



Simulation of thunderstorms over Odisha using lightning parameterization Schemes in WRF

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सार – पूर्वी भारत में मानसून-पूर्व अवधि (मार्च-मई) के दौरान आने वाले तूफानों तथा बार-बार होने वाली आकाशीय बिजली के कारण मानव जनहानि की घटनाएँ अत्यधिक होती हैं। इस अध्ययन में ओडिशा क्षेत्र के लिए मौसम अनुसंधान एवं पूर्वानुमान (Weather Research and Forecasting–WRF) मॉडल की विभिन्न विद्युत-चमक पैरामीट्रीकरण योजनाओं का उपयोग करते हुए आकाशीय बिजली की फ्लैश संख्या का मूल्यांकन किया गया है। अध्ययन में विशेष रूप से प्राइस-रिंड (Price-Rind–PR92) की दो विद्युत-चमक पैरामीट्रीकरण योजनाओं–बादल की आधार ऊँचाई (Cloud Base Height–H) [योजना 1] तथा अधिकतम ऊर्ध्वाधर पवन वेग (Maximum Vertical Wind Speed–W_{max}) [योजना 2]–पर ध्यान केंद्रित किया गया है। इसके साथ ही, मॉडल द्वारा उत्पन्न तूफानी मापदंडों से आकाशीय बिजली की फ्लैश संख्या के आकलन हेतु ऑफलाइन नैदानिक विधियों का भी मूल्यांकन किया गया है। मॉडल द्वारा अनुकरण की गई कुल विद्युत-चमक फ्लैश संख्या का तीन चयनित घटनाओं के लिए विद्युत-चमक संसूचन नेटवर्क (Lightning Detection Network–LDN) से प्राप्त प्रेक्षणों के साथ सत्यापन किया गया। सतही मौसम संबंधी मापदंडों के अनुकरण का प्रदर्शन संतोषजनक पाया गया। 2-m तापमान (T₂) के लिए मूल माध्य वर्ग त्रुटि (RMSE) लगभग 3 K रही तथा मॉडल ने इसकी परिवर्तनशीलता को अच्छी तरह अभिव्यक्त किया। परिणामी 10-m पवन वेग (परिमाण) के लिए स्टेशनों पर दो मामलों की RMSE < 3 m s⁻¹ रही, जबकि कुछ क्षेत्रों में U10 और V10 के सहसंबंध अपेक्षाकृत कमजोर पाए गए। 25 km ग्रिड पर पुनर्ग्रिड की गई तीन-घंटे की वर्षा ने अधिकतम वर्षा के स्थानिक प्रतिरूप को पुनरुत्पादित किया, जिसमें मामले 1 और 2 में क्रमशः ~ 56 किमी और ~96 किमी का स्थानिक विस्थापन पाया गया। संचित वर्षा के लिए समतुल्य खतरा स्कोर (Equitable Threat Score–ETS) उच्च रहा, जो घटना की पहचान की सुदृढ़ क्षमता को दर्शाता है। जहाँ प्रेक्षण अधिक सघन थे वहाँ बादल-से-भूमि (Cloud-to-Ground–CG) विद्युत-चमक के संचित फ्लैश के स्थानिक ETS का मान भी अधिक पाया गया, जिससे मॉडल की फ्लैश संख्या को अभिव्यक्त करने की क्षमता प्रमाणित होती है। योजना 1 में CG फ्लैश संख्या का व्यवस्थित रूप से अधिक आकलन किया गया तथा इसकी पहचान की प्रायिकता अधिक रही, किंतु इसके साथ अधिक स्थानिक प्रसार और विचलन भी पाया गया। इसके विपरीत, योजना 2 में फ्लैश संख्या का कम आकलन हुआ, लेकिन इसमें गलत चेतावनियाँ कम रहीं तथा उत्तरी ओडिशा में अधिकतम फ्लैश गतिविधि का बेहतर स्थान-निर्धारण किया गया। अधिक सही ऋणात्मक परिणामों के कारण इसकी समग्र सटीकता अधिक रही। तड़ित संभाव्यता सूचकांक (Lightning Potential Index–LPI) आकाशीय बिजली की गतिविधि का एक अप्रत्यक्ष माप है और उपर्युक्त वर्गीकृत मापदंडों द्वारा इसका मूल्यांकन नहीं किया जा सकता; तथापि, यह अधिकतम CG फ्लैश दर की प्रभावी पहचान करता है। समग्र रूप से, योजना 2 में CG आकाशीय बिजली का कम आकलन होने के कारण यह पूर्वानुमान के लिए अपेक्षाकृत कम उपयुक्त है, जबकि योजना 1 CG फ्लैश के स्थानिक प्रसार को बेहतर ढंग से दर्शाती है, किंतु गलत चेतावनियों को कम करने के लिए इसमें अतिरिक्त परिशोधन (filtering) की आवश्यकता हो सकती है।

ABSTRACT. In eastern India, pre-monsoon (March–May) thunderstorms and frequent lightning result in significant human fatalities. In this study, we evaluate lightning flash counts using various lightning parameterization schemes of the Weather Research and Forecasting (WRF) model over Odisha focusing on two Price-Rind (PR92) lightning parameterizations; Cloud Base Height (H) [Scheme 1] and Maximum Vertical Wind Speed (W_{max}) [Scheme 2]. Additionally, offline diagnostic methods are assessed for estimating lightning flashes from model-generated storm

parameters. The simulated total lightning flashes are validated using observations from the Lightning Detection Network (LDN) for three selected events. Baseline surface skill is reasonable; 2-m temperature (T2) shows RMSE ~ 3 K and the model captures its variability well. Resultant 10-m wind speed (magnitude) shows RMSE < 3 ms $^{-1}$ at stations in two of the cases, while U10 and V10 correlations are weaker in some regions. Three-hourly precipitation regridded to 25 km reproduces the spatial pattern of peak rainfall with positional errors of ~ 56 km (case 1) and ~ 96 km (case 2). Equitable Threat scores (ETS) for accumulated rain are high, indicating robust event detection. Spatial ETS for accumulated cloud-to-ground (CG) flashes is likewise elevated where observations are densest, demonstrating the ability of the model to capture flash counts. Scheme 1 systematically overestimates CG flash counts and has high probability of detection, but with greater spatial dispersion and bias. Scheme 2 underestimates flash counts yet produces fewer false alarms and better localization of the peak over northern Odisha, with higher overall accuracy due to more correct negatives. The Lightning Potential Index (LPI) is an indirect measure of lightning activity and cannot be evaluated using the aforementioned categorical metrics, however, it effectively identifies peak CG flash rates. Overall, Scheme 2 underestimates CG lightning making it less suitable for forecasting while Scheme 1 captures the spatial spread of CG flashes but may require additional filtering to reduce false alarms.

Key words – Thunderstorm, Lightning, WRF, Parameterization.

1. Introduction

Thunderstorms are violent, short-lived weather disturbances that pose severe threats to human life—primarily through lightning which remains one of the deadliest natural hazards worldwide (Mohan *et al.* 2021). At any given time, approximately 1000 thunderstorm systems occur all over the globe as estimated from climatological observations, satellite data, and inferences from electrical observations (Cecil *et al.*, 2015; Heymsfield *et al.*, 2014). These systems predominantly develop in tropics, semi-tropics, and temperate zones with rare occurrence in polar regions. While lightning is a year-round phenomenon, it is most frequent over land during spring and summer during the midafternoon. Satellite observations confirm that the thundercloud formation and lightning discharges are significantly more prevalent over land than over oceans (Mohan *et al.* 2021).

Consistent with recent climatologies (Mohan *et al.* 2021; Priya *et al.* 2023), lightning occurrence peaks over eastern India but with pronounced intrastate gradients and mesoscale hotspots along Odisha, Jharkhand, and West Bengal that are evident 50 km $\times$ 50 km resolution as presented in Fig. 1. Lightning has major impacts, with 1,256 deaths in Odisha and over 9×10^5 lightning strikes from April to July, so developing robust predictive frameworks is essential for operational meteorology and disaster mitigation (Mishra *et al.* 2022).

Accurate lightning prediction depends on a comprehensive understanding of storm-scale dynamics and the micro-physical processes governing lightning generation. Despite its significant impact, lightning forecasting in the Indian subcontinent remains inadequate (Mohan *et al.* 2021), necessitating further research in understanding its underlying mechanism that is crucial for improving predictive capabilities. Extensive research has established links between lightning activity, cloud microphysics and atmospheric dynamics (Qie *et al.* 2014; Rutledge *et al.* 1993). Advanced in lightning detection have

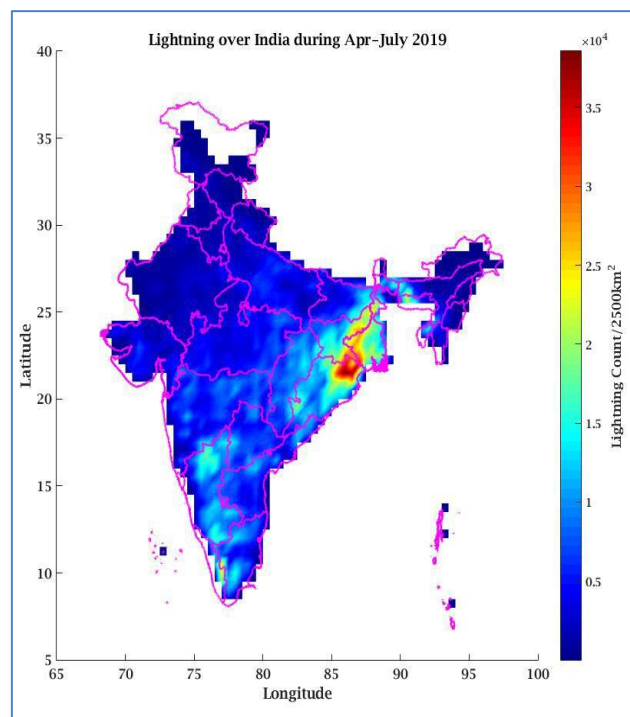


Fig. 1. Lightning strikes spread over India for the period 1 April 2019 to 31 July 2019 [Source: Mid-monsoon lightning Report (2019)]

enabled correlations between lightning occurrence and key storm characteristics, such as precipitation, reflectivity, cloud hydrometers, and instability (Kamra, 1985; Gatlin and Goodman, 2010; Pineda *et al.* 2018; Schultz *et al.* 2011). Price and Rind (1992) (PR92 hereafter- detailed discussion in Section 2) identified a key empirical relationship between flash rate, cloud top height, and maximum updraft velocity while later studies demonstrated a direct or slightly nonlinear dependence on ice water content (IWC) (Blyth *et al.*, 2001; Petersen *et al.*, 2005). Liu and Zipser (2009), further established a strong correlation between lightning and extent of mixed phase.

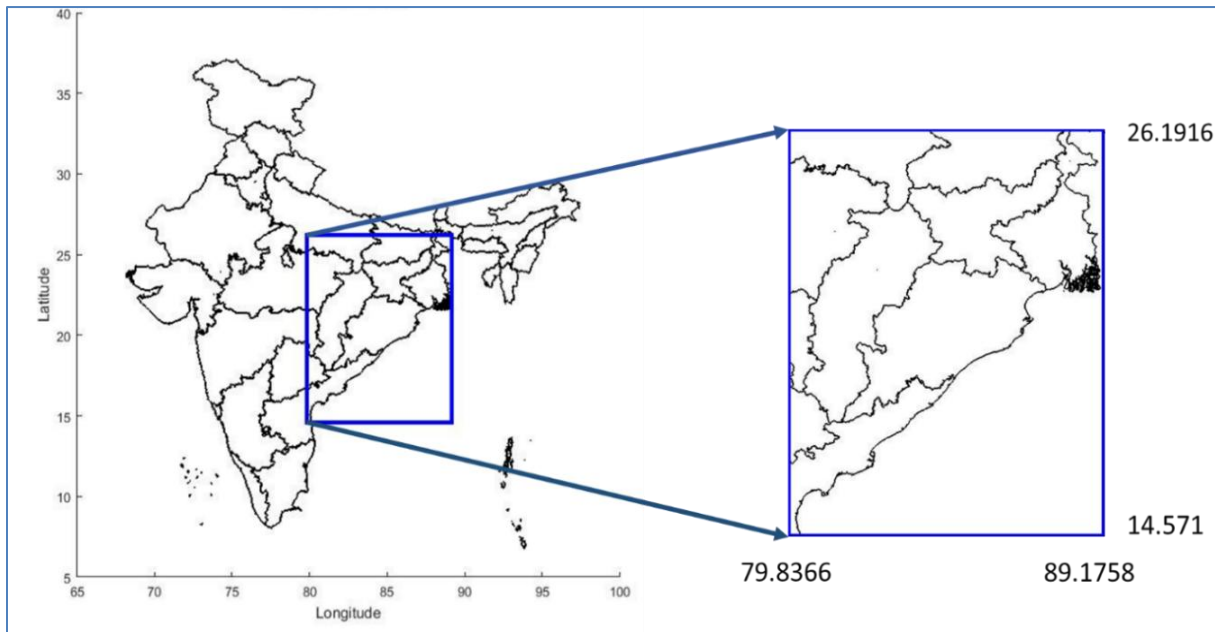


Fig. 2. Domain selected for model simulations, shown by blue bounding box

storm regions exceeding 35 dBZ. Lightning Potential Index (LPI) (Yair *et al.* 2010) provides an additional metric for quantifying charge separation potential in convective thunderstorms enhancing lightning assessment and prediction

Barthe, *et al.* (2010) evaluated six microphysical predictors of lightning in Alabama and found mixed skill: precipitation-ice metrics tracked trends but not magnitudes, ice-water path overpredicted weak storms, updraft volume correlated poorly, cloud-top height matched mainly weaker storms and maximum vertical velocity was reliable only in severe storms. As much of the prior works target the United States squall lines, supercells and multicell clusters, these relationships may not transfer directly to Indian context. In eastern India, convection is often widespread but less organized and driven by warm, moist Indian Ocean advection, underscoring the need for region-specific lightning parameterizations for forecasting.

Several studies have employed the Weather Research Forecasting (WRF) model to analyze convection in India, demonstrating the utility of high-resolution region-specific simulations for predicting severe thunderstorms (Litta and Mohanty, 2008; Siripurapu *et al.* 2014; Singh *et al.* 2017; Osuri *et al.* 2017; Priya *et al.* 2021). Research has also explored the sensitivity of WRF microphysical schemes for thunderstorms (Litta and Mohanty 2008; Madhulatha *et al.* 2013; Rajeevan *et al.* 2010, 2012), with traditional convective indices such as Lifted Index, K Index, Surface

Lifted Index, Humidity Index, Bulk Richardson Number, CAPE, CINE, and Cloud Physics Thunder Parameter used for forecasting thunderstorms and lightning activity (Chaudhari *et al.* 2010; Tyagi *et al.* 2012). Building on this foundation, recent advancements have further refined lightning simulations and parameterization schemes. Kundu *et al.* (2024) investigated severe lightning events in Northeast India using WRF, validating storm characteristics such as vertical wind velocity, cloud ice water content and radar reflectivity to improve lightning prediction. Mondal *et al.* (2023) examined the relationship between lightning occurrence and thunderstorm-related atmospheric parameters, utilizing model skill scores like Probability of Detection (POD), False Alarm Rate (FAR), and Equitable Threat Score (ETS) to assess the accuracy of WRF-simulated lightning events over Rajasthan and West Bengal. Mondal *et al.* (2024) further analyzed thunderstorm indices from ERA5 reanalysis, determining optimal thresholds for indices like CAPE, K Index, and Energy Helicity Index (EHI) to enhance severe thunderstorm forecasting.

Our research aims to enhance lightning prediction over Odisha by assessing parameterizations derived from observed storm characteristics. Given the high lightning incidence and fatalities in this region, a reliable forecasting framework is crucial for mitigating risks. We employ the WRF model to evaluate lightning flash estimation methods, focusing on two diagnostic approaches: (i) PR92CTH, which relates lightning flash rate to cloud top height, and (ii) PR92W, which utilizes maximum vertical velocity as a

TABLE 1

Model configuration used in the study

Model Configuration	Description
Grid size	900 West to East Grid points
	1200 North to South Grid points
Grid Resolution	1000 m
Map projector	Mercator
Center reference	Latitude: 20.5
	Longitude: 84.5
Model time step	5 seconds
Micro Physics	Morrison-Gottelman Version 3 (MG3)
Radar reflectivity option	On
Radiation schemes	For longwave, RRTM scheme
	For shortwave, Dudhia scheme
Surface layer option	Monin-Obukhov (Janjic Eta) scheme
Surface layer parameterization	Unified Noah land-surface model
Planetary boundary layer physics	Mellor-Yamada-Janjic (Eta) TKE scheme
Number of land categories	MODIS including lake category
Lightning parameterization options	PR92 based on maximum w redistributes flashes within dBZ > 20 (PR92CTH)
	PR92 based on 20 dBZ top, redistributes flashes within dBZ > 20 (PR92W)
Lightning time interval	Same as model time step, 5 seconds
Start time for calling lightning parameterization	700 seconds
Flash rate factor	A scaling factor for the flashes predicted, 1 for the simulations conducted
IC:CG partitioning method (ratio)	The ratio value is set 0 since we want to focus only on the CG flashes predicted by the model

proxy. These methods are tested against observed lightning occurrences to determine their effectiveness in capturing spatial and temporal lightning distributions.

Building on prior research that has explored lightning microphysics, storm dynamics, and parameterization schemes, our study integrates these advances to refine lightning estimation techniques suited to the Indian subcontinent. By analyzing convective storm parameters and their correlation with lightning activity, we aim to bridge the gap between theoretical models and operational forecasting needs. The insights gained from this work will contribute to the development of a high-resolution, region-specific lightning prediction system, improving early warning capabilities and enhancing disaster preparedness.

2. Data and methodology

The state-of-the-art non-hydrostatic, fully compressible, mesoscale, advanced research version of WRF (ARW-WRF v3.9.1) (Skamarock *et al.*, 2008) was used to simulate the lightning events. The study employs a single high-resolution domain (1 km grid spacing) encompassing Odisha and adjoining regions as presented in Fig. 2. The model is set up with 51 terrain-following hydrostatic vertical pressure (σ) coordinates (Janjić 1990). The σ coordinates are placed close together in the lower atmosphere (12 levels below 850 hPa and 22 levels below 500 hPa) and are relatively coarser in the upper atmosphere. The grid structure follows the Arakawa C-grid. The horizontal and vertical resolution was based on prior results involving thunderstorm simulations and the model performance, by choosing a high horizontal grid resolution the need for a calibration factor was mentioned in the paper by Price and Rind (1994). The model begins with initialization using the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) 3-hourly data with a 0.25°x0.25° resolution and boundary conditions as well. The parameterization schemes for this study are detailed in Table 1.

The physics parameterization schemes are identified based on the previous sensitivity studies to ensure the consistency (Siripurapu *et al.* 2014; Osuri *et al.* 2017; Priya *et al.* 2021). To determine the appropriate lightning parameterization scheme for the region, key physics options remained fixed across all simulations as provided in Table 1. The Morrison scheme incorporates a six-class, double-moment microphysics scheme with prognostic variables, while the cumulus parameterization operated at 1 km horizontal grid spacing to resolve convective processes more effectively. Several other options fine-tune the model output including flash rate factor (a scaling parameter for matching model-simulated lightning to observations), storm cell counting methods, and intra-cloud (IC) to cloud-to-ground (CG) flash partitioning ratios. The storm cell counting method is automatically selected based on domain size, with tile-wide counting used for large domains and domain-wide counting for single-storm cases. If a regional IC:CG climatological ratio is available, it can be integrated into the model for improved accuracy. However, this study primarily focuses on CG flashes due to their significant role in damage and fatalities. The model operates with a 36-hour lead time to simulate lightning activity effectively.

2.1. Background on lightning parameterization scheme

The development of lightning parameterization schemes has evolved over several decades, beginning with

TABLE 2

IC & CG Flash counts and selected case dates

Case no	Date of the case	CG Flashcount	IC Flashcount	Total
1	20-05-2019	9297	19066	28363
2	28-05-2019	11762	27384	39146
3	12-06-2019	18608	17647	36255

empirical relationships between storm properties and lightning activity. Williams (1985) and Price and Rind (1992) demonstrated that the electrical power within a convective cloud is proportional to the fifth power of the storm height, leading to a simple yet effective parameterization for estimating global lightning distribution. Their work formed the basis of the widely applied cloud-top height scheme, details of which are provided in Section 2.2.

Subsequent refinements introduced additional storm characteristics, such as updraft velocity, precipitation ice mass, and graupel content. Price and Rind (1994), extended their original formulation by introducing a parameterization based on maximum vertical velocity, which is also discussed in Section 2.2 as it is directly relevant to this study. Later research (Wang *et al.*, 2018; Mohan *et al.*, 2021) incorporated microphysical and radar derived parameters, demonstrating that hybrid approaches can further improve lightning prediction skill.

2.2. Price and rind lightning schemes

This study employs the lightning parameterization schemes proposed by Price and Rind (1992, 1994) to estimate lightning flash rates based on storm characteristics. Two diagnostic approaches are utilized: one relating lightning flash frequency to cloud top height (PR92CTH) and another based on maximum updraft velocity (PR92W). These parameterizations are implemented within the Weather Research and Forecasting (WRF) model, utilizing model-derived storm properties as input. The outputs are validated against observed lightning data to assess their accuracy in capturing the spatial and temporal distribution of lightning activity.

The PR92CTH method establishes an empirical relationship between convective cloud top height H and lightning flash rate F , based on the assumption that electrical power within a convective cloud scale with the fifth power of cloud height. The general form of this relationship is expressed as:

$$F = aH^b$$

where a and b are empirically determined coefficients that vary for continental and maritime thunderstorms. Price and Rind (1992) found that for continental storms, the relationship follows:

$$F_c = 3.44 \times 10^{-5} H^{4.9}$$

where F_c is the continental flash rate (flashes/min). For maritime storms, the lower updraft velocities lead to a weaker dependence:

$$F_m = 6.4 \times 10^{-4} H^{1.73}$$

where F_m is the marine flash rate. The PR92W method introduces maximum vertical velocity W as a predictor of lightning activity, given that stronger updrafts enhance charge separation and increase flash rates. The empirical relationship between W and H is given by:

$$W = cH^d$$

a and d are coefficients determined from observational datasets. For continental thunderstorms, this relationship is typically:

$$W_c = 1.49H^{0.9}$$

Given the known relationship between flash rate and updraft velocity, the lightning flash frequency can also be expressed as:

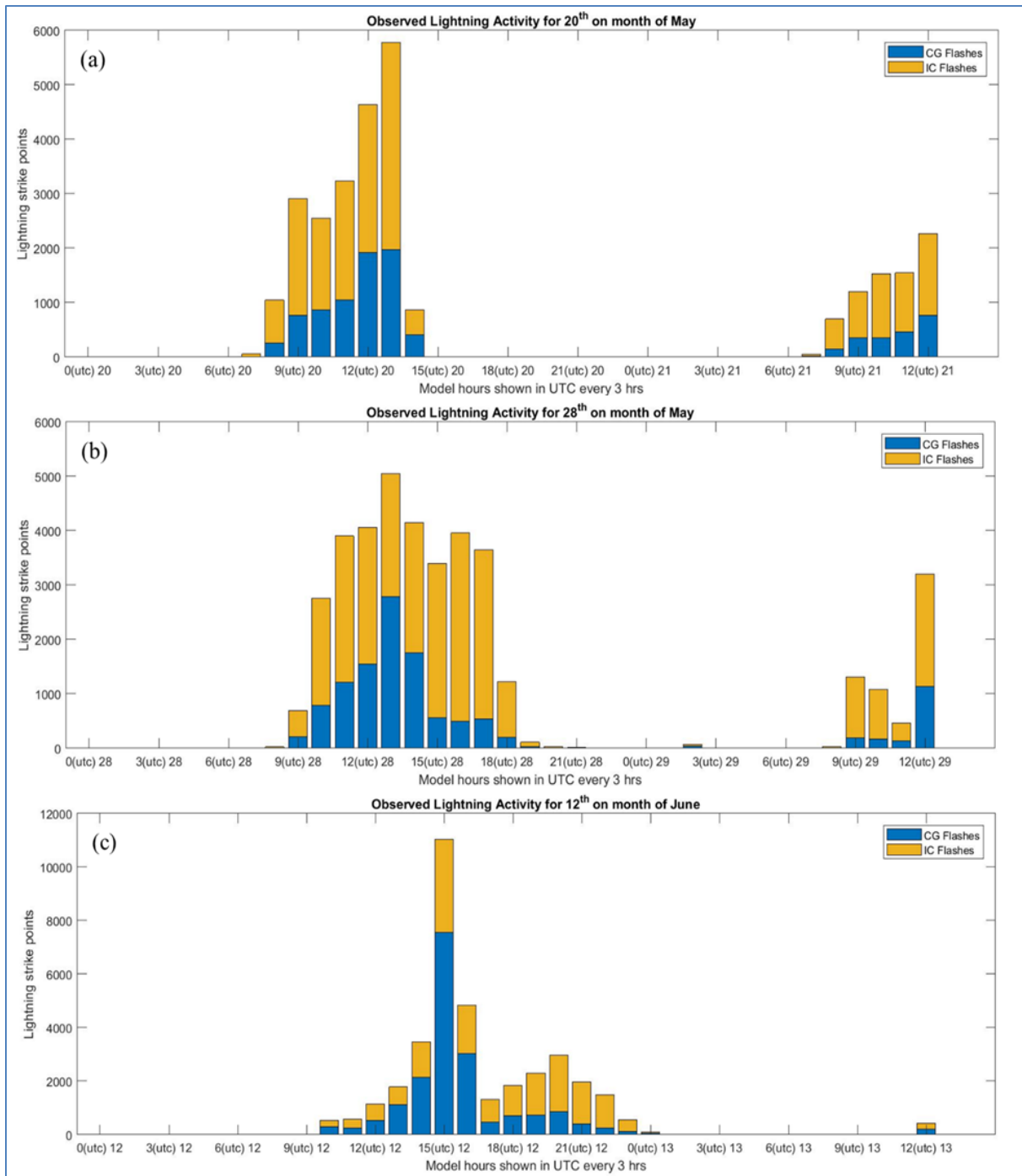
$$F = kW^n$$

where k and n are empirical constants derived from observational studies.

Both parameterizations are incorporated into WRF simulations for pre-monsoon convection over Odisha, India. Model outputs, including cloud top height and updraft velocity, are used as inputs to these formulations to estimate lightning flash rates. The results are compared against observed lightning distributions to evaluate the effectiveness of each method in predicting lightning occurrence and intensity.

2.3. Simulation Details w.r.t. Lightning Flash

The cases for this region were selected based on observed lightning activity in the domain of interest followed by Zepka, *et al.* (2013). It is defined as a heavy thunderstorm event using the criteria based on observed lightning flashes, when more than 400 total lightning flashes are observed consecutively for four hours. Based on this criterion, numerous cases within the domain were examined to identify those exhibiting the highest lightning activity in Odisha. A threshold of 400 consecutive cloud-



Figs. 3(a-c). The observed lightning activity with time over Odisha for simulated case dates; (a) 20th May, 2019; (b) 28th May, 2019 and (c) 12th June, 2019

to-ground flashes over a four-hour period was employed for filtering purposes, resulting in the selection of three such cases. The specific dates of these cases occurred two in May and one in June, are provided in Table 2 with the details of IC and CG lightning flash count. Fig. 3 provides the observed lightning activity over Odisha during the

simulated cases tracked over time. From the figure, it is inferred that the lightning activity picks up around 9 UTC *i.e.*, around 2:30 pm IST and continues to increase till the evening (~12-15 UTC: 5:30-8:30 pm IST). Peak lightning activity is observed in case 1 from 10 UTC to 15 UTC on 20 May 2019, whereas case 2, from 11 UTC up to 18 UTC

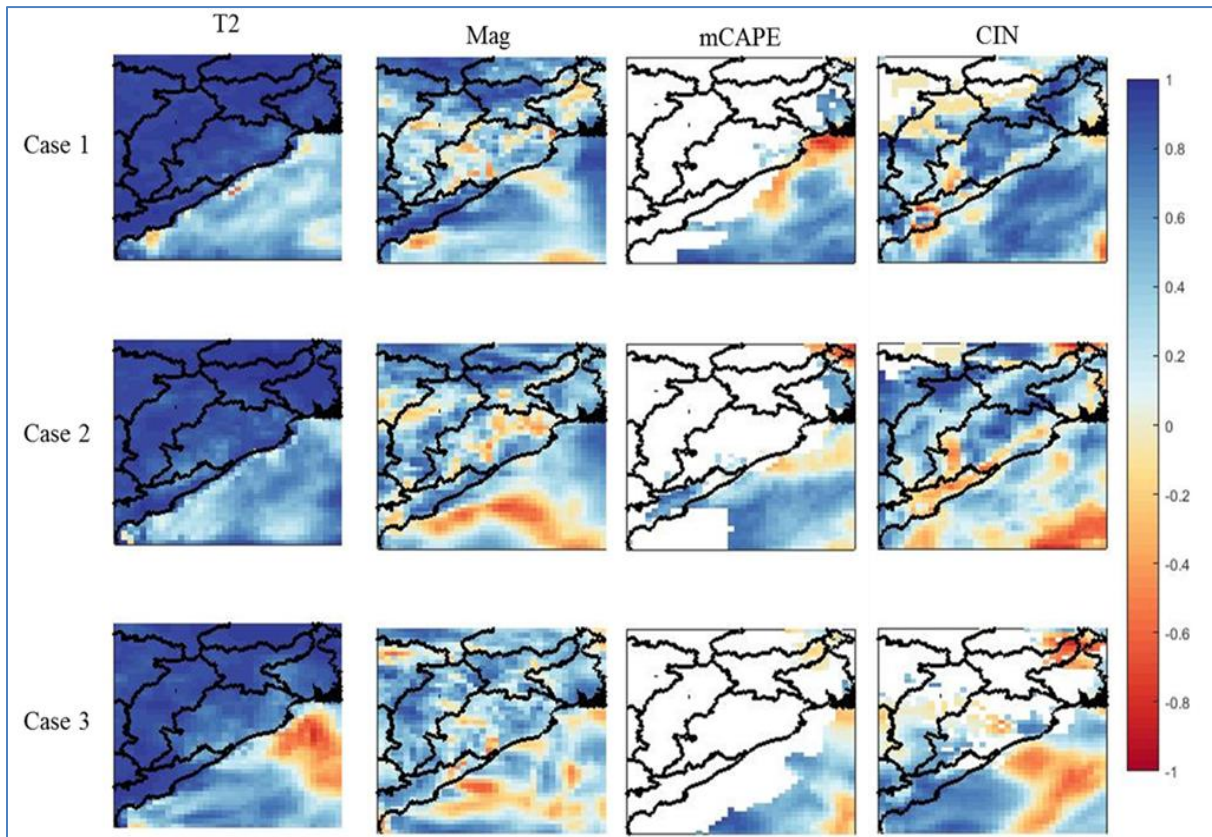


Fig. 4. Spatial Correlation plots for the surface variables, where positive correlation is blue & negative correlation is red

on 28 May 2019 and case 3, from 13 UTC up to 21 UTC on 12 June are observed with the maximum lightning intensity. During this peak period, the lightning flash count exceeds 400 flashes according to the previously specified criteria. This peak aligns with the behavior of the sea breeze in the evening, which provides moisture, and also the orographic effect of the mountain ranges, acting as a lifting mechanism. It is to be noted that the verification of surface parameters has been carried out for the model performance and the lightning analysis and assessment were conducted for both the lightning schemes used in the study. Flash rates are validated with the Indian Institute of Tropical Meteorology (IITM) observational network.

2.4. Statistical Verification

For verification, correlation coefficient and Normalized Root Mean Square Error (NRMSE) are calculated for simulated cases. The NRMSE equation is described in the equation below

$$NRMSE = \frac{RMSE}{\max(RMSE)}$$

where RMSE is the root mean square error. The NRMSE is calculated to investigate the relative spread of the RMSE error and evaluate a general measure to identify which parameter is captured well by the model. The NRMSE value varies from 0 to 1 with 1 representing the maximum RMSE value and 0 representing zero RMSE error.

3. Results and discussion

For each thunderstorm case, three model runs were executed to assess the utility of each lightning parameterization schemes. The lightning schemes act as an additional equation for calculating lightning parameters, independent of their influence on the microphysics schemes. Consequently, all model outputs remain consistent except for the lightning parameters. The results are categorized according to the validated parameters and the region of interest

3.1. Validation of surface variables

Model simulated surface parameters such as U10, V10, T2, and wind magnitude (Mag) are validated in terms.

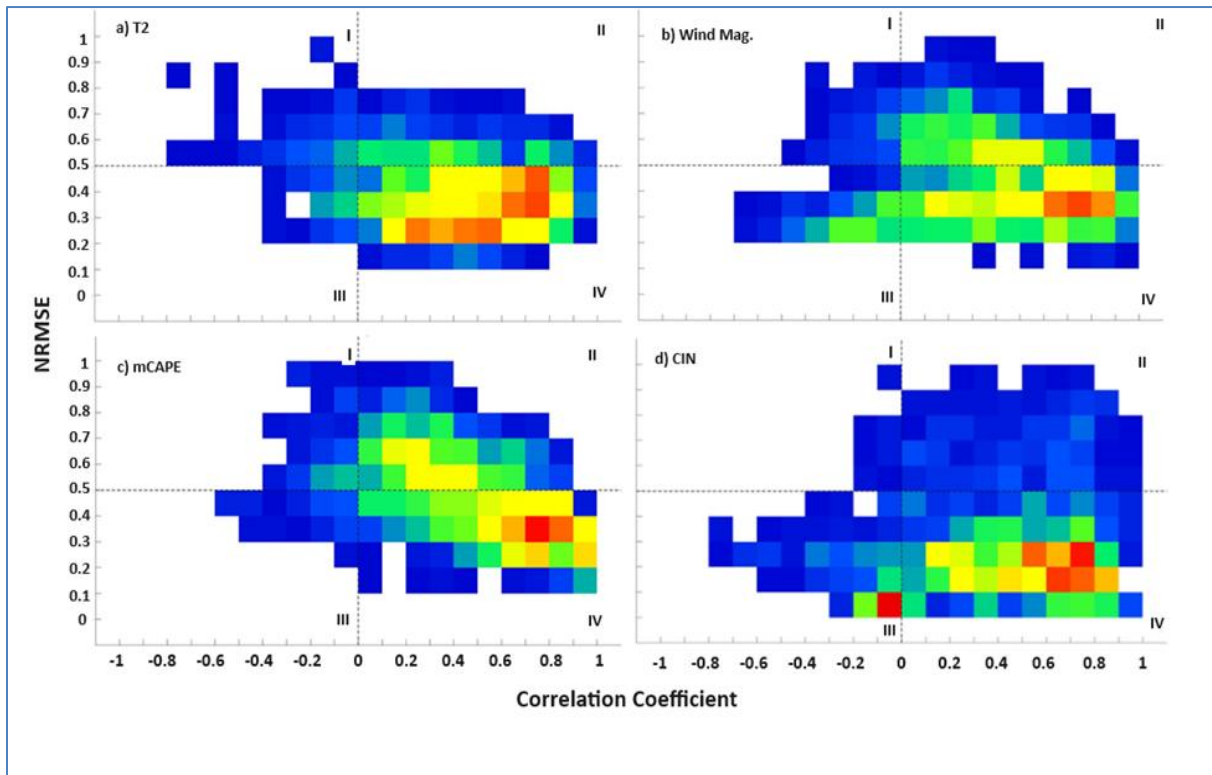


Fig. 5. Bivariate Histogram defined by NRMSE & Correlation Coefficient (CC) values for (a) T2, (b) Wind mag., (c) mCAPE and (d) CIN computed over all the grid points

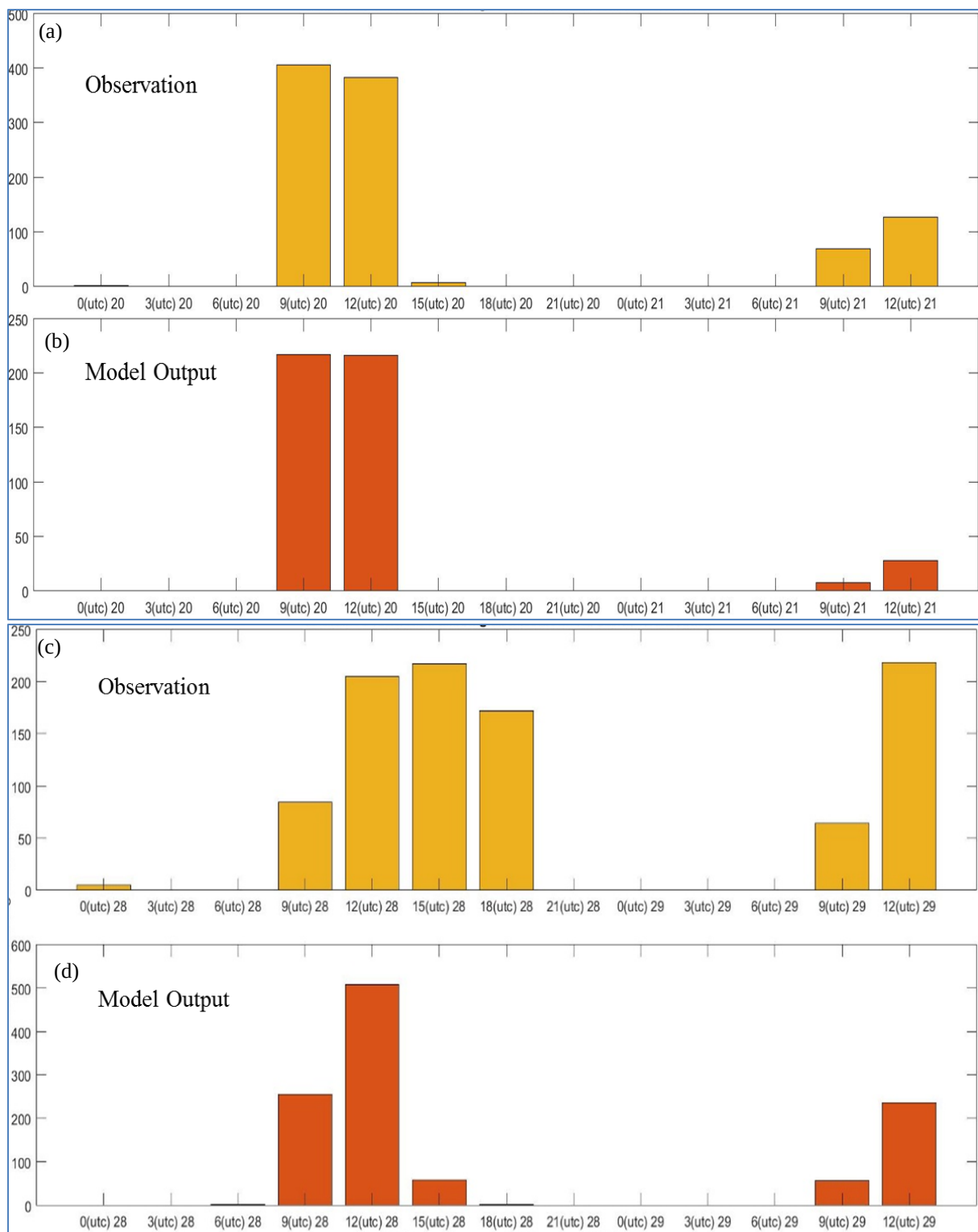
of RMSE (Root Mean Square Error), MAE (Mean Absolute Error), and Correlation Coefficient (CC) by considering the closest grid value to the meteorological observatories distributed over domain viz. Bhubaneswar, Ranchi and Kolkata. The correlation coefficient in all the grid points for Surface Temperature at 2 m height (T2) is reasonably good and RMSE is found to be ~ 3 K. The CC for Mag is above 0.5 for all the grid points in cases 1 & 3 and RMSE is below 3 ms^{-1} . The correlation values for U10 and V10 are quite low in Bhubaneswar and Kolkata as well. The time series analysis (not shown) revealed that the model can capture the temperature variability well. The variability of surface wind is also well captured by the model, but the magnitude is overestimated after 6 hours of the model run (spin up). However, it closely matches thereafter in all three cases over Bhubaneswar. The model underestimates the mCAPE value with considerable error in all three cases. As the correlation values were calculated for Bhubaneswar, CC is calculated for each grid point within the model wherever the data is available from the observation to validate. The spatial spread of CC is plotted in Fig. 4. It shows the correlation values are positive over land in most of the grid points for the variables T2, Mag and CIN in Fig. 4. mCAPE observations are not available for all grid points of the domain, however it is observed to have good correlation over the ocean. For the state of Odisha,

variables T2 and CIN variability are well captured, whereas the other variables such as U10, V10, and Mag have poor correlation over the region

To analyze how well the model captures these surface variables, Normalized Root Mean Square Error (NRMSE) and CC are calculated at all the grid points within the model domain used for simulation over the 36-hour analysis period shown in Fig. 5. The range of CC was between -1 and 1 while NRMSE values spanned 0 to 1. Dashed lines divide the CC and NRMSE space into four quadrants, enabling a clear assessment of model skill. Parameters located closer to the quadrant with low NRMSE and high CC indicate better model performance.

The color pixels in the figure denotes the number of grid points if most of the grid points lie in:

- (i) Lower Right Quadrant (IV), the model can capture the variability as well as the magnitude of the surface variable for which it is plotted.
- (ii) Upper Right Quadrant (II), the model can capture the variability well but the model is either underestimating or overestimating.



Figs. 6(a-d). 3-hourly accumulated rainfall within the domain plotted from observations (a) and model simulation (b) for case 1. (c) and (d) is the same as (a) and (b) but for case 2 (y-axis unit is mm hr⁻¹)

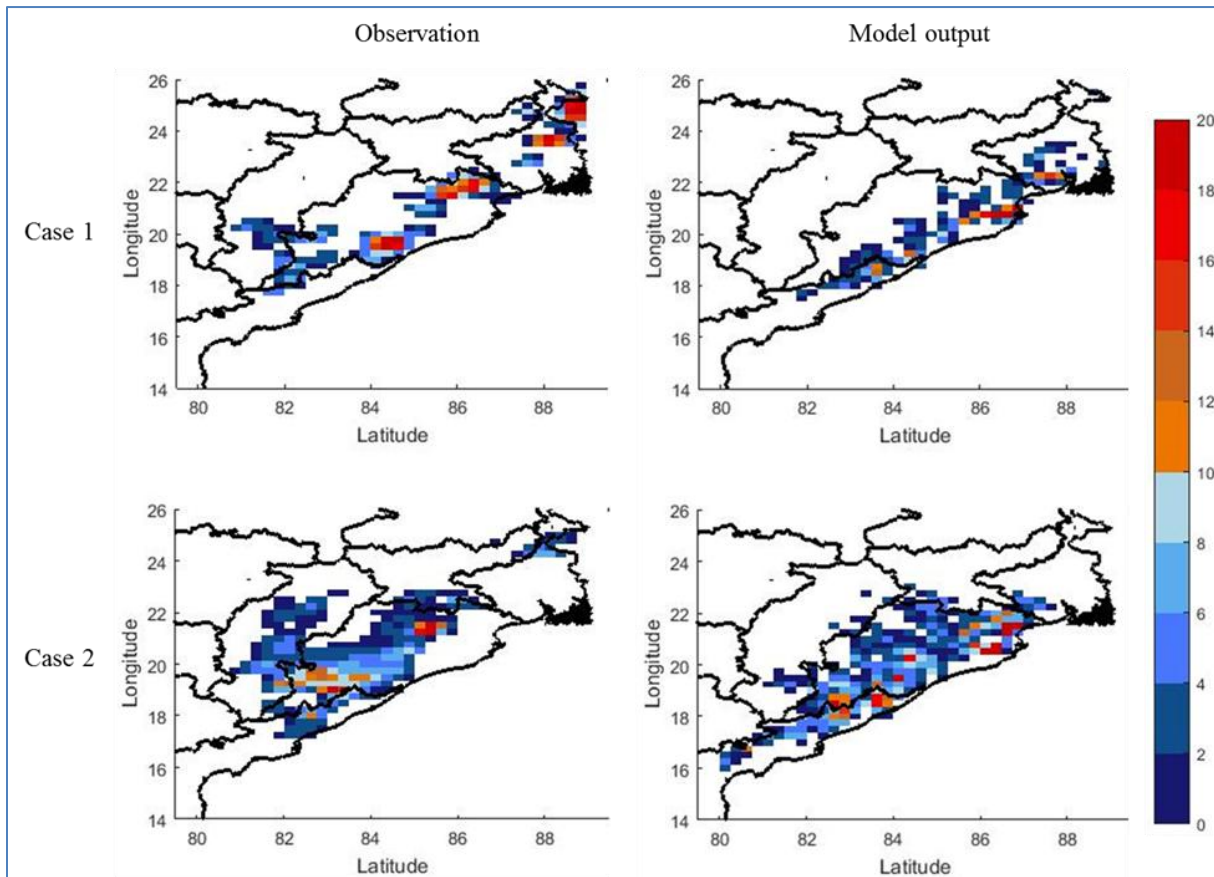


Fig. 7. Accumulated Rainfall (mm) from the TRMM (left panel) and model simulated (right panel) for cases 1 and 2. The units of the rainfall is mm.

(iii) Lower Left Quadrant (III), the model can capture the magnitude of the variable of interest but there is either a delay or lag in capturing the variation of the variable of interest.

(iv) Upper Left Quadrant (I) implies that the model performance is poor to capture the parameters, thus restricting to exhibit the variation and magnitude of the variable of interest.

From the 'r' v/s 'NRMSE', we can observe how well the surface temperature is captured (since most of the points lie in the IV Quadrant). The spread for U10 and V10 is wider where many points lie in Quadrants I, II, and III, however the highest number of grid points lie in Quadrant IV (not shown). The resultant wind Magnitude (Fig. 5b) has its peak in the Quadrant IV for all the cases. For mCAPE, its peak lies in Quadrant II (Fig. 5c), hence the model can capture the variability but with underestimation. The model fails to accurately represent the actual CAPE value for the entire domain, possibly due to inadequate observation

coverage over land in all the cases. However, for CIN, there is a strong correlation value across the domain as depicted in the spatial correlation plot. Moreover, the highest number of grid points falls within Quadrant IV (Fig. 5d), which implies the model can represent CIN reasonably good in comparison.

3.2. Rainfall prediction

For rainfall (R), the validation is carried out for every 3 hrs time step of the simulated output, and the model output is re-gridded to 25 km to match the resolution of TRMM data. To see whether the model can capture peak rainfall activity temporally, a time series bar plot (Fig. 6) is used for this purpose. For temporal validation, the rainfall values in all the grids are summed up (only the grid points where the precipitation is above 1 mm are considered). Accumulated rainfall is validated for cases 1 and 2 only. The spatial rainfall is plotted from the TRMM and model simulations for cases 1 and 2 are shown in Fig. 7. From this figure, it can be observed that the rainfall between 1 mm hr⁻¹

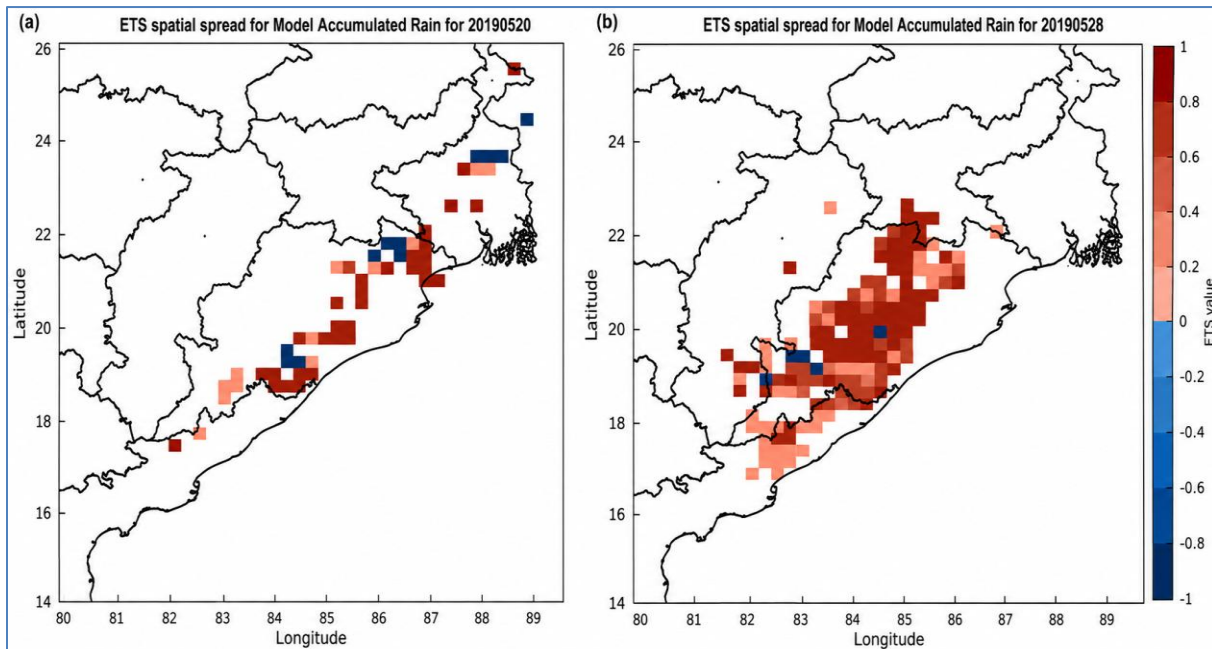


Fig. 8. ETS spatial spread over the domain, for Case 1 (LHS) & Case 2 (RHS)

$1 < R < 10 \text{ mm hr}^{-1}$, shown by blue shades, and the rainfall in the range $10 \text{ mm hr}^{-1} < R < 20 \text{ mm hr}^{-1}$ and above is shown in the red shade to identify where the peak rainfall activity has been occurred in the model. The spatial distribution of the rainfall peaks is captured well and the spread for the accumulated rain for the model run is well represented by the model. The higher rainfall grids have been captured by the model with a positional error of 56 km and 96 km for case 1 and case 2, respectively. For the rainfall validation, accumulated rain for the entire model simulation time, and the observed is plotted for the two cases. Considering the accumulated rainfall from the model outputs, the Equitable Threat Score (ETS) for all the selected cases are calculated and has been presented in the Fig. 8. The ETS value is calculated at each grid point to visualize how well the accumulated rainfall is captured within Odisha. For the spatial ETS, all the null values are removed and negative ETS is presented by blue shade to identify the poor ETS points as this is more crucial than focusing on magnitude. The ETS values for the rainfall are notably high, thus demonstrating the proficiency of model in capturing the rainfall events.

3.3. Lightning prediction

In this Section, the lightning validation is carried out spatially and temporally for the state of Odisha, and as well as for the Northern Odisha region where climatologically high lightning activity has been observed. For spatial

distribution validation, several model scores are evaluated with special focus to ETS over the state of Odisha for the accumulated lightning considering the entire model simulation time for each case. ETS evaluated at every grid point for the two schemes that provided CG flash rates is represented in Fig. 9. The results indicate that Scheme 1 tends to overestimate and exhibit greater dispersion over the domain compared to Scheme 2. When considering the entire domain for accumulated CG flash rate, both schemes effectively represent the overall extent of lightning spread. Scheme 2 more accurately identifies the peak of accumulated lightning and exhibits lower spatial dispersion compared to Scheme 1. However, the CG flash rate value for Scheme 2 is lower than the observed value. In all cases, the CG flash rate peak for Scheme 1 is located in southern Odisha. However, the flash rate equation based on cloud base height, which is effective for identifying single-cell thunderstorms, exhibits poor performance in spatially identifying the peak region.

In Scheme 2, the CG flash rate is underestimated, but the spread is shrunk resulting in fewer false alarms. The peak of accumulated CG flash rate is much closer to observation in cases using Scheme 2. This implies that the flash rate equation based on maximum vertical wind speed ($W_{\max}$) which is effective for identifying multi-cell thunderstorms, serves as a superior indicator of peak activity with spatial distribution over northern Odisha (Mohan *et al.*, 2021).

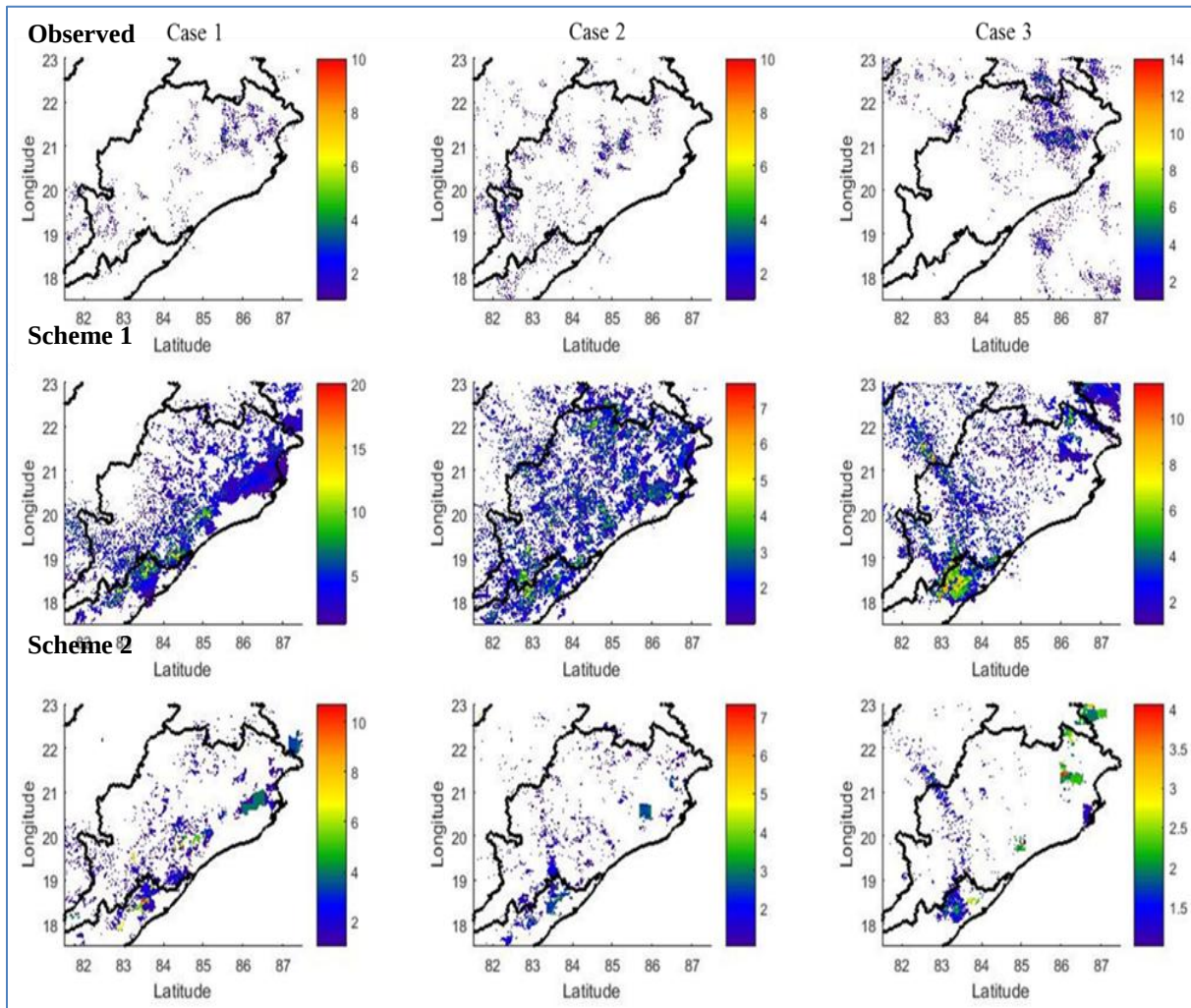


Fig. 9. Accumulated CG lightning Flash rate for Observation (First Row), Scheme 1 (Second Row), Scheme 2 (Third Row), for Cases 1, 2 & 3

Spatial ETS is calculated by extracting the lightning data at each grid point along time for observation and model output (Fig. 10). The model generates an accumulated CG flash rate, requiring the observations to be converted into the accumulated format for all time steps in the model run. The ETS is then calculated for this accumulated CG flash rate. High ETS values coincide with the areas where observations are most abundant demonstrating the capability of the model in accurately capturing observed flash counts as shown in Fig. 9.

Further, to assess the model performance, the accumulated lightning within Odisha is validated against the observations in-terms of various statistical metrics outlined in Table 3. It is to be noted that these skill scores have been computed for the accumulated lightning. Table 3

presents the model performance scores for lightning flash simulations under three different cases using two model schemes (Scheme 1 and Scheme 2). Several statistical metrics, including Accuracy, Bias, Success Ratio, Probability of Detection (POD), and False Alarm Ratio (FAR), were evaluated to assess the model skill. Overall, Scheme 2 consistently outperforms Scheme 1 across most metrics. The accuracy values of Scheme 2 range from 0.82 to 0.88, indicating a good agreement between simulated and observed lightning occurrences, whereas Scheme 1 shows relatively lower accuracy (0.47–0.68). The bias values reveal that Scheme 1 considerably overestimates lightning flashes in all three cases (bias > 3), while Scheme 2 provides a more realistic estimation with bias values closer to unity (0.79–2.79). The success ratio remains low for both schemes, suggesting that although the models can

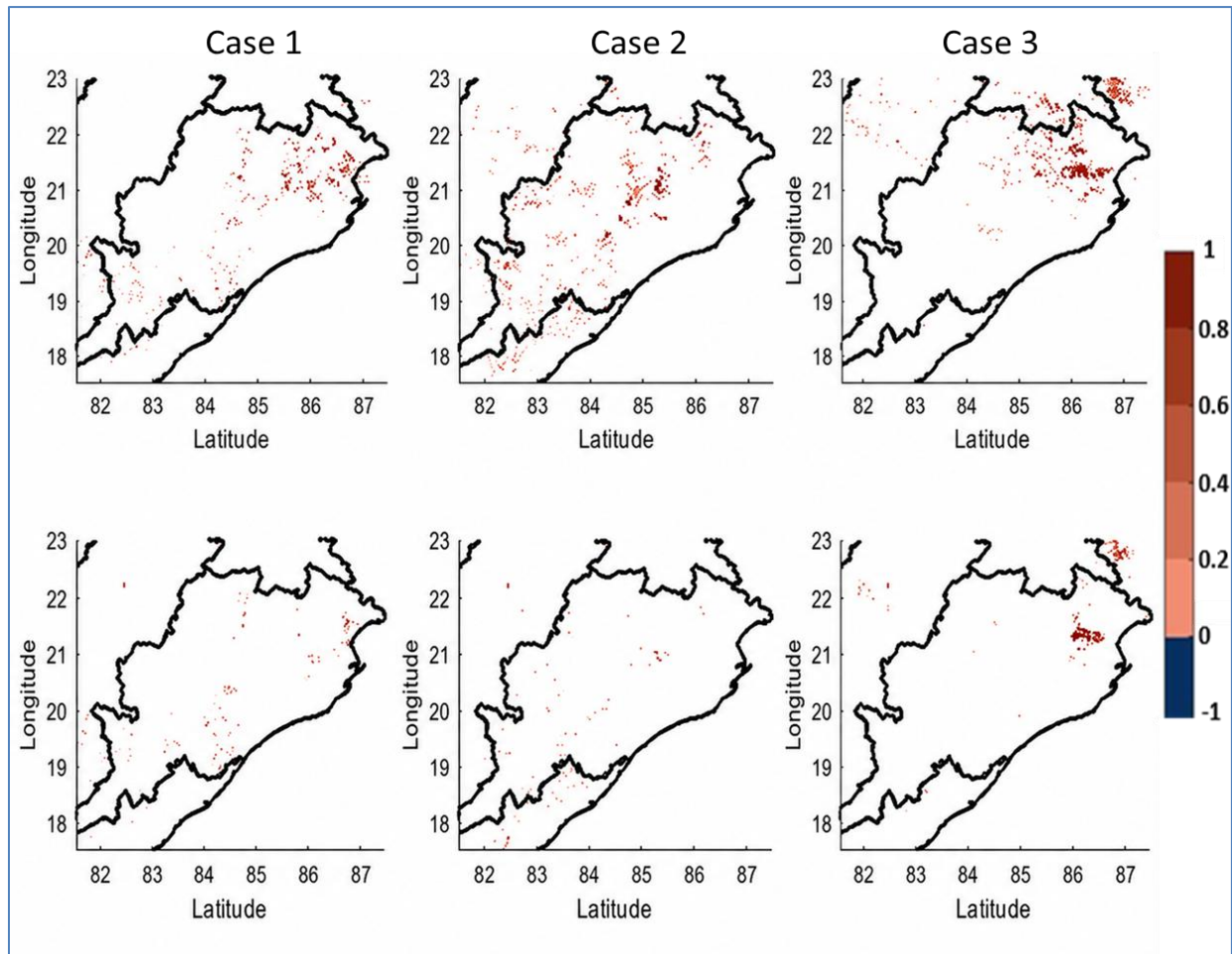


Fig. 10. ETS spatial spread for lightning activity for Scheme 1 (First Row), Scheme 2 (Second Row), for all the cases

TABLE 3

Model Scores for lightning flashes

Model Score	Model Scheme	Case 1	Case 2	Case 3
Accuracy	Scheme 1	0.63	0.47	0.68
	Scheme 2	0.82	0.86	0.88
Bias	Scheme 1	7.26	8.37	3.62
	Scheme 2	2.79	1.34	0.79
Success Ratio	Scheme 1	0.06	0.06	0.08
	Scheme 2	0.05	0.05	0.14
Probability of Detection	Scheme 1	0.47	0.48	0.30
	Scheme 2	0.13	0.07	0.10
False Alarm Ratio	Scheme 1	0.94	0.94	0.92
	Scheme 2	0.95	0.95	0.86

identify lightning occurrences, there are limitations in correctly classifying the exact grid locations. Similarly, the probability of detection is moderate for Scheme 1 (0.30–

0.48) but relatively low for Scheme 2 (0.07–0.13), implying that Scheme 1 detects more lightning occurrences but at the cost of higher false alarms. The false alarm ratio (FAR)

values for both schemes are high (0.86–0.95), indicating frequent false detections of lightning events. However, Scheme 2 shows a slightly better performance in Case 3, with a lower FAR of 0.86 compared to 0.92 for Scheme 1. In summary, while Scheme 1 tends to overpredict lightning activity, Scheme 2 demonstrates more balanced performance with higher accuracy and lower bias, albeit with slightly reduced detection efficiency. The statistical analysis indicates that the model forecast performs well for the flashes occurring over the northern Odisha (upper right region in Fig. 8). Here, while Scheme 1 demonstrates a probability of detection due to overestimation, the success ratio is relatively low. The accuracy is high for Scheme 2 since there are more correct negatives in Scheme 2 based Model runs, while Scheme 1 exhibits a higher bias compared to Scheme 2. The false alarm ratio is of similar value for both schemes. Overall analysis shows that PR92, based on maximum vertical wind, redistributes flashes within the dBZ > 20 approach (Scheme 1). This shows higher skill when compared to the PR92 based on a 20 dBZ top that redistributes flashes within dBZ > 20 approach (Scheme 2). However, the present study is a preliminary attempt to predict the flash counts using the high-resolution regional models and further needs to be improved with assimilation of weather radar reflectivity datasets (Siripurapu *et al.* 2014) and land surface initialization (Osuri *et al.* 2017).

4. Conclusions

This study demonstrates the ability of the Weather Research and Forecasting (WRF) model to simulate lightning activity using different parameterization schemes, highlighting the strengths and limitations of each approach. Scheme 1 (based on Cloud Top Height) shows a high probability of detection but tends to overestimate CG flash rates, while Scheme 2 (based on Maximum Vertical Wind Speed) underestimates flash counts but better captures the spatial distribution of lightning in northern Odisha. The findings suggest that Scheme 2, which is more effective in identifying multi-cell thunderstorms, provides a better representation of peak lightning activity in regions with high thunderstorm frequency.

Despite these insights, the study identifies key limitations in the model performance, particularly in the simulation of surface wind components (U10, V10) and Maximum Convective Potential Energy which exhibited considerable errors over Odisha. The underestimation of Maximum Convective Potential Energy, possibly due to inadequate observational coverage, suggests the need for improved initialization of thermodynamic conditions. Spatial displacement in the simulated peak rainfall and lightning activity further indicates biases in the model's representation of convective

processes. Additionally, while the ETS values for accumulated rainfall and lightning demonstrate good predictive skill, overestimation in Scheme 1 and underestimation in Scheme 2 point to inherent uncertainties in lightning detection efficiency, particularly in capturing high-flash-density regions.

To improve lightning prediction in the region, future research should focus on refining PR92-based schemes by incorporating region-specific modifications, such as adaptive CAPE, vertical ice graupel, and $W_{\max}$ thresholds, to reduce false alarms. The assimilation of high-resolution radar reflectivity datasets (Siripurapu *et al.*, 2014) and improved land surface initialization (Osuri *et al.*, 2017) could enhance the accuracy of convective storm representation. Future advancements in lightning prediction can be achieved by refining the PR92 approach using a masking filter (Giannaros *et al.*, 2015), which optimizes thresholds for Qice, CAPE, and $W_{\max}$ to reduce false alarms and improve forecast accuracy. Furthermore, incorporating charge separation equations (Mansell *et al.*, 2005; Fierro *et al.*, 2013) within the WRF framework could enhance the simulation of electrification processes in convective storms. Additionally, integrating machine learning techniques (Banik *et al.*, 2021) to develop empirical flash rate models, along with lightning data assimilation within WRF (Gharaylou *et al.*, 2019), may significantly enhance operational forecasting capabilities. This study advances the understanding of lightning parameterisation by providing a comparative evaluation of two widely used schemes in a high-impact lightning region. The results highlight the need for region-specific improvements in lightning modeling, contributing to broader atmospheric research by improving thunderstorm electrification representation in numerical weather prediction models.

By addressing these challenges, this study lays the groundwork for improving operational lightning forecasting and early warning systems, particularly in Eastern India, where lightning remains a significant natural hazard. The proposed advancements in parameterization and data assimilation techniques can contribute to more accurate predictions, ultimately aiding disaster preparedness and risk mitigation efforts in lightning-prone regions.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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