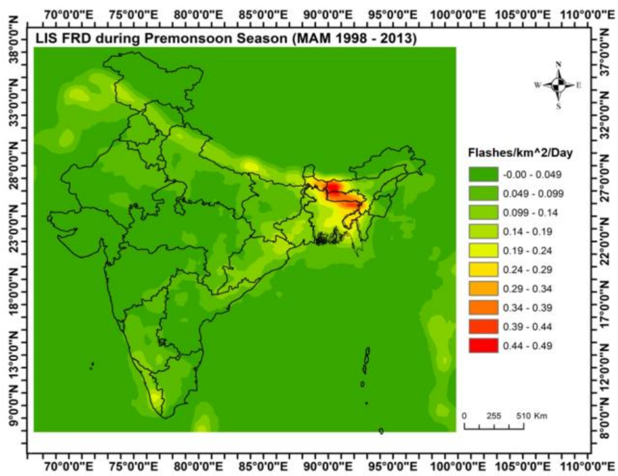

Fig 1: Lightning strike density over India and adjoining areas during pre-monsoon season obtained using the LIS sensor data on-board the TRMM satellite

An accurate lightning nowcasting system has the potential to save thousands of lives every year. It is therefore of paramount importance to have a national/state level system for lightning early warning up to the last mile dissemination. However, while the forecasting/nowcasting of severe storm has improved over the years, the nowcasting of lightning, particularly the lightning time and location nowcasting with an acceptable accuracy has remained challenging. Several attempts by public sector organizations as well as private sector agencies to provide such warning services are ongoing at national level in India. The current study focuses on possibilities of developing a lightning forecasting system for the North Eastern Region of India.

2. Study area and meteorology

The study has been taken up by looking at the atmospheric conditions over the entire eastern and NE region of India and Bangladesh covering the area bounded by the box from 20° - 30° N Latitude and 90° - 100° E Longitude as shown in Figure 2. The pilot scale study has been taken up to forecast thunderstorms over the NE region of India consisting of eight states viz., Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura.

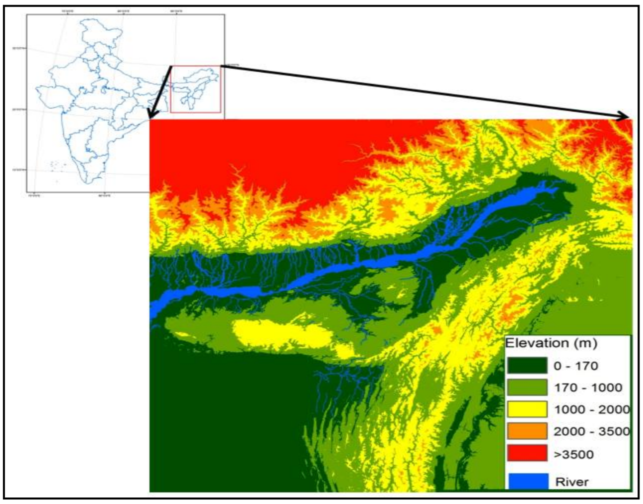

Fig 2: The study area with elevation profile. The unique terrain over the study region makes it vulnerable to severe lightning

The study area can broadly be divided into three ecological and geographical zones: the Eastern Himalayas, the Brahmaputra and Barak river basins, and the hilly terrains of Northeast India. Each of these zones is characterized by distinct ecological and biodiversity features (Singh et al., 2002). Based on Köppen's climate classification, the majority of Northeast India falls under a humid subtropical regime (Cwa and Cfa), although high-altitude regions such as Arunachal Pradesh and Sikkim experience alpine conditions, with cold, snowy winters and milder summers (Kottek et al., 2006). The region's climate is profoundly influenced by its diverse physiography—comprising the Himalayan ranges to the north, the Meghalaya Plateau to the south, and the rugged hills of Nagaland, Manipur, and Mizoram to the east (Sen Roy & Balling, 2004). Additionally, the Barail range serves as a climatic divide between the Brahmaputra plains in the north and the Cachar plains to the south, shaping local variations in precipitation and temperature (Das et al., 2010).

The season in NE region of India can be divided into four seasons. The months of March to May are classified as pre-monsoon season. The widely known monsoon season passes through June to September months while the post-monsoon season in from October and November months. The NE region's winter season is covered during the December to February months (India Meteorological Department, 2010). The weather in Northeast India is strongly influenced by the Bay of Bengal and the region's hilly landscape. The plains along the Brahmaputra and Barak rivers usually experience warm temperatures and high humidity. As you move up into the hills, the air becomes cooler and less humid, and in the higher parts of the Himalayas, temperatures can drop below freezing. Some of these areas near the Indo-Tibet border even have snow throughout the year. This region also shares borders with several countries — China to the north, Myanmar to the east, Bangladesh to the southwest, and Bhutan to the northwest.

3. Data and methodology

The data from multiple sources have been used for the study. The lightning information has been taken from the WWLLN (World Wide Lightning Location Network) and the Indian national network of lightning detectors set up by Indian Institute of Tropical Meteorology (IITM), Pune. The satellite data in Thermal Infrared channel from INSAT 3D/3DS, and Doppler Weather Radar (DWR) data from the Sohra (erstwhile Cherrapunjee), Meghalaya, India has also been used. The numerical model WRF (Weather Research and Forecasting) and WRF-ELEC has been used to simulate the lightning.

The WRF model is developed by National Centers for Environmental prediction (NCEP). The model produces atmospheric variables like winds, temperature, soil moisture, precipitation, etc. WRF model is used by researchers across the globe for forecasting rainfall, temperature, humidity, and even to forecast lightning. A new physics parameterization method was proposed by Price and Rind (1992) which can be used to assess the count of lightning flash. We can also use another parameter called the lightning potential index (LPI) that is also available in WRF model. A famous publication by Fierro et al. (2013) used the scale of cloud-resolving level for studying the Physics behind the charging and discharging within a convective cloud system.

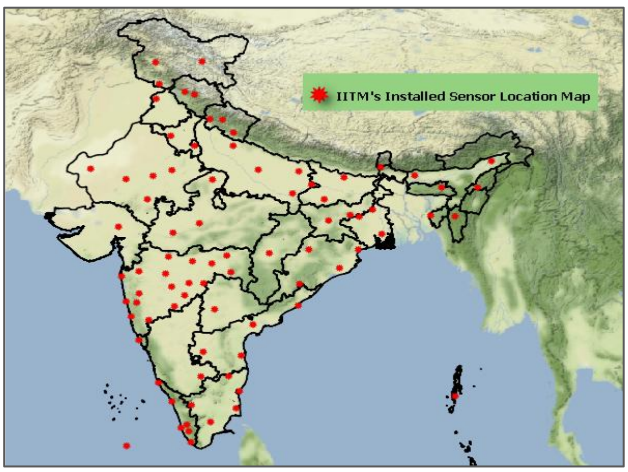

Fig 3: The location of lightning sensors across India as set up by IITM, Pune (courtesy: IITM, Pune)

We had performed the simulations in three domains, with the outer domain at 27 km, followed by a inner domain at 9 km, and finally at 3 km for the inner most domain containing the NER of India. Lightning physics schemes are activated, and lightning data from the WWLLN as well as the IITM lightning detector data were assimilated (Figure 3). We assimilated the lightning data using nudging by adjusting the first condition of the atmosphere also known as initial condition. We run the model was three times a day with recurring data assimilation.

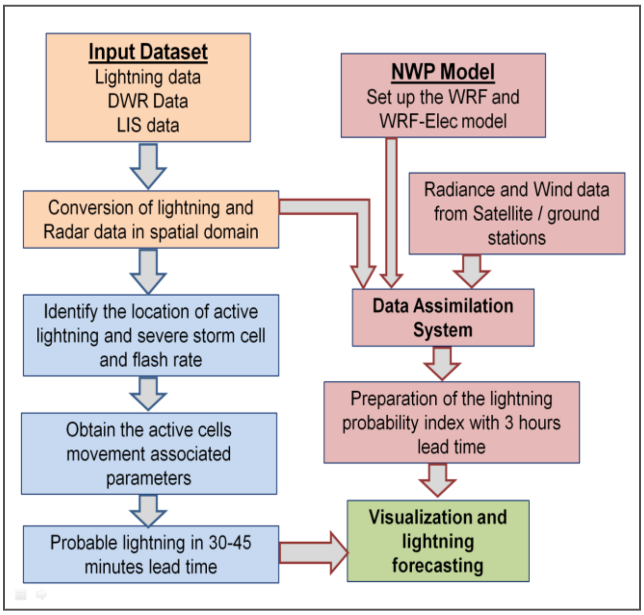

Fig 4: The overall methodology followed for development of lightning forecasting system for NE region of India

The forecast was validated using the observation from the IITM lightning data. The lighting data having the locations of each lightning were plotted in GIS domain over the area and positions of each of the intense lightning zones were identified. Such zones were tracked using an algorithm and areas that these convective zones were likely to impact in next one hour were identified. The overall methodology is shown in figure 4. The schemes and configuration used for the WRF-ELEC model is shown in table 1.

Table 1: Configuration details for the WRF-ELEC model

Horizontal resolution	27 km, 9 km, and 3 km
Number of vertical levels	35
Time steps	30 s
Simulation duration	18 h
Planetary Boundary layer scheme	MYJ (Janjic, 1994)
Long wave radiation scheme	RRTM (Mlawer et al. 1997)
Shortwave radiation scheme	Dudhia (Dudhia, 1989)
Microphysics scheme	NSSL two-moment microphysics scheme (Mansell et al., 2010)

4. Results and Discussions

4.1. Characteristics of thunderstorms associated lightning over NE Region of India

A cumulonimbus cloud has a life cycle that passes through initiation phase, mature which then followed by dissipation phase. Our objective was to understand the lightning behaviors in different phases of the cloud. For example, a meso-scale convective weather system rapidly grows into a multi-cell thunderstorm system and often causes hail and lightning. We studied all types of thunderstorms.

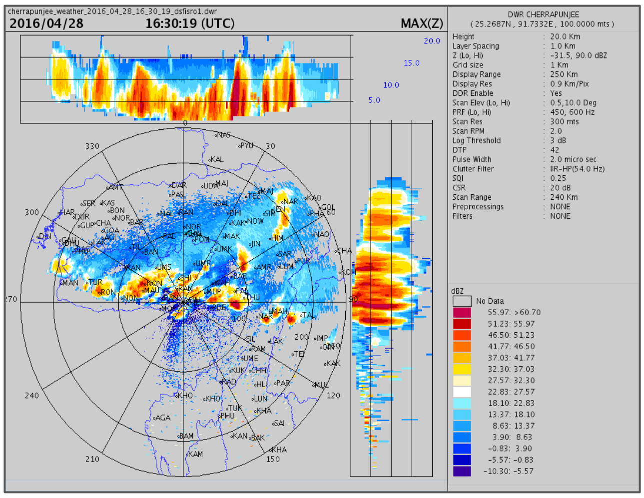

Fig 5: A multi-cell thunderstorm over the study region as seen by an S-band DWR located at Sohra, Meghalaya

Figure 5 shows a multicell thunderstorm that passed over the study region. By the help of DWR data, it was investigated that the altitude of these thunderstorm reaches 12-15 km, and remain live for three to four hours. It impresses that in April all the thunderstorms moved from western / north western Meghalaya and Bangladesh to eastward / southeastern that covers upto Tripura / Mizorma area. Possibly the strong, cold, and dry westerly that coming from Himalayan region converses with weak, hot, and moist southerly that moved from Bay of Bengal in April and first week of May. This makes a strong convection over the Assam / West Bengal boarder area that pushed over this direction. There are more than 50 such severe storms that affect the NE region of India annually.

In mid of May as temperature over the area increases that makes the wind waves from Bay of Bengal become stronger and more moisture passes over the NER during that duration when the westerly cold wave starts to weaken. Based on the Radar observation, it was noticed that many of the convective system, during this time of the year, started moving from south western to northeastern direction with a maximum altitude of 7-10. In the afternoon hours, the thunderstorm normally become stronger over the Bangladesh area and moved eastward by evening to late night. In June, as the summer monsoon sets in, the southerly wind dominates and brings a lot of moisture from the Bay-of Bengal over the study region. During this time, most of the cloud systems were found to have their altitude remaining in the range of 5-7 km with weaker echo and large spatial coverage in a weather radar image. These thunderstorms are very frequent and stay longer over Eastern part of Meghalaya and Tripura region. In addition, most of the thunderstorm in the last week of June developed late afternoon to evening time and brings heavy precipitation that often extend up to next day morning. The known fact is that heat and moisture from the plain area supports to formation of thunderstorm associated with hail near the foothills (Nisi et al., 2016, 2018).

4.2. Lighting forecasting using the WRF-ELEC model

To reduce the risk from lightning and severe weather, several initiatives have been taken worldwide using various methodologies. The existing system of lightning early warning across India using different techniques are calibrated for giving the forecast with different lead times. Some forecast come with lead time of more than 24 hours while some has lead time of less than one hour (Srivastava et al., 2015; Bennett, 2018). We need region based well calibrated NWP models to forecast lightning with higher lead time and with great accuracy (Mohan et al., 2021).

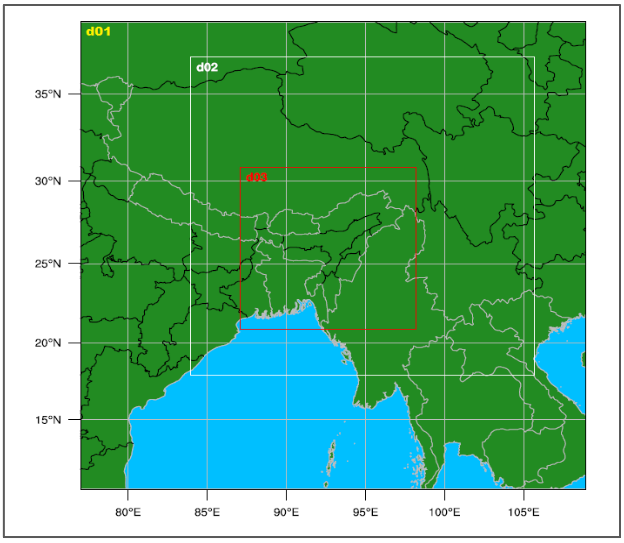

Fig 6: WRF-ELEC model domain in nesting

When we evaluated the performance of WRF-ELEC model, it was observed that lightning potential over a region is unique to the region and at the same time it depends on the initial conditions. The weather condition, environmental condition including the aerosol concentration was also found to play critical role in electrification of clouds. The WRF-ELEC model was run on a daily basis by using the GFS data as the initial condition. The output was generated for nine hours with hourly integration. The model is run every three hours by assimilating the lightning data in a loop. The domains used for running the model are shown in figure 6.

The observations made using the ground based lightning detectors were used to validate the forecast. It was observed that in most of the cases, the observation tallied well with the forecast over space and time. However, the intensity of the forecast was, in general, overestimated. The probability of detection decreased with increasing false alarm ratio as the forecast lead time increased. The forecast was more than 75% accurate for lead time of upto 4 hours. This gave confidence towards utilizing the WRF-ELEC based forecast for lightning disaster mitigation. The forecast beyond 4 hours also was found useful on some occasions, but with higher false alarm ratio. Figure 7 provides the lightning forecast over the NER of India made by assimilating ground based lightning data in WRF-ELEC model with lead time of three hours.

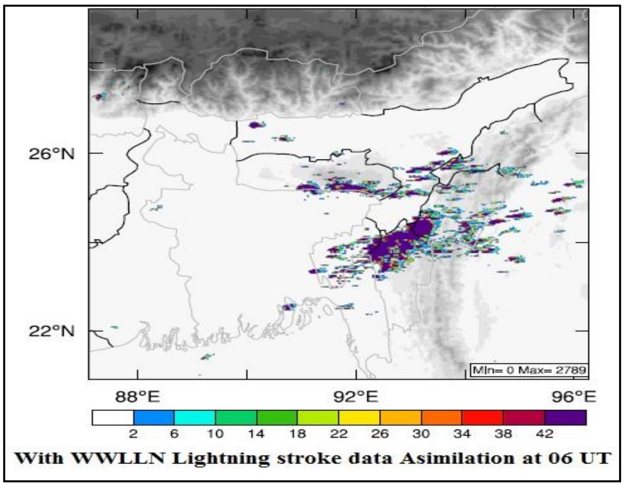

Fig 7: Lighting forecast using the WRF-ELEC model

For the purpose of testing the model performance we have used the output of the model on a daily basis. The forecast normally matched with the location where actual lightning occurred, however in a few cases we observed that we could not forecast the location where lighting will occur (figure 8). We noticed that, overall the model was biased in severe thunderstorms by analyzing 870 samples from 67 thunderstorm days with 9 hours lead-time.

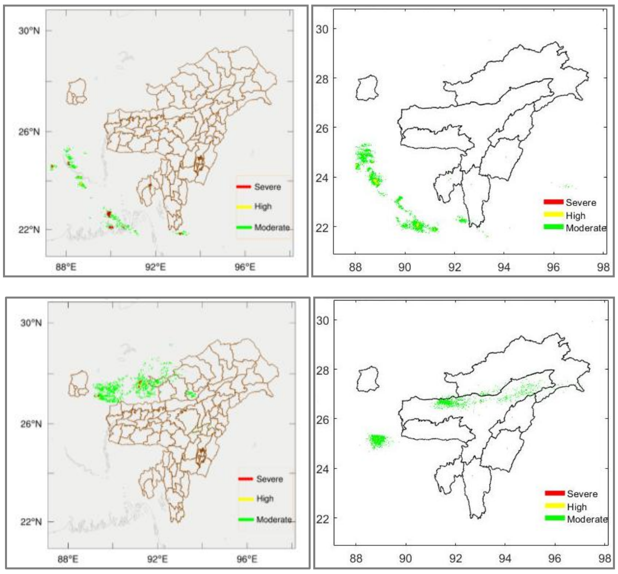

Fig 8: Comparison of model forecast (images in the left) against observed lightning (images on the right) over the NE region on 27th April, 2022 (15 Hrs UTC, top images) and 28th May 2022 (11 Hrs, UTC, bottom images).

In the Figure 9, we have shown how the forecast varies with respect to the location of the place where forecast is issued against the location where the lightning actually happened. We can easily see that as we increase the lead time, the distance between the locations for forecast to actual lightning event increases. However, for lead time of three to four hours, the error is not significant and such forecast can be used for operational purpose.

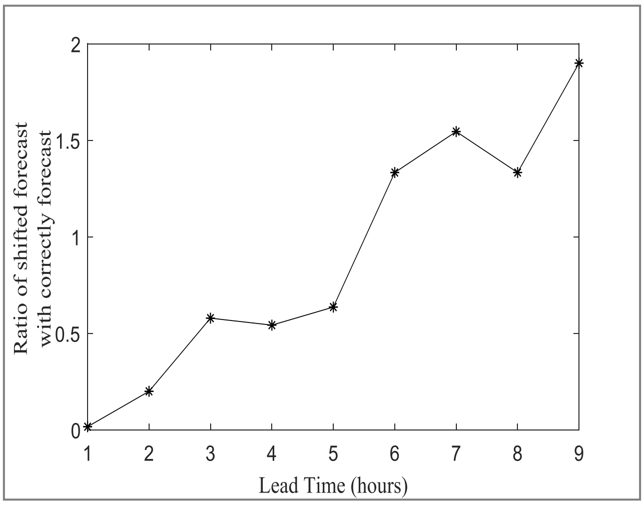

Fig 9: Figure showing how the forecast location differs from the actual lightning location as we increase the lead time for forecast. The results are good for upto four hour lead time.

To evaluate the performance of weather forecasts, several statistical metrics are commonly used. Probability of Detection (POD) measures how well the forecast system is able to correctly predict events that actually occurred. A POD of 1 means all observed events were successfully forecasted, while a POD of 0 means none were. However, POD alone does not account for false alarms. This is where the False Alarm Ratio (FAR) becomes important—it indicates the proportion of predicted events that did not actually happen. A lower FAR is desirable, as it shows fewer false alarms.

The Critical Success Index (CSI), also known as the threat score, provides a balanced measure by considering both missed events and false alarms, making it useful for rare event forecasting. The Success Ratio (SR) is the complement of FAR and reflects the proportion of correct positive forecasts among all positive forecasts made.

Lastly, the bias score tells us whether the system tends to over-forecast or under-forecast events. A bias value of 1 indicates a perfectly balanced forecast, while a value greater than 1 suggests over-forecasting, and less than 1 indicates under-forecasting. Together, these metrics provide a comprehensive understanding of the strengths and limitations of a forecast system.

We calculated these parameters for the year 2022 over the study area. We found that for upto three hours, the POD was more than 0.67, FAR was below 0.45. The CSI and SR also were acceptable range till three hour of lead time. As we increase the lead time, all the performance matrices showed poor results. We continue our work to improve the performance of these parameters. Our primary target is to increase the POD and reduce the FAR. This is very important to ensure that the user of the alerts and services keep their faith on the forecasting system. However, during the development phase of such warning system, a little more high FAR is acceptable, provided we maintain a good POD and don’t miss any big event.

4.3. Lightning tracking and forecasting

Lightning is such a phenomenon that is primarily seen in convective and deep convective clouds. We are normally unable to measure in which direction a convective cloud will move at what speed, particularly over Tropical regions (Murphy and Holle, 2006). These lightning are either cloud-to-ground (CG) lightning or intra-cloud (IC) lightning. If we have a system to measure these IC and CG lightning in a time domain, we can have an idea about the place of convective system and by looking at these lightning over time, we can also estimate their speed and direction of movement. We can also use data from Doppler weather radar and satellites for the same purpose. But, the frequency of data is high in this case.

For developing a very accurate and operational system for lightning, a very efficient system will be to use the combined data from radar, satellite, and the above mentioned ground based lightning detectors (Betz et al., 2008; Dixon and Wiener, 1993). If we know the initial few minutes to hours of condition of a convective system using data from the above mentioned sources, we can develop a tracking system using extrapolation technique and can tell where the deep convective clouds will move in next hour. The WRF-ELEC model provided forecast of lightning at spatial distribution of 3 km X 3 km. The forecast had hourly integration and performed well to capture the areas of lightning activity on a given time. The lightning is a very localized event and impulsive in nature. Saving human life requires that lightning forecasting is provided with high accuracy, is location specific, and also time specific. The numerical model based forecast is not able to meet all these requirements with the desired level of accuracy. To overcome this problem, a new approach was taken to forecast lightning.

There are two major types of lightning, the cloud to ground (CG) lightning and inter-cloud or intra-cloud lightening known as IC. Lightning is pre-dominantly observed with deep convective cloud over the study region. During the evolution of a convective cloud, as the charge develops within the cloud through different micro-physical processes, there is a dominance of IC lightning in general. We leveraged this early signs of development of deep convective cloud and tracked them. The data from the ground stations come at a very fast rate of every second. By monitoring the initial electrical activities within a cloud, we could assess the intensity as well as the direction of such convective systems.

The lightning detected by the ground based network is plotted in a GIS (Geographic Information System) domain with village level information at the back-end. The extent of the convective systems is identified and their velocities are estimated. This information is used to forecast the areas that are likely to be impacted by lighting as shown in figure 10. The forecast is disseminated to all users through the web-portal (www.nerdrr.gov.in, north eastern regional node for disaster risk reduction). This system provides a lightning forecast with localized information and lead time of one hour. As the system is fully GIS enabled, one can estimate the likely impact on the number of villages and population, households, type of land cover, etc. that will be very helpful to plan for mitigation measures. Figure 11 demonstrates the system with live information on convective systems and demarcation of areas that are likely to be impacted. The satellite and DWR data are also integrated into the system to fill the gaps, where the instruments are not able to measure the convective activities.

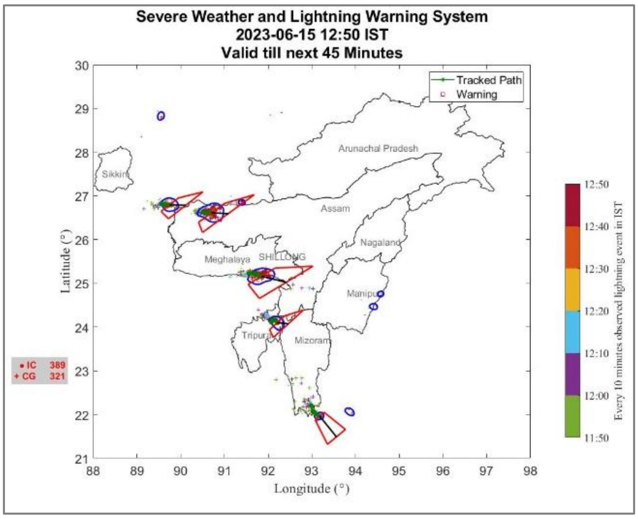

Fig 10: Thunderstorm tracking system over the NER of India

While weather radar scans the sky and updates data every 15 minutes, total lightning data, which includes both cloud-to-ground and in-cloud lightning, is captured almost instantly. This lightning information can be very useful because it often appears in the early stages of thunderstorm development, even before the radar shows a clear signal. As a result, it can provide extra lead-time for detecting rapidly forming storms. Using lightning data along with radar observations can give a more complete picture of how a thunderstorm is growing and moving. Combining both sources of information could help in building better systems for tracking thunderstorms and issuing early warnings, which can be very important for public safety and disaster preparedness in the future.

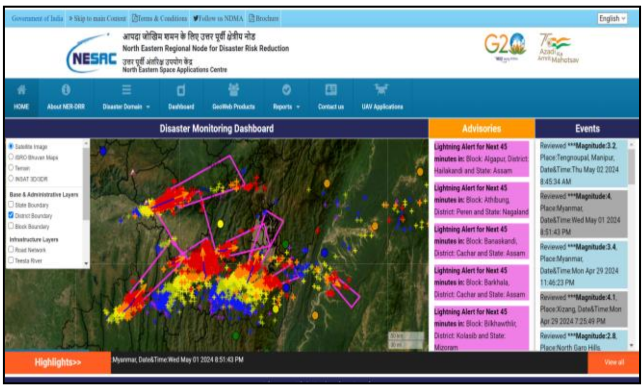

Fig 11: Near real time location of lightning as well as forecasted areas of impact by the convective systems.

5. Conclusion

The study demonstrated here was to develop a thunderstorm forecasting system for the NE region of India that is one of the lightning hot spot regions in the entire world. We used the numerical model WRF-ELEC, where the model was initialized with GFS data and assimilation of ground based lightning data was done to achieve greater accuracy. The model results were validated using the actual lightning information obtained from the India national network of lightning detectors set up and operated by IITM. The following conclusions are made

- The WRF-ELEC model was able to achieve POD of 0.91 with one hour lead time that is sufficient for taking action to save precious life, when the lightning data was assimilated.
- The model continued to perform with actionable accuracy for lead time of up to 3-4 hours.
- When we took the mean of all performance for upto nine hour of lead time, with hourly data, it was found that the mean was more than 65%.
- The performance of the model decreases with all performance parameters showing poor result as the lead time is increased.
- While the model is able to capture the lightning events, the place where forecast is made and where actual lightning happens are different and this distance increases with increasing lead time.
- More research is required to improve the performance of lightning nowcasting services over tropical regions, where the weather is very dynamic. But, WRF-Elec model shown great promise to provide lightning early warning over mountainous regions.
- The NE region of India poses additional challenge due to its complex terrain, high vegetation and water-body cover, orography induces cloud intensification, etc.
- The system developed to track the convective clouds, its direction of movement, and speed using the ground based lightning data with lead time of 45 minutes is very effective.
- The impact of such tracking enhances if the DWR data and satellite data are integrated with the system.

This study highlights the effectiveness of earth observation data combined with the in-situ data and numerical models to provide very location specific and time specific forecast of lightning. With proper awareness on the Dos and Don’ts during a lightning, large number of lives can be saved through proper dissemination of the forecast, as soon as the same is generated.

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