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Integrated Thermodynamic and Microphysical Framework for Thunderstorm and Lightning Prediction over Bangladesh

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Abstract

Bangladesh is located within the highly lightning-prone region (30N-30S belt) and experiences significant casualties and property loss, particularly during the pre-monsoon and monsoon season due to lightning activity. Traditional thunderstorm and lightning forecasting methods are mostly rely on thermodynamic instability indices. These indices have limitations in forecasting the intensity, duration, and spatial distribution of the lightning. Recent advances in high-resolution Numerical Weather Prediction (NWP) have facilitated the development of microphysics and cloud electrification-based techniques, such as the Lightning Potential Index (LPI) and Lightning Flash Density (LFD). They improve lightning forecasts with greater spatial accuracy but have a very shorter lead time. This study investigates four severe thunderstorm events occurring between May and July 2023 over Bangladesh using Weather Research and Forecasting (WRF) model with electrification scheme (WRF-Elec). Here, we investigate an integrated approach of thermodynamic and microphysical framework to improve lightning forecasting in both temporal and spatial dimensions. We find that microphysical fields like maximum reflectivity, LPI, and LFD capture the lightning activity with 2-6 hours lead time and spatial accuracy of 1.5×1.5 deg boundary. On the other hand, the conventional thermodynamic fields predict convective activity 12-18 hours lead time but provide the information of little to no spatial boundary. In the integrated approach combining microphysical and thermodynamic fields we find the lightning prediction with a significantly larger lead time while maintaining spatial accuracy for lightning activity. These results suggest that the integrated microphysical–thermodynamic approach should be further tested and incorporated into operational lightning prediction systems over Bangladesh.

Keywords: Microphysics, Thermodynamics, LPI, LFD, WRF-Elec

1 Introduction

Lightning is a perilous natural phenomenon that poses significant risks to life, property, and socioeconomic stability, especially in vulnerable regions like Bangladesh. Bangladesh is situated within the 30°N–30°S latitudinal belt, where nearly 78% of global lightning strikes are concentrated (Christian et al., 2003). More lightning fatalities occur during the pre-monsoon season (March-May) and the monsoon season (June–September). From 2016, the Bangladesh government has started considering lightning strikes as a catastrophic weather event due to loss of life and property (Dewan et al., 2017). Unfortunately, the forecast of lightning in Bangladesh is not yet fully developed. Hence, a systematic and efficient lightning flash prediction and resilience is a necessity.

For this concern, meteorologists all over the world have typically relied on indices like Total-Totals Index (TTI), K index (KI), Convective Available Potential Energy (CAPE), Convective Inhibition (CIN) and other thermodynamic fields to forecast thunderstorm probabilities. Although these indices are widely used, they all have significant drawbacks. They primarily rely on thermodynamic probabilities and ignore important dynamical and microphysical processes that govern storm electrification, including charge separation mechanisms, ice-graupel interactions, and mesoscale convection organization (Lynn and Yair, 2010; Paul et al., 2019, 2022). This makes them effective at capturing the potential for thunderstorm initiation (Bondyopadhyay and Mohapatra, 2023) but less effective at predicting the intensity, duration, or lightning hazard associated with specific events(Kunz, 2007). Furthermore, in areas like Bangladesh that have complicated terrain or extremely variable boundary-layer conditions, their predictive accuracy is frequently limited by their coarse spatial and temporal resolution.

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Consequently, world forecasting community has moved toward microphysics based indices derived from NWP models that explicitly represent storm microphysics and electrification processes. Among these, the Lightning Potential Index (LPI) has emerged as a promising diagnostic tool. Yair et al. (2010) and Lynn and Yair (2008) show that LPI is positively correlated with observed lightning density and also heavy rainfall, and suggested that LPI could be used to predict the potential for the occurrence of lightning. In recent times, the lightning prediction from numerical models has gathered a lot of interest because of its promising results (Vani K et al., 2022; Rabbani et al., 2022; Paul et al., 2022). Conventional techniques frequently rely on statistical relationships obtained from surface or upper-air observations and provide a broad prediction of the likelihood of thunderstorms. However, high-resolution NWP models that take environmental variability, dynamics, and microphysics into account, can simulate atmospheric processes. This approach improves the accuracy of identifying the lightning location (Ahasan et al., 2021; Ferdaus et al., 2021). However, the usefulness of LPI for prediction is limited, as it is typically available only when convection has already developed and the event is imminent. Consequently, LPI serves primarily as a nowcasting tool rather than a true forecasting indicator with meaningful lead time.

Another promising and computationally efficient approach for predicting lightning activity in WRF is the lightning parameterization scheme (WRF-Elec). This scheme is based on the electrification framework introduced by Mansell et al. (2005, 2010), which represents explicit non-inductive charging, charge separation, and discharge processes within convective storms. The implementation in WRF-ARW was further developed and expanded by Fierro et al. (2013), enabling more realistic simulation of storm electrification across a range of weather systems. With these parameterizations, WRF model able to diagnose key lightning-related microphysical quantities such as flash density and electric-field magnitude. These are critical for operational lightning forecasting and early hazard detection. There are several recent studies that have used this electrification scheme and demonstrated its capability to capture convective activity, including lightning (Gharaylou et al., 2019, 2020; Rabbani et al., 2022).

Despite increasing global interest in lightning research, only a limited number of studies have examined lightning activity over Bangladesh, focusing either on thermodynamic indices or microphysical variables. For example, Paul et al. (2019) demonstrates that thermodynamic indices such as CAPE, CIN, TTI, and KI can effectively predict thunderstorm occurrence at relatively long lead times. However, these indices generally fail to capture the spatial location of lightning events. Similarly, Paul et al. (2022) analyzed a simulated thunderstorm event and assessed the strengths and limitations of the Lightning Potential Index (LPI), showing that although LPI can accurately detect thunderstorm occurrence and location, its predictive lead time window remains very short. More recently, Rabbani et al. (2022); Paramanik et al. (2024) demonstrated that the WRF-Elec simulated LPI offer higher accuracy for operational lightning forecasting with comparable computational cost. While these studies highlight the capability of WRF-Elec and its associated lightning schemes to reproduce specific lightning events and evaluate parameterization performance, critical information regarding lead time is still lacking. In addition, no comprehensive assessment has evaluated the model's ability to predict lightning in Bangladesh using a coupled thermodynamic–microphysical framework capable of providing both extended lead times and improved spatial accuracy.

Addressing this issue requires an analysis of the coupled approach. To investigate this, we designed the present study as follows: Section 2 describes the datasets, model configuration, and experimental design. Section 3 presents the results and discussion, including an evaluation of key predictors and their relevance for lightning activity over Bangladesh. Finally, Section 4 summarizes the major findings, outlines the conclusions of this work and recommendations of future work.

2 Data & Methodology

2.1 WRF Model and Data

We use National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data to run the WRF model in this study. The FNL dataset is produced operationally by NCEP using the Global Data Assimilation System (GDAS), which assimilates a wide range of in situ and satellite-based observations to generate gridded analyses of the atmospheric state.

Table 1: WRF Model Configuration

Parameter	**Configuration**
DX, DY	4 km
Microphysics scheme	NSSL 2-moment (Mansell et al., 2010)
Electrification	ON(Ziegler and MacGorman, 1994)
Boundary layer scheme	Yonsei University scheme (YSU) (Hong et al., 2006)
Land surface model	Unified Noah Land Surface Model (Tewari, 2004)
Radiation	RRTMG (Iacono et al., 2008)

The NCPE-FNL datasets are available every six hours (at 00, 06, 12, and 18 UTC) on a $1^\circ \times 1^\circ$ latitude–longitude grid, providing global coverage of essential meteorological variables such as temperature, pressure, humidity, wind components, and surface fluxes. The FNL data were dynamically downscaled using the WRF model using the confirmation in Table 1 to generate the high-resolution initial and boundary conditions required for simulating mesoscale convective systems and associated lightning activity over Bangladesh. The lateral boundary conditions were updated every six hours to maintain consistency with the evolving large-scale flow, while the model topography and land–surface fields were interpolated to the finer computational grid. The WRF confirmation are chosen as the same way as other lightning study of Bangladesh (Paul et al., 2022; Rabbani et al., 2022; Paramanik et al., 2024).

Table 2: Case Date, Time and Coordinate

Case	Date	Time (UTC)	Coordinate (1.5×1.5 deg)
Case 1	May 23	1110	89°–90.5°E, 22.5°–24°N
Case 2	June 21	1130	89°–90.5°E, 24°–25.5°N
Case 3	June 27	1200	88.5°–90°E, 22.5°–24°N
Case 4	June 30	1800	89.5°–91°E, 23.5°–25°N

2.2 Case Selection

Four intense lightning events for year 2023 is selected for detailed evaluation in this study (Table 2). Initially, several cases were selected based on lightning activity, deep convective development, and associated severe weather phenomena (e.g., gusty winds) using data from different weather stations of the Bangladesh Meteorological Department. From these, the final four cases are confirmed and finalized using lightning flash observations from Meteologix, which provides near–real-time lightning monitoring across Bangladesh.

2.3 Observation Data

To assess convective activity, we utilize multiple observational datasets. INSAT-3D, a geostationary meteorological satellite, provides multispectral imagery at six wavelengths, enabling monitoring of cloud development, surface conditions, and storm evolution. Blended thermal-infrared and visible images from the Meteorological and Oceanographic Satellite Data Archival Center (MOSDAC) are used to evaluate cloud coverage for lightning cases. Additionally, lightning flash data from Meteologix provide high-resolution spatial and temporal information on lightning activity across Bangladesh. Together, these datasets allow a comprehensive assessment of convective conditions and validation of lightning events in the study region.

3 Results & Discussions

The performance of the integrated lightning forecasting framework is analyzed by combining microphysical parameters: maximum reflectivity, LPI and lightning Flash Density (LFD) with thermodynamic fields: most unstable CAPE (mCAPE), most unstable CIN (mCIN), vertical velocity, KI, and TTI.

To begin, we examine the individual property of the microphysical and thermodynamic fields for each case. In Figure 1a, the area enclosed by the black rectangle exhibits very low brightness temperatures from MOSDAC, indicating the presence of deep convective clouds and substantial hydrometeor loading conditions that are highly favorable for electrification. The lightning analysis product from Meteologix further confirms active lightning during this period (Figure 1b). Correspondingly, the WRF-Elec simulated fields show a markedly strong response, with maximum reflectivity reaching 60 dBZ, LPI values of around 10 m^2 s^{-2}, and LFD exceeding 50 flashes per grid column within the black triangle highlighted in Figures 1c-1e. These simulated features accurately capture both the spatial organization and timing of the observed lightning activity with high fidelity. Similar agreement is found across the remaining cases (Figures SI 1-SI 4), demonstrating consistent model performance. This shows the role of microphysical parameters and highlights the model's capability to represent the key physical processes leading to lightning initiation.

As microphysical fields effectively capture both the location and time of lightning, we next analyze area weighted localize mean profile within the coordinate boundary (Table 2) for each case to evaluate the potential lead time for forecasting lightning. For Case 1, max reflectivity, LPI, and LFD begin to increase around 08:50 UTC that is two and half hours prior to the actual lightning event (Figure 2). For the remaining cases, these microphysical indicators start rising between three and six hours before the lightning occurrence. This show that the temporal evolution of max reflectivity, LPI and LFD can provide an early warning signal with a lead time of two to six hours for convective electrification within a 1.5×1.5 deg spatial domain. These

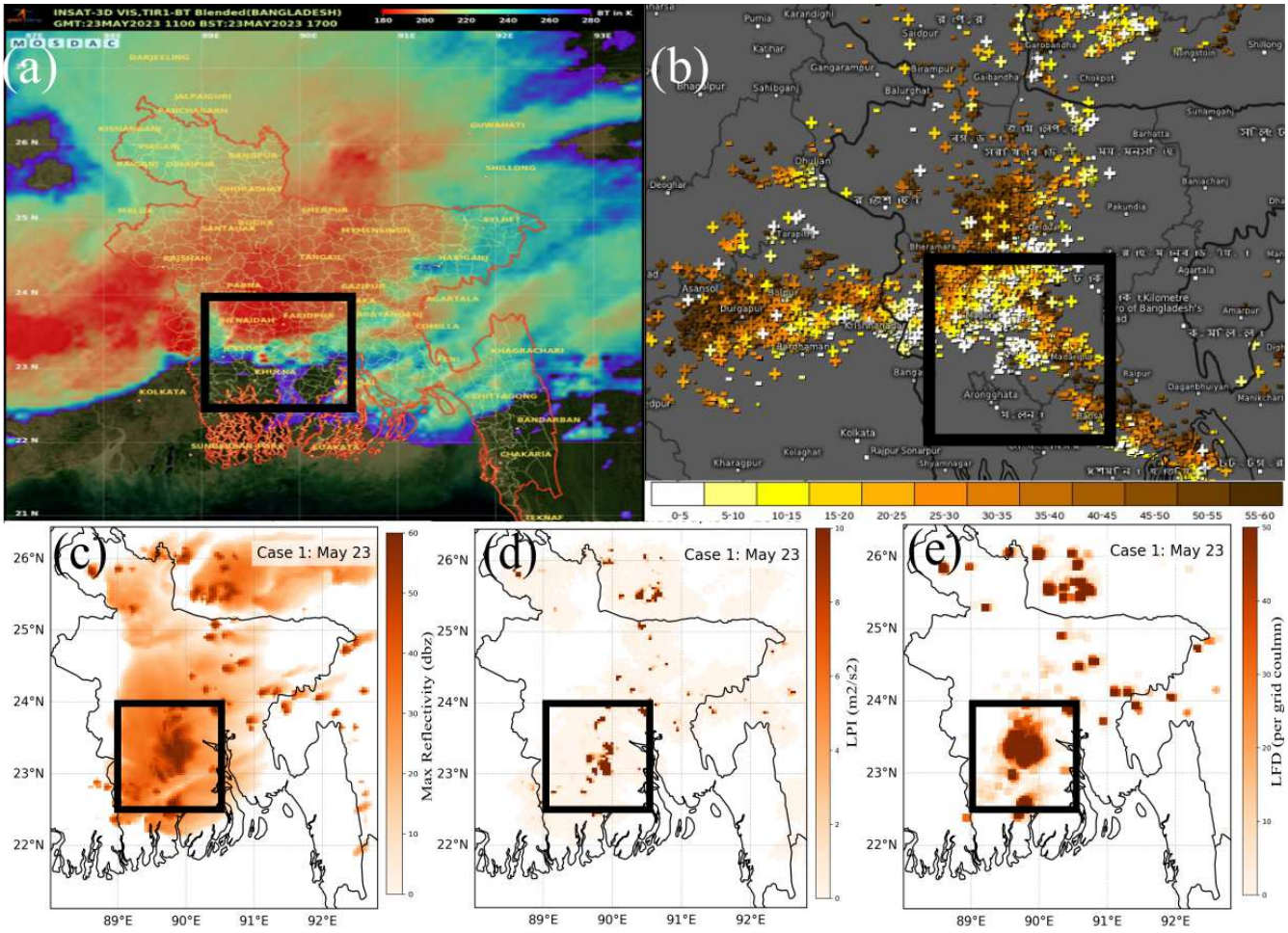


Figure 1: Observation and simulated variables for case 1: May 23. (a) cloud top brightness temperature from MOSDAC at 1100 UTC, (b) lightning flash analysis from Meteologix at 1115 UTC, (c) maximum reflectivity from WRF simulation at 1110 UTC, (d) same as panel-c but for LPI, (e) same as panel-c but for LFD. The back triangle in each panel are the representative area of the case coordinate mention in Table 2

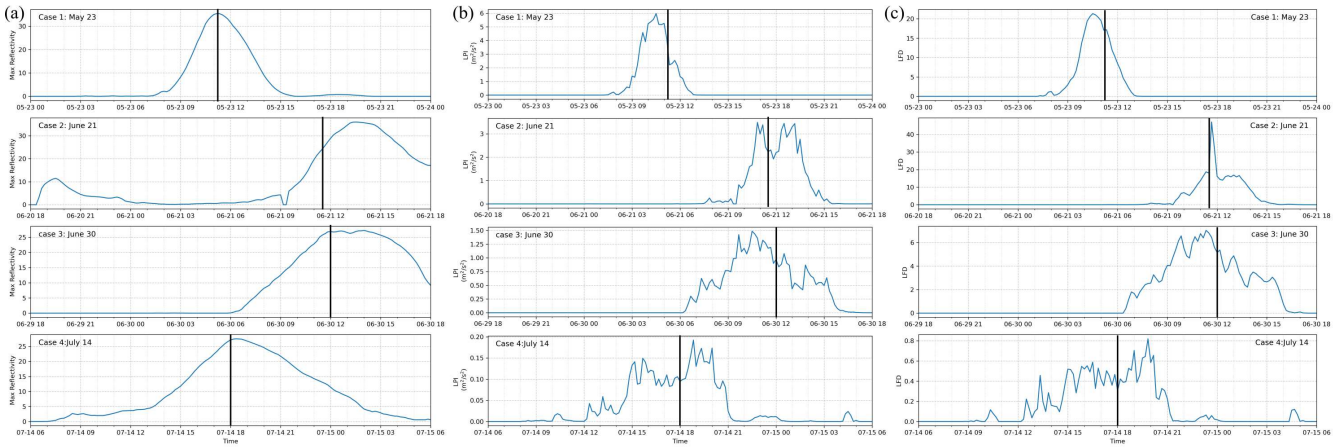


Figure 2: Model simulated weighted area-average (a) maximum reflectivity (b) LPI and (c) LFD for the four case studies, with each row corresponding to one case. The black horizontal line represents the exact time of the case. The averaging domains are defined in Table 2

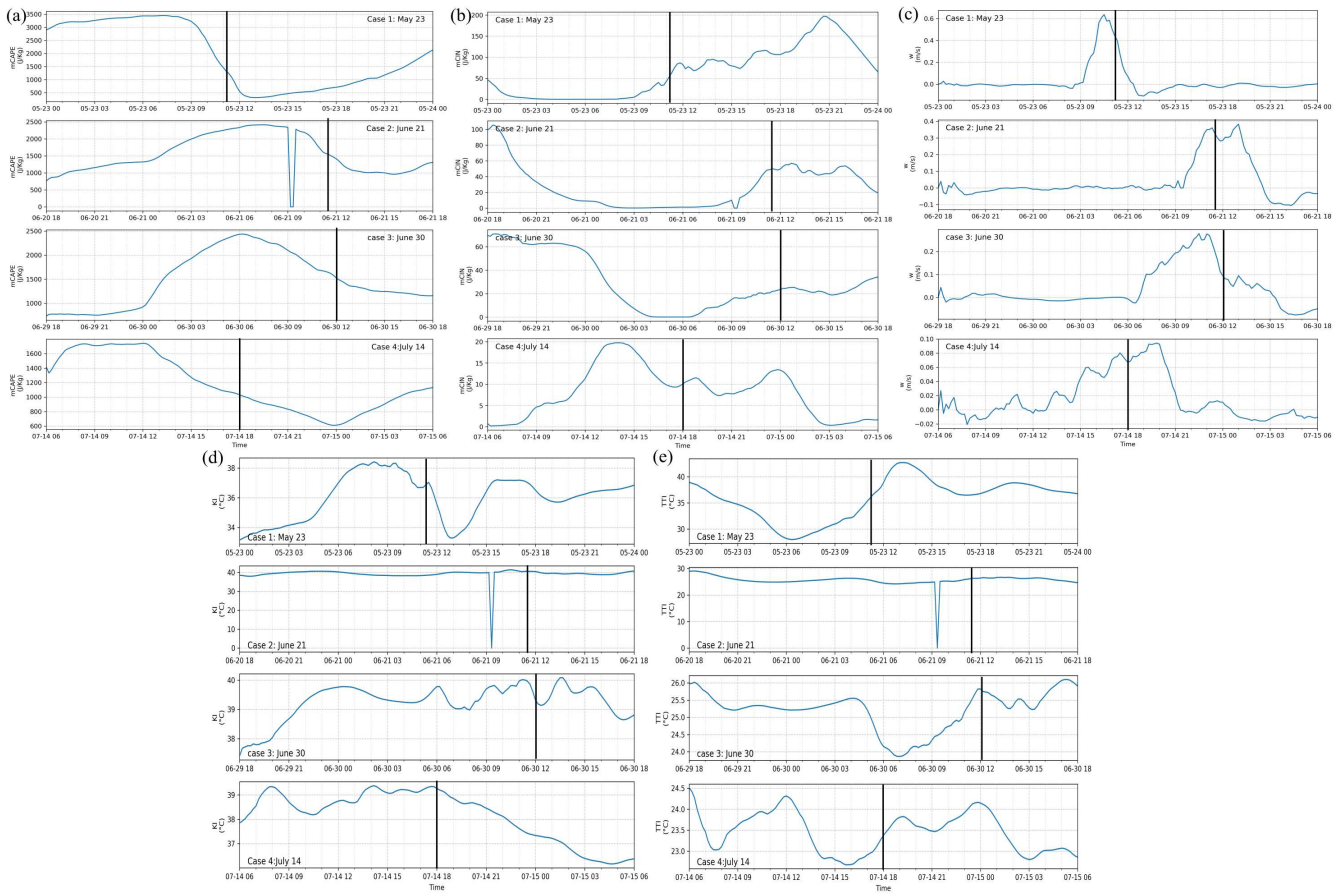


Figure 3: Same as Figure 2 but for (a) mCAPE, (b) mCIN, (c) vertical velocity at 500hPa, (d) KI and (e) TTI

results illuminate the potential utility of microphysical parameters for short to medium term lightning forecasting and offer insights into the timing of convective processes relative to observed lightning events.

We next examine the performance of thermodynamic parameters for lightning forecasting and find that these thermodynamic indices exhibit signals much earlier (Figure 3) but with less precise spatial information (Figure SI 5). For instance, mCAPE reaches high values 12–18 hours prior to the lightning events, while mCIN shows correspondingly low values during the same period, indicating favorable conditions for convection. Similarly, vertical velocity, KI and TTI begin to indicate potential convective activity 12–18 hours in advance. However, all of the thermodynamic fields exhibit broadly elevated values across the entire domain, indicating favorable conditions for convection but offering little guidance on the precise location of lightning activity (Figure SI 5). These results highlight that thermodynamic indices are valuable for early warnings but lack spatial specificity. This same conclusion has also been found for thermodynamic fields in recent studies (Paul et al., 2019; Johns and Doswell III, 1992; Rajasekhar et al., 2016). Therefore, coupling microphysical and thermodynamic indicators can deliver both longer lead times and precise spatial predictions.

With the integrated approach i.e., information from both microphysical (Figure 2) and thermodynamic (Figure 3) we find that lightning prediction 3-6 hours lead time with an spatial information of 1.5×1.5 deg boundary. For instance, in Case 3, maximum reflectivity, LPI, and LFD begin to increase approximately six hours before the actual lightning activity within the coordinate boundary, indicating the growing stage of hydrometeor (e.g., hail, graupel). In addition, we find favorable values for convection such as significantly high mCAPE, low mCIN, high vertical velocity, high KI, and high TTI roughly ten hours prior to the event. In another example for Case 1, microphysical fields provide a lead time of 2-3 hours and thermodynamic fields indicate consistently favorable atmospheric conditions for thundering up to 6-10 hours before the actual event. These results show that combined approach enables both early detection and accurate spatial predictability of lightning events that is not possible in either approach alone.

4 Conclusions

This study represents the the roles of microphysical and thermodynamic processes together in lightning prediction. We find that microphysical fields such as maximum reflectivity, LPI, and LFD most accurately capture the spatial distribution of lightning events with 2–6 hours lead time. In contrast, thermodynamic variables such as mCAPE, mCIN, vertical velocity, KI, and TTI offer very high lead time of 12–18 hours but lack spatial information of lightning. Together, these results indicate that a coupled framework provides the most robust pathway for improved spatial accuracy lightning forecasting with 6-10 hours lead time.

This work provides a comprehensive analysis of lightning prediction using coupled microphysical and thermodynamic indicators, but still there are several limitations. First, our evaluation is based on only four severe lightning case studies. Although these cases offer valuable insight, a more robust assessment will require a larger sample size along with standard verification metrics such as probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI). Second, we consider a $1.5\times1.5^\circ$ grid for assessing localized accuracy. In the future, smaller boundaries such as $0.5\times0.5^\circ$ or even smaller could be tested to develop more precise, high-resolution lightning prediction algorithms. Third, this study uses FNL data as the initial and boundary conditions. For real-time operational implementation, future work should instead incorporate Global Forecast System (GFS) data to assess model performance under realistic conditions. Overall, this study should be viewed as an initial step toward developing an integrated lightning prediction framework and expanding both the dataset and verification strategies will be essential for advancing its operational utility in Bangladesh.

Declarations

Funding

No specific funding was received for this research.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' Contributions

PP contributed to the study conception, methodology development, model simulations, data analysis, interpretation of results, and manuscript writing. JFJ contributed to the analysis and interpretation of the initial results. Both authors reviewed and approved the final manuscript.

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Supplementary Information (SI)

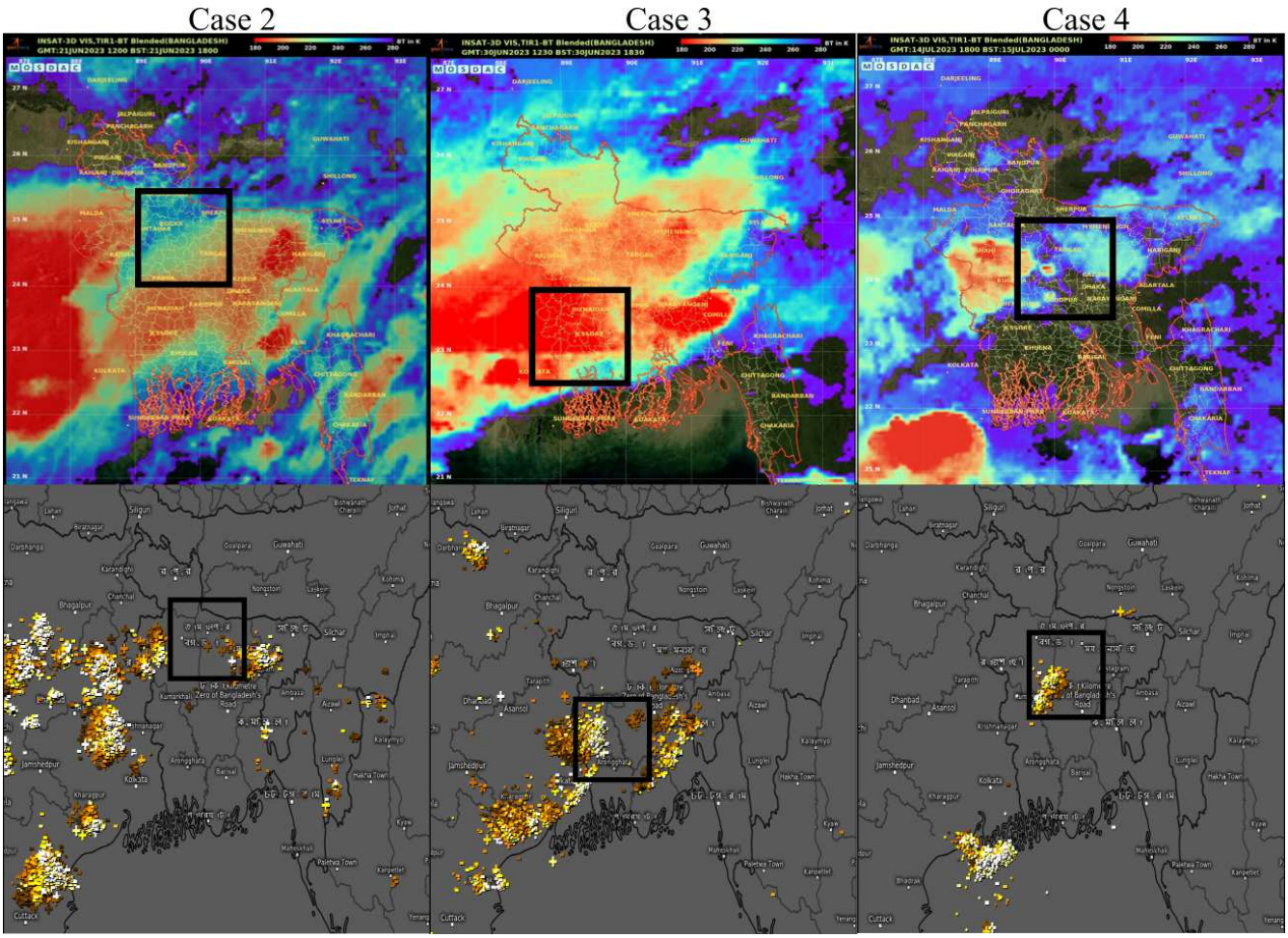


Figure SI 1: MOSDAC and Metologix observations for case 2-4

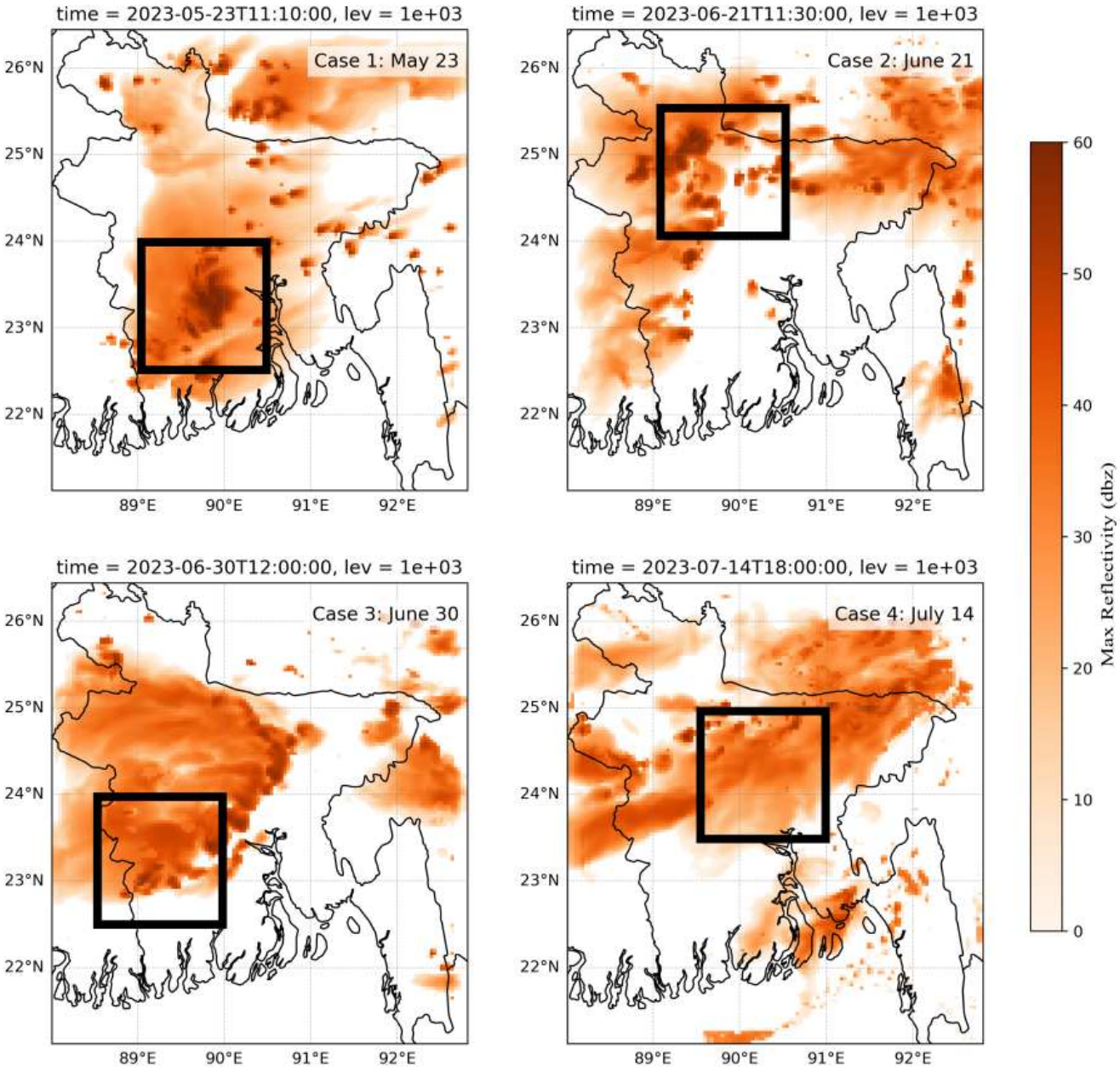


Figure SI 2: Max Reflectivity map for four cases at the time of case. The back triangle is the representative area of the case coordinate mention in Table 2

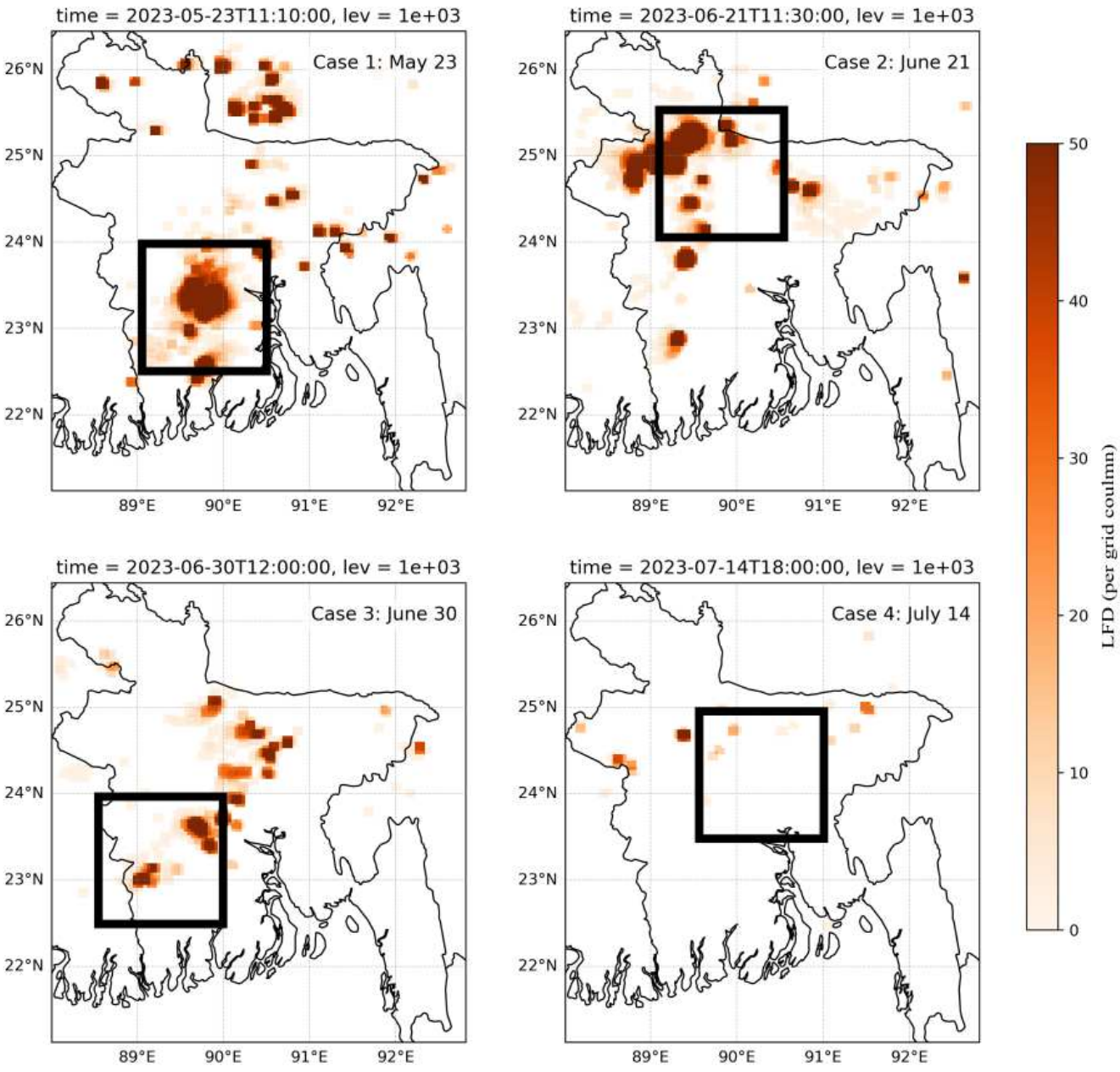


Figure SI 3: Same as Figure SI 1 but for LFD

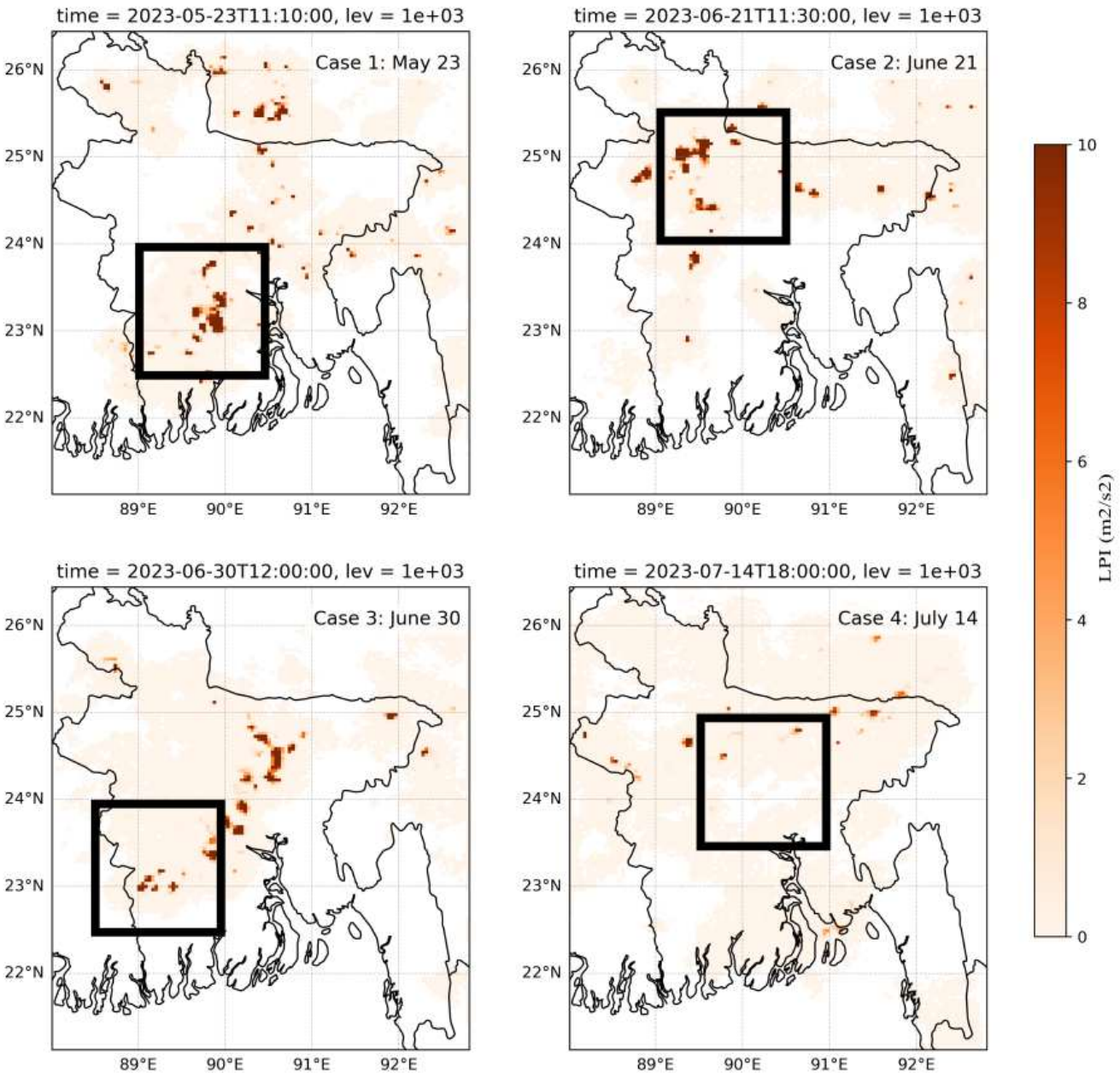


Figure SI 4: Same as Figure SI 1 but for LPI

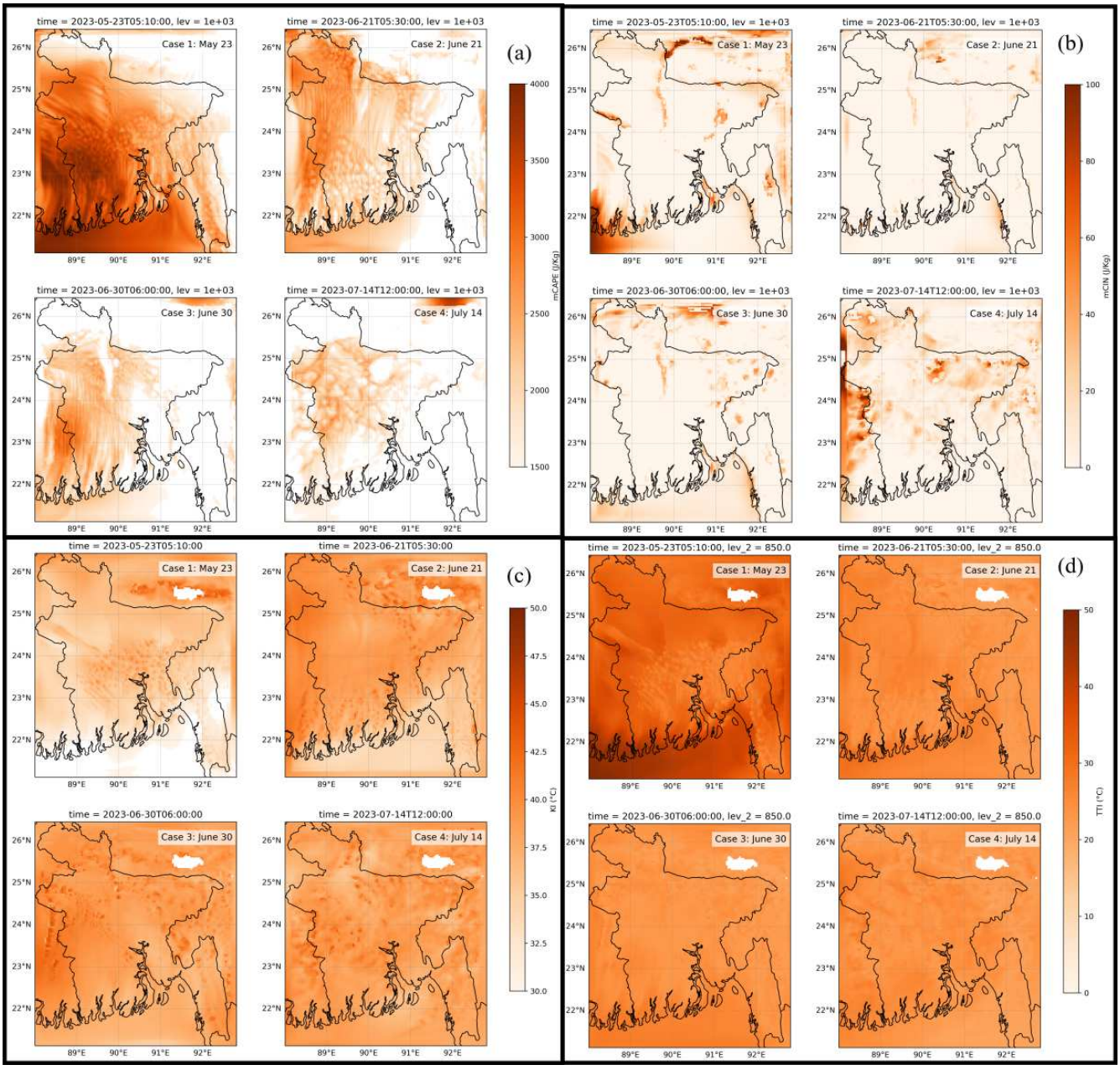


Figure SI 5: Model Simulated thermodynamic Indices 6-hours prior to the cases (a) mCAPE, (b) mCIN, (d) KI and (e) TTI