On the Prediction of Cloud-to-Ground Lightning Occurrences over the Indian Region using Different Initial and Boundary Conditions

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Abstract: Atmospheric lightning, one of the deadliest natural disasters globally, poses significant risks, making research in this area crucial for risk reduction. This study evaluates the performance of the Weather Research and Forecasting (WRF)-Elec model for forecasting lightning occurrences over India during September 2023, utilizing initial and boundary conditions from the Global Forecast System (GFS) and the one from the modified GFS from the National Centre for Medium Range Weather Forecasting (NCMRWF), viz. NGFS. The WRF model outputs are compared with data from the National Remote Sensing Centre's Lightning Detection Sensor Network (NRSC-LDSN). Results indicate that NGFS provides better forecasting accuracy compared to GFS, as reflected by higher Probability of Detection (POD) of 0.79 and lower False Alarm Ratio (FAR). We suggest that The NGFS data's integration of advanced assimilation techniques and comprehensive observational data improves the model performance, emphasizing the importance of localized and enhanced inputs for accurate lightning forecasting, which is crucial for mitigating lightning-related risks.

Keywords: Lightning, Climate, Hazards, Prediction, Risk, WRF

1. Introduction

Atmospheric Lightning occurring in the forms cloud-to-cloud (CC), intra-cloud (IC) and cloud-to-ground (CG) is an extreme weather phenomenon which is considered a climate change indicator (e.g., Reeve and Toumi, 1999). It is one of the rare phenomena having direct impact on the upper atmospheric dynamics (e.g., Patil et al., 2024), the lower atmosphere (Gautam et al., 2022) and on the ground (Veina et al., 2023). In particular, the cloud-to-ground (CG) lightning is classified as a natural disaster worldwide. With model studies suggesting increase in the lightning occurrences with climate getting warmer (Romps et al., 2014), Owing to the impetus on understanding the climate change impact on the society, it has become essential to monitor the extreme phenomena such as lightning. In this regard, the global understanding in the characteristics of the lightning occurrences have significantly improved in last couple of decades owing to the advancements in the space-borne (e.g., Cecil et al., 2014, Minobe et al., 2020, Chandra et al., 2021) and long-range ground based (e.g., Betz et al., 2009; Lu et al., 2021, Dementyeva et al., 2023) monitoring capabilities. Using the gridded climatology of total lightning flash rates observed by the space borne Optical Transient Detector (OTD) onboard the MicroLab-1 satellite and Lightning Imaging Sensor (LIS) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite during the years 1995 – 2010, Cecil et al (2014) reported that Congo, Eastern India, Northern Pakistan, Central Africa to be the location where large lightning flash rates are observed. For the continuous lightning detection at inter-continental scale, World Wide Lightning Location Network (WWLLN) has been widely utilized for understanding the diurnal and seasonal variations of CG lightning (e.g., Lay et al., 2007). Virts et al. (2013) used the WWLLN lightning climatology and found it to be consistent with in-situ rainfall observations and also with the TRMM climatology around the globe.

When it comes to India, Khandalgaonkar et al (2005) utilized the LIS data and reported that highest lightning occurs in the pre-monsoon season with lowest during post-monsoon. Recently, Unnikrishnan et al. (2021) used the LIS as well as ground-based lightning data during the years 1998-2014 and reported that the diurnal amplitude in the central and south-west India are about 15%. They report large differences in the peak lightning occurrence time from region-to-region and also found a significant increase in the annual lightning occurrences over the South-Western India. In another recent study, Taori et al. (2023) utilized the ground based long range detection sensor network and reported the diurnal variability in the CG lightning occurrences over the six monsoon zones in India and reported the time of peak

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lightning occurrences to vary from one zone to the other. They also reported a substantial increase in the CG lightning occurrences over India with some zones exhibiting occurrences to double. This is important as the CG lightning occurrences have economical and mortality risk associated with it (e.g., Yair, 2018). For example, in terms of energy security, the lightning is assessed as a major threat (Saunders, 2013, Dimitriou et al., 2016). Further, it is found that mortality over India is also on rise (e.g., Singh and Singh, 2015, Mishra et al., 2022). In this regard it becomes important to mitigate the losses occurring due to the lightning. It is also understood that a comprehensive planning including the monitoring, forecasting, now-casting and information dissemination are important component (e.g, Taori et al., 2023).

When it comes to the lightning forecast over India, there had been a steady progress. For example, several case studies have been conducted on forecasting of the lightning occurrences over India has been examined (e.g., Mohan et al., 2021) which enabled the understanding the efficiency. Also, on state level forecasting efforts has been carried out (e.g., Kumar et al., 2021). In a recent study, Venkatesh et al. (2023) used numerical weather prediction model and analyzed the efficacy of the forecasting on pan-India basis for January – December 2022 duration and reported the probability of detection to vary from 0.6 to 0.9. The present study evaluates the performance of the Weather Research and Forecasting (WRF)-Elec model during 07-12 September 2023 by utilizing initial and boundary condition inputs from (i) the Global Forecast System (GFS) of National Centers for Environmental Prediction (NCEP) and (ii) N-GFS provided by the National Centre for Medium Range Weather Forecasting (NCMRWF) (hereafter NGFS). The outputs thus obtained are compared with the lightning detection sensor network (LDSN) data which is operated by the National Remote Sensing Centre (NRSC). Results suggest that more localized inputs are required for making the forecasting systems better.

2. Data and Methodology

2.1 NRSC-LDSN data

The LDSN uses long range LRX sensors of Boltek make having a frequency range of 1 Hz to 30 MHz (Taori et al., 2022) with 98% detection accuracy within the 300 km range. Figure 1 shows the existing network of NRSC-LDSN with 49 sensors installed across India. The waveform data collected from the multiple locations (time-synchronized) are sent instantaneously to a central server located at NRSC through the internet. The location of the lightning occurrence is obtained by the time of arrival algorithm. When lightning occurs, a constant difference in arrival time is noted between two stations defining a hyperbola.

Multiple stations provide multiple hyperbolas and the intersection of those defines the location. When at least 4 sensors detect this discharge, the location is mapped for lightning. This data is stored every second in near real-time for further processing which can be found at https://bhuvan-app1.nrsc.gov.in/lightning/. The LDSN data was compared with co-existing sensor networks by Taori et al (2022, 2024).

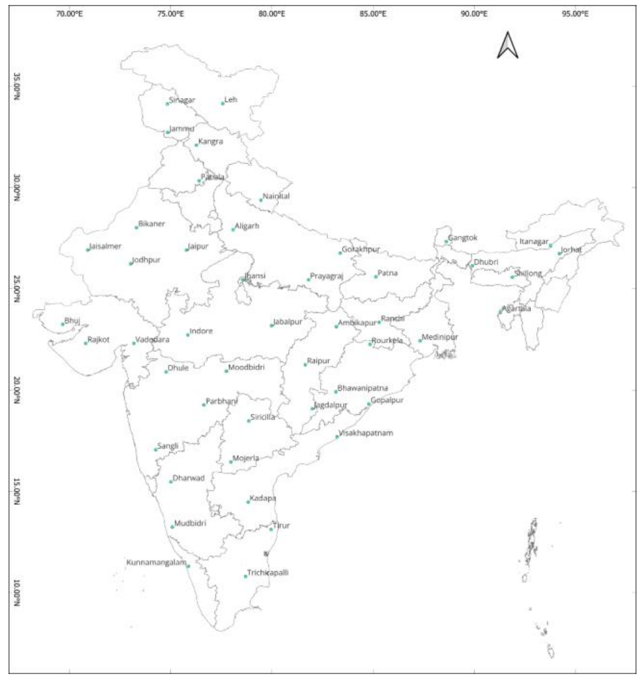


Figure 1. Location of NRSC-LDS Sensors covering mainland India.

2.2 WRF model

The WRF model is a fully compressible, non-hydrostatic atmospheric model, which uses a terrain-following hydrostatic vertical pressure coordinate (e.g., Shamrock et al., 2005). As elaborated by the Venkatesh et al (2023), at present, WRF version 3.9.1.1 is utilized. The model setup included a coarse 24 km grid and was run using a 150 s time step. A rapid radiative transfer model of long-wave radiation (Mlawer et al., 1997) with the Dudhia shortwave radiation scheme (Dudhia, 1989) is used. An extra package (referred to as ELEC) in the WRF model was coupled with the National Severe Storms Laboratory (NSSL) microphysics scheme in WRF (referred to as WRF-ELEC). The model was initialized using GFS and NGFS boundary conditions in the model. The model simulation duration ranged between 18 and 36 h. Further, as the model needs at least 6 h to spin up, in the present study model outputs after t + 6 h have been used for both GFS and NGFS based forecasting outputs.

Figure 2 illustrates the modeling domain used for the WRF model simulation. The domain, highlighted by a yellow square, encompasses a complete extent of India is the study region. The geographic boundaries of the domain extend approximately from 65°E to 105°E longitude and 5°N to 40°N latitude.

The WRF model was executed using a single domain configuration with a horizontal resolution of 16 km, enabling detailed atmospheric simulations over the region. The utilized initial and boundary conditions (IC/BC) for the present model simulations were taken from a) NCEP-GFS, and, b) NGFS. These two IC/BC provide the needed meteorological inputs to initialize and run the model. The final results then are subjected to comparative analysis of the model performances.

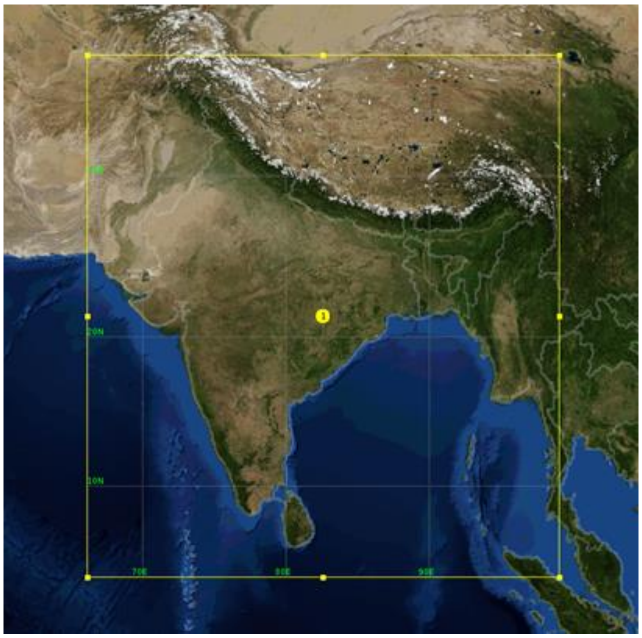


Figure 2: Modeling domain used for the WRF model simulations is highlighted in yellow box.

2.3 Improvements in the NGFS over the GFS

In comparison to the traditional GFS, NGFS represents significant advancements. The NGFS integrating state-of-the-art assimilation techniques which uses improved observational data from both conventional and satellite sources. The transition from Spectral Statistical Interpolation (SSI) to Grid-point Statistical Interpolation (GSI) is performed in the NGFS which offers more flexibility across various modeling systems. The NGFS incorporates most of the available ground based meteorological observations over India which that make it better suited for the Indian region. Here are the key observations and inclusions that contribute to its effectiveness:

Satellite Data Integration: INSAT Satellites: NGFS utilizes data from Indian geostationary satellites (INSAT-series data). These satellites provide crucial atmospheric observations such as temperature, humidity, and cloud cover over the Indian region.

Megha-Tropiques: This joint mission between India and France provides data on tropical water cycles, a vital input for monsoon dynamics.

Radar and Surface Observations: NGFS integrates data from ground-based weather radars distributed across India. These radars provide information on precipitation patterns.

Upper-Air Observations: The NGFS also incorporates data from upper-air observations (temperature, humidity, and wind profiles) collected by weather balloons launched from various stations across India on regular basis.

Oceanographic Data: NGFS also includes oceanographic observations from buoys and ships in the Indian Ocean and Arabian Sea. These observations provide data on sea surface temperatures, ocean currents, and other parameters that influence weather patterns and tropical cyclone development in the region.

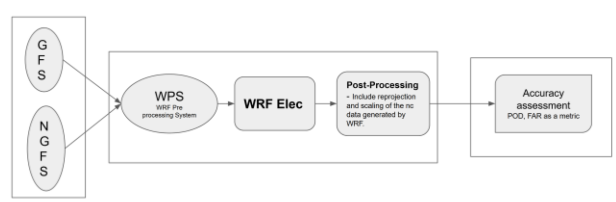
Local Land Surface Data: The NGFS assimilates the data from ground-based weather stations across India. Thus, the of temperature, humidity, wind speed, and precipitation at various locations have representation of local weather conditions and improving forecast accuracy.

The assimilation cycles for NGFS-GDAS is performed at six-hour intervals, generating new estimates of the atmospheric state every 6 hours to initialize global model forecasts. While the background for each analysis is the previous 6-hour forecast, a 9-hour forecast is also carried out which is necessary for time interpolation of synoptic observations. This data becomes the initial conditions for subsequent forecasts.
Using the NGFS, Singh et al (2021) have reported the improved forecasting efficiencies for rainfall. Further, Mukherjee and Ramakrishnan (2023) reported that the cyclogenesis and predictions of rapid intensification of cyclone was better when NGFS is utilized.

2.4 WRF Model Simulation and Evaluation

The WRF model simulation workflow is elaborated in Figure 3. These process includes the following stages:

(i) Initial and Boundary Conditions: The simulation begins with ingestion of initial and boundary conditions from two primary sources: the NCEP based GFS or the NCMRWF based NGFS. These datasets provide the essential meteorological inputs to initialize the WRF model.



Initial conditions and boundary conditions required for the forecast are taken from NCEP, GFS (Global Forecast System)- US, forecast data and NCMRWF GFS - Indian, forecast data.

Figure 3: Workflow for forecast using different IC/BCs.

(ii) WRF Preprocessing System (WPS): The data from GFS/ NGFS is processed through the WRF Preprocessing System (WPS). This step involves interpolating the input data to the model grid, defining the simulation domain, and generating the boundary conditions required for the model run.

(iii) WRF Model Execution: The preprocessed data from step (ii) is given as input to the WRF model, where the core numerical weather prediction calculations take place. This involves running the model's dynamical and physical schemes to simulate atmospheric conditions over the specified domain and time period.

(iv) Post-Processing: After the WRF model run is completed, the output data undergoes post-processing. This stage includes refining the data, extracting specific variables and visualizing these results. In present study the post-processing is carried out using Python libraries such as GeoPandas for geospatial data manipulation, Seaborn for statistical data visualization, and NumPy for numerical data processing.

(v) Accuracy Assessment: The final step involves assessing the accuracy of the model simulations. This is done by calculating the Probability of Detection (POD) and False Alarm Ratio (FAR) to evaluate the model's performance on daily basis. In the present study, the python libraries facilitate this comparison and analysis, ensuring a thorough evaluation of the model's predictions.

2.5 Computational set up

As elaborated by Venkatesh et al. (2023), the methodology employed in this study encompasses the integration of National Severe Storms Laboratory (NSSL) two-moment microphysics scheme electrification processes into the Weather Research and Forecasting (WRF) model.

As shown in Table 1, the implementation of forecasting system begins with the configuration of WRF-ELEC. We utilize WRF-V3911 version on a server equipped with 64 logical cores, each operating at 2.26 GHz, along with 64GB of DDR4 RAM and 1TB of storage capacity. The model setup involves the integration of the initial and boundary conditions from the GFS and NGFS. The land surface physics in the WRF-Elec model are represented by the Unified NOAH Land Surface Model (LSM) (Tewari et al., 2004), while the cumulus parameterization is incorporated through the Grell-Devenyi ensemble scheme (Grell & Devenyi, 2002). Further, land use and land category data are derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) dataset, providing realistic representations of surface characteristics (Justice et al., 1998). The NSSL two-moment microphysics scheme, as proposed by Mansell et al. (2010), is selected for its comprehensive treatment of microphysical processes, including the prediction of mass mixing ratios and concentrations for various hydrometeors such as raindrops, ice crystals, cloud droplets, snow, hail, and graupel.

Incorporation of these schemes is the foundation for parameterizing electrification processes within the WRF model. As stated by Venkatesh et al (2023), the simulation setup involves configuring WRF-ELEC with a lightning time step of 150 seconds and a flash rate factor of 1, ensuring the accurate representation of lightning activity. Simulations are conducted at a resolution of 16 kilometers, capturing mesoscale features relevant to convective weather systems. The choice of resolution balances computational efficiency with the ability to resolve the required atmospheric processes of interest

Table 1. List of Model configuration and parameterization utilized.

Process	Parameterization Option
Model	WRF V3911 Elec
Server Used (rack server)	64 Logical cores(2.26 GHz each), 64GB(DDR4), 1TB
Initial Conditions / Boundary Conditions	NCEP GFS, NCMRWF GFS
Radiation	Rapid Radiative Transfer Model
PBL	Yonsei University Scheme
Land surface physics	Unified NOAH Land Surface Model
Cumulus Physics	Grell-Devenyi Ensemble scheme
Cloud Microphysics	NOAA Severe Storm Laboratory (NSSL)
Land use / Land Category	MODIS
Lightning time steps	150 sec
Flash rate factor	1
Resolution	16 KM
Chemistry	Switched OFF

It is important to state here is that the temporal and spatial resolution of the WRF model is a trade-off among the inputs and computational resources available. In our case, the model domain is carefully selected to encompass the region of interest while minimizing computational costs. Throughout the simulations, diagnostic output is collected to analyze model performance and assess the impact of electrification parameterization on simulated atmospheric conditions. Validation of WRF-ELEC simulations is conducted against observational LDSN datasets to evaluate the model's ability to reproduce key features of convective systems and lightning activity. Sensitivity experiments may be conducted to investigate the influence of various model parameters and configurations on electrification processes and forecast accuracy.

3. Results and Discussion

The WRF model was run on GFS and NGFS IC/BC for 07-12 September 2023 duration and 10 and 11 September 2023 results are elaborated here. The results of lightning forecast as the day-ahead lightning occurrence outlook maps generated using the GFS and NGFS IC/BC for 10 and 11 September 2023 are shown in Figure 4 together with the observations. In figure 4a, left panel show the forecasting result on the lightning occurrences using the GFS conditions while the right panel shows the same using the NGFS IC/BC. The middle panel shows the observed CG lightning occurrences using the NRSC-LDSN. It is evident that both, the GFS and NGFS results have broad agreement with the observations. The GFS data show large number of lightning occurrences in near continuous patches spanning over the Maharashtra, Madhya Pradesh, Uttar Pradesh, Bihar, Jharkhand, Telangana, Odisha, and West Bengal, while, the observations reveal the lightning occurrences to be less intense over the Telangana. The NGFS, on the other hand suggests the occurrences to be in Maharashtra, Madhya Pradesh, Uttar Pradesh, Bihar, Jharkhand, Odisha and West Bengal which is somewhat similar to the observations. Further, one may note that northwest extension of the lightning occurrences is clear in both, GFS and NGFS outputs and a similar is noted in the observations except in Gujarat. However, the NGFS show lesser number of lightning occurrences compared to the GFS which agrees with the observed distribution. Figure 4b depicts a comparison among the NRSC-LDSN observations and the forecasting results based on the GFS and NGFS IC/BC. The observations reveal that West Bengal and Uttar Pradesh witnessed the large number of CG lightning occurrences compared to the other states. Also, when we look at the distribution of lightning occurrences from Uttar Pradesh to the Gujarat, it appears that occurrences had four distinct pockets with strongest in Uttar Pradesh, followed by two weak pockets over Madhya Pradesh and another strong region near Gujarat. The WRF model results based on the GFS and NGFS, both show large occurrences over West Bengal and Uttar Pradesh which agrees with the observed data. However, large differences in the spatial distribution from the observations are noteworthy, in-particular over the north-east India and western coast where often model show large number of lightning occurrences. In comparison to the GFS, the NGFS data show somewhat better correspondence with the observed data. For example, the north-west extension of a streak of lightning occurrences spanning from Uttar Pradesh to the Himachal Pradesh was clearly noted in both, the data and NGFS based WRF model results. Similarly, the patchy distribution of the lightning occurrences which was observed was better captured in the NGFS results.

The statistical significance of the forecasting is assessed in terms of the scores obtained by comparing the model output and the observed data. We utilize the Probability of Detection (POD) and False Alarm Ratio (FAR) as elaborated by Rajeevan et al., 2012; Gharaylou et. al., 2020. The POD values range from 0 (poor) to 1 (good).

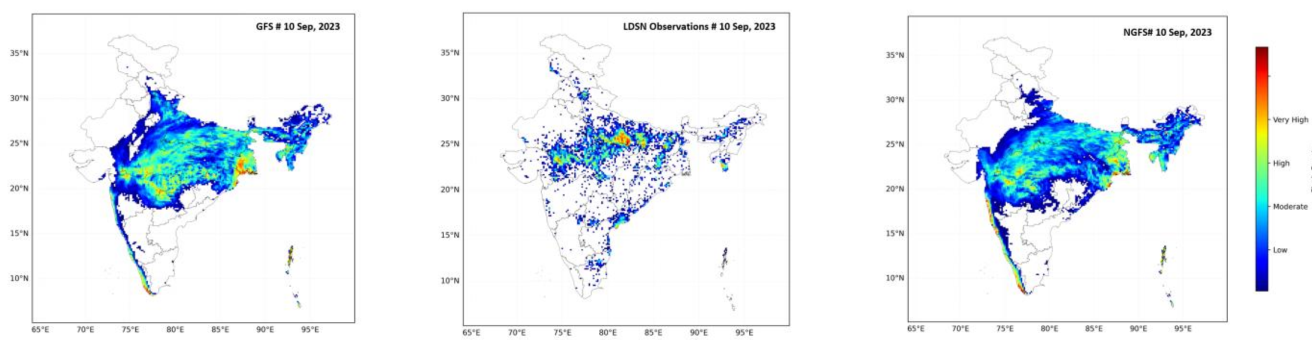


Figure 4a: Lightning occurrence outlook maps generated using the GFS (left side) and NGFS (right side) IC/BC on 10 September 2023 along with observed lightning occurrences (center)

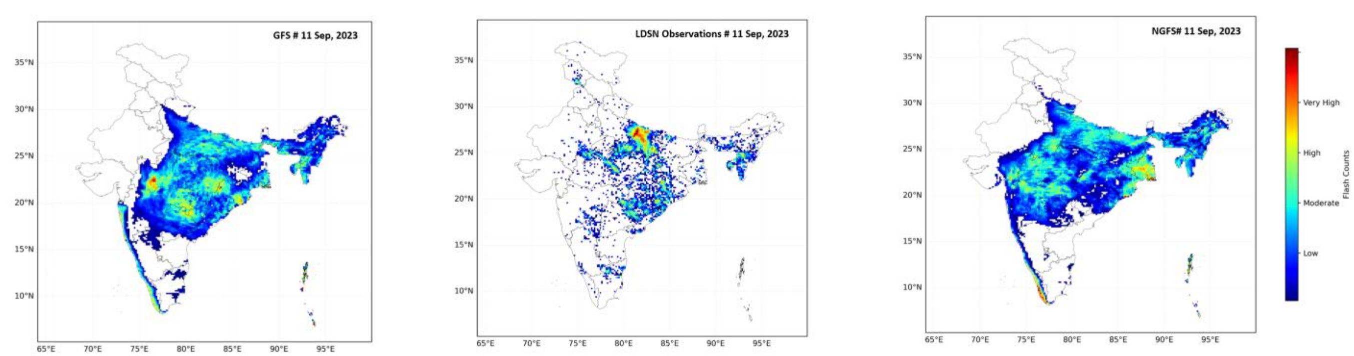


Figure 4b: Same as figure 4a, but for 11 September 2023

This indicates the model efficiency in terms probability of lightning occurrences with observational reference. The FAR relates to the scenario where the model predicts the occurrence without any signatures in the observations. These statistical quantities are defined as following.

$$POD = \frac{Hits}{(Hits+Misses)} \qquad \text{--- (1)}$$

And,

$$FAR = \frac{False\ Alarms}{(Hits+False\ Alarms)} \qquad \text{--- (2)}$$

The POD and FAR values for 10 September 2023 was found to be 0.72 and 0.63 in case of GFS IC/BC while they are noted to be 0.71 and 0.64 when NGFS is utilized in the WRF simulations. Similarly, in case of 11 September 2023, the POD and FAR are found to be 0.76 and 0.63 when GFS is used and when NGFS IC/BC are used, they are 0.79 and 0.57. This clearly indicates that by using the NGFS in the WRF model, forecasting has been improved significantly. The WRF-Elec forecasting using the GFS and NGFC IC/BC were carried out during 07-12 September 2023 and results are summarized in Table 2. It is noteworthy that the results show that by using the NGFS, the forecasting show significant improvement in terms of POD and FAR.

Table 2. The POD and FAR values of the model results

Date	IC/BC	POD	FAR
07-Sep-23	GFS	0.6191	0.3789
	NGFS	0.6934	0.3959
08-Sep-23	GFS	0.6863	0.5352
	NGFS	0.7248	0.5238
09-Sep-23	GFS	0.689	0.6072
	NGFS	0.7226	0.6099
10-Sep-23	GFS	0.7183	0.6427
	NGFS	0.7231	0.6322
11-Sep-23	GFS	0.7581	0.6368
	NGFS	0.7893	0.5783
12-Sep-23	GFS	0.7721	0.5567
	NGFS	0.7981	0.5324

Prior to the present investigations, there are very limited results on the use of NGFS for the lightning forecasting. Singh et al. (2021) utilized the Indian Monsoon Data Assimilation and Analysis reanalysis (IMDAA), Global Data Assimilation Forecasting System (GDAFS) at NCMRWF (viz., NGFS Reanalysis), and European Centre for Medium-Range Weather Forecasts (ECMWF), known as ERA5 for the rainfall prediction over India and suggested that the NGFS based results were better compared with the observations and in particular extreme events were well captured.

Further, Mukherjee and Ramakrishnan (2023) used the GFS, NGFS and ERA5 IC/BC and suggested that reanalysis datasets ERA-5 and NGFS based model simulated the cyclone 'Shaheen' better than when the GFS was used. In this context, our study revealing that during 07-12 September 2023, the WRF model forecasting yielded better results when NGFS IC/BC are utilized are in agreement with the above studies which also suggest significant improvement when assimilated data based IC/BC such as NGFS/ERA-5 are utilized. Although, the desired accuracy and spatial resolution of the lightning forecasting needs to be further improved, the community efforts are progressive. The forecasting efforts together with the near real-time data assimilation with advanced techniques such as use of artificial intelligence and machine learning may prove pivotal in the years to come. Apart from these efforts the community may also assimilate the available and upcoming satellite data for further improvements.

4. Conclusions

The assessment of WRF-Elec model performance and efficacy has been carried out during the months of monsoon, 2023. Performance of the model has also been studied by integrating the model with input initial and boundary conditions from NCEP GFS and NCMRWF NGFS. In both the cases model configuration remains same and model integrated to generate day-ahead forecast at 16 km spatial resolution. Simulated CG counts have been compared against the NRSC lightning network data LDSN (Lightning Detection Sensor Network) and it is noted that NGFS yields better results compared to the GFS over India.

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