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WRF-Based Simulation of Thunderstorm Dynamics and Physical Processes over Complex Terrain: A Case Study

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ABSTRACT

This study presents a high-resolution analysis of a severe nocturnal thunderstorm that occurred over Guwahati, Northeast India, on 10 May 2025, using the Weather Research and Forecasting (WRF) model along with multiple observational datasets. The simulation employs nested domains at 9 km and 3 km resolution, initialized using Global Forecast System-Final Analysis (GFS-FNL) data. For model validation, observational datasets from ERA5 (European Reanalysis version 5), IMERG (Integrated Multi-satellite Retrievals for Global Precipitation Measurement) precipitation estimates, radiosonde soundings, and high-frequency ground-based meteorological data from the Central Pollution Control Board (CPCB) are used. The results reveal intense low-level moisture transport from the Bay of Bengal (BoB), high convective instability with Convective Available Potential Energy (CAPE) values exceeding 800 J/kg, and elevated K Index values (>30), all of which contributed to the initiation and intensification of the thunderstorm. Vertical cross-sections reveal organized updrafts, enhanced mid-tropospheric relative humidity, and pronounced wind shear conditions favourable for deep convection and lightning generation. While the WRF model effectively captures the storm structure and temporal evolution, it tends to underestimate near-surface humidity and overestimate wind speed. Overall, the study demonstrates the effectiveness of high-resolution WRF simulations, particularly when supported by dense observational networks, in improving the understanding of thunderstorm dynamics over complex terrain. The findings hold important implications for improving convective storm forecasting and strengthening disaster preparedness efforts in the vulnerable northeastern region of India.

Key words: *WRF, Thunderstorm, NWP, Severe weather, Convective instability*

Introduction

In a rapidly warming world, thunderstorms are emerging as formidable agents of natural disasters, posing escalating threats to the society. Among these, mesoscale convective systems (MCSs) represent some of the most intense and organized forms of deep convection, capable of producing widespread heavy rainfall, damaging winds, and flash floods (Rajeevan *et al*., 2010). Thunderstorms occur more frequently (over 40 days per year) across eastern and northeastern India, with particularly high intensity and hazard levels over the northeastern states. These storms are often referred to as nor'westers due to their characteristic northwest-to-southeast movement across the region (Singh *et al*., 2011). In the northeastern Indian state of Assam, the frequent convergence of abundant low-level moisture and complex terrain creates a highly favorable environment for the initiation and intensification of strong to severe convective storms (Mahanta *et al.,* 2020). This intense convective activity during the pre-monsoon months makes the region one of the most lightning-prone areas in the country, with lightning flash densities reaching up to 30-45 flashes per square kilometer per year. As a result, lightning-related fatalities have been significant, with approximately 297 deaths reported between 2000 and 2012 in the region (OGD 2025; Yadava *et al.,* 2020; Mondal *et al*., 2022). Therefore, gaining a deeper understanding of these convective storms and their characteristics is crucial for improving early warning systems and enhancing the forecast accuracy, ultimately helping to mitigate their impact on lives and property.

Although numerous modelling studies have been conducted worldwide to investigate the physics and dynamics of thunderstorms, such efforts remain relatively limited over northeastern India (Srivastava *et al*., 2023; Choudhury *et al*., 2020; Biswasharma *et al*., 2025; Mondal *et al*., (2023, 2024)). This gap is particularly concerning given the increasing frequency of convective storms in the region (Zahan *et al.,* 2021). A key reason for the limited understanding of these events is the lack of high-resolution, case-specific simulations, which is essential for accurately capturing the detailed structure, development, and evolution of such storms. The integration of numerical weather prediction models along with collocated observational data adds significant value in advancing the understanding of storm processes. The integration of numerical weather prediction models with collocated observational data significantly enhances the ability to understand storm processes, providing a more comprehensive and precise depiction of how storms form, evolve, and interact with their environment (Litta *et al*., 2013). The accuracy of storm forecasting and realistic simulation critically depend on the dynamical core and physical parameterizations of numerical weather prediction models (Olson *et al.,* 2019). The Weather Research and Forecasting (WRF) model has emerged as one of the most advanced and widely used numerical weather prediction models, offering a broad range of physical parameterization schemes that enable flexible and detailed atmospheric simulations. Due to the wide availability of parameterization options in WRF model, several studies have conducted sensitivity analyses to evaluate how different parameterization schemes affect the simulation of convective storms (Rajeevan *et al.,* 2010; Baki *et al*., 2021; Banks *et al*., 2021; Gómez-Navarro *et al*., 2015, Jiménez *et al.,* 2020). Choudhury *et al*., 2020 found that the Morrison microphysics scheme was able to reasonably simulate thunderstorms and squall events over the complex terrain of Northeast India. The simulation storm evolution closely resembled observational data, although some lead-lag time discrepancies were noted.

Motivated by the above literature review, this study aims to investigate the dynamics of a severe thunderstorm event through a high-resolution numerical simulation using the Weather Research and Forecasting (WRF) model, with a specific focus on Guwahati, a city surrounded by complex terrain. The event under consideration is a nocturnal thunderstorm that occurred on 10 May 2025 around 19:00 IST, resulting in strong winds that uprooted trees, along with heavy rainfall and intense lightning activity. This study evaluates the synoptic-scale features and mesoscale dynamics captured by the WRF model and validates them against observational data from the Central Pollution Control Board (CPCB) monitoring network.

Study area and methodology

Study area

Northeast India (NEI), comprising the eight states of Assam, Tripura, Meghalaya, Manipur, Mizoram, Nagaland, Sikkim, and Arunachal Pradesh, spans a geographic area of approximately 262,179/km² lying between 21°562153N to 29°292463N latitude and 89°412573E to 97°262163E longitude. The region shares international borders with Bhutan, Nepal, Bangladesh, Tibet, and Myanmar (Grogan *et al*., 2012; Das *et al*., 2021; Barman *et al*., 2024). NEI is topographically diverse (Figure 1), encompassing the Eastern Himalayas, extensive river valleys, and undulating hill terrains.

The landscape is predominantly covered by natural forests and croplands, particularly along the Brahmaputra floodplains. Climatically, the region falls under the humid subtropical category, influenced by both the southwest and northeast monsoons. It experiences hot and humid summers, intense monsoon rainfall, and mild winters. Annual

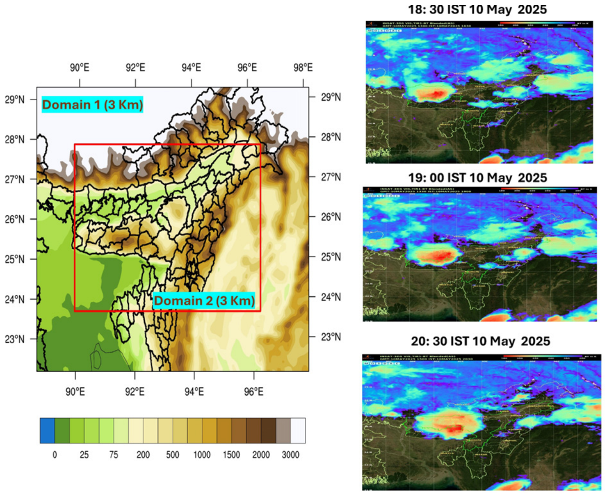

Fig. 1. Model domains (9 km and 3 km resolution) over Northeast India with INSAT-3D brightness temperature showing convective cloud systems.

precipitation ranges from 1,000/mm to over 7,000/mm, while temperatures vary from about 7/°C in the highlands to 28/°C in the plains (Dash *et al*., 2012). The Shillong Plateau in Meghalaya represents the highest elevation in the region and maintains relatively cooler temperatures year-round (Sahu *et al*., 2024).

Methodology

Model setup and variables

To simulate the severe thunderstorm event of 10 May 2025, the Weather Research and Forecasting (WRF) model version 4.1 was used, utilizing the Advanced Research WRF (ARW) non-hydrostatic core. The model was initialized with the GFS-FNL (Global Forecast System-Final Analysis) global analysis dataset at 0.25° spatial resolution. The simulation was conducted from 09 May 2025, 12:00 UTC to 11 May 2025, 12:00 UTC, with the first three hours treated as model spin-up time. A two-way nested domain configuration was implemented, with the outer domain (d1) having a 9 km resolution, covering the region from 22.19°N to 29.30°N and 88.70°E to 97.85°E, while the inner domain (d2) was configured at a 3 km resolution, encompassing 23.72°N to 27.90°N and 89.94°E to 96.27°E. Domain and data preprocessing were performed using the WRF Preprocessing System (WPS). The model time step was set to 30 seconds, with outputs saved at 30-minute history intervals. Figure 1 illustrates the layout of the simulation domains, including both the outer and inner grids. Model outputs were evaluated against observations from the Central Pollution Control Board (CPCB) monitoring network, specially averaged over the Guwahati station, which lies within the high-resolution inner domain. Guwahati was selected due to the availability of high-resolution observational data, recorded at 15-minute intervals, enabling a robust comparison with model simulations. The specific physical parameterizations used in the model are summarized in Table 1.

Datasets

For this study, multiple observational and reanalysis datasets were utilized to enable a comprehensive analysis of the thunderstorm event. The European Reanalysis version 5 (ERA5) reanalysis dataset, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) using the Integrated Forecasting System (IFS) Cy41r2, was used to examine surface wind patterns through the 10/m u- and v-wind components. With a spatial resolution of 0.25^{p} (~31/km), ERA5 provides high-quality

Table 1. WRF models physical and dynamical configuration

Category	Option
Map projection	Lambert
Meteorology BC	NCEP FNL
Vertical levels	33 Eta levels
	Physics
Microphysics	Morrison 2-moment Scheme (Morrison *et al.*, 2009)
Cumulus	Grell 3D Ensemble Scheme (Grell and Freitas, 2014)
PBL	Yonsei University Scheme (YSU) (Hong *et al.*, 2006)
Land Surface	Unified Noah Land Surface (Tiwari *et al.*, 2004)
Longwave Physics	RRTM Longwave Scheme (Mlawer *et al.*, 1997)
Shortwave Physics	Dudhia Shortwave Scheme (Dudhia, 1989)
Sf_sfclay_physics	Revised MM5 scheme (Jiménez *et al.*, 2012)

gridded atmospheric fields making it suitable for validation and synoptic scale analysis (Hersbach *et al.*, 2020). To assess vertical atmospheric instability, upper-air profiles were obtained from the Global Radiosonde Archive, which provides radiosonde observations of wind, temperature, and humidity (NECI, 2025). Precipitation analysis was conducted using IMERG (Integrated Multi-satellite Retrievals for GPM) Real Time data, offering a spatial resolution of 10/km (Huffman, 2025). These data were aggregated into 2-hour accumulations and interpolated to the ERA5 grid (0.25^{p} resolution) to facilitate improved visualization and comparison. Near-surface meteorological parameters-such as temperature, humidity, wind speed, and wind direction were obtained from CPCB's live air quality monitoring network, specifically from stations located within Guwahati city. These stations are spatially distributed across various parts of the urban area and are integrated with Automatic Weather Stations (AWS), provide high-frequency measurements that are valuable for validating model outputs (CCR, 2025).

Thunderstorm Parameters calculation

K index

The K Index is a commonly used thermodynamical parameter for assessing the potential for thunderstorm development [6]. It combines information on the vertical temperature lapse rate and the moisture content and distribution in the lower and mid-troposphere. The index is calculated using the following formula:

$$\text{K Index } (^{o}C) = (T_{850hpa} + Td_{850hpa} - T_{500hpa} - DD_{700hpa}.)$$

Where T represents temperature (pC), Td represents dew point temperature and DD represents dewpoint depression at the indicated level.

Convective Available Potential Energy (CAPE)

Convective Available Potential Energy (CAPE) quantifies the amount of buoyant energy available to a rising air parcel and is widely used to evaluate convective potential. It is derived under the assumptions Parcel Theory, where the parcel ascends moist adiabatically, does not mix with the surrounding environment, experiences no water loading, and remains in pressure equilibrium with the surrounding atmosphere (Rastogi *et al.*, 2024). CAPE is computed as the vertically integrated buoyancy force from the level of free convection (LFC) to the equilibrium level (EL), and is expressed by the following equation:

$$\text{CAPE} = g. \int_{LFC}^{EL} \left(\frac{T_{parcel} - T_{env}}{T_{env}}\right) dz$$

Where, g is the acceleration due to gravity (9.8 m/s^2), T_{parcel} and T_{env} are the virtual temperature of the parcel and environmental, respectively and dz is the vertical height increment. Larger CAPE values indicate greater atmospheric instability and a higher potential for strong convection, such as thunderstorms and severe weather events.

Results and Discussion

Synoptic Conditions

Figure 1 shows the INSAT-3D satellite imagery depicting the cloud cluster associated with the thunderstorm system. Based on the satellite observations, the convective system spans an estimated area of approximately 100 km² (Houze *et al.*, 2004). The Cloud Top Temperature (CTT) over the core region drops to around 180 K, indicating deep vertical development of the storm. As the system approaches the Shillong Plateau, CTT values decrease further, suggesting that orographic interaction contributes to the enhancement of updraft strength. Figure 2 presents the time evolution of precipitation along with large-scale surface wind patterns during the event.

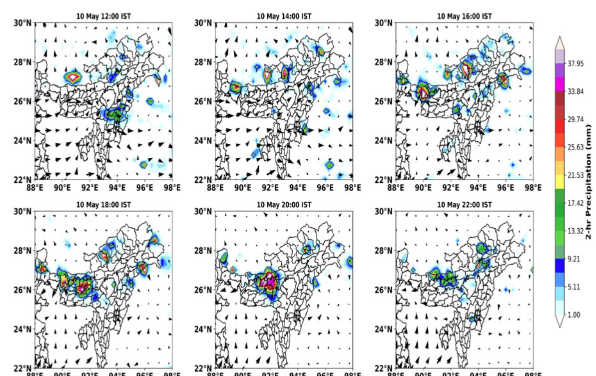

Fig. 2. Synoptic wind patterns at surface from ERA5 and 2-hourly accumulated precipitation from IMERG, indicating mesoscale features.

`The surface wind field highlights low-level winds originating from the Bay of Bengal, contributing a substantial influx of moisture, which serves as a key ingredient for thunderstorm formation. As the system matures, it initiates over the northern part of

Assam (Kokrajhar district) and propagates eastward, following a typical Nor'wester trajectory (Singh *et al*., 2011; Mahanta *et al*., 2020).

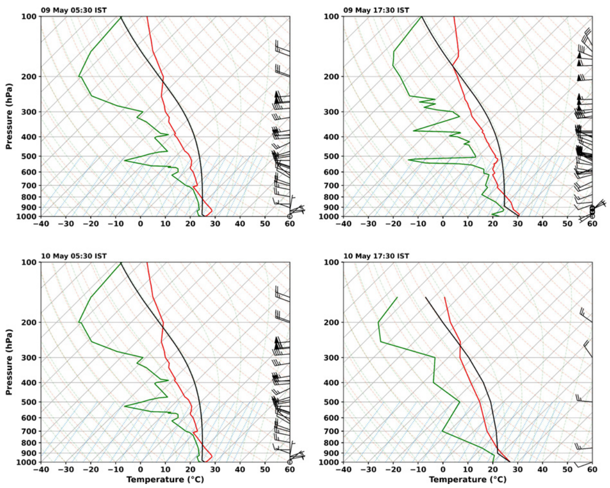

Fig. 3. Evolution of atmospheric soundings over Guwahati during a two-day period, capturing vertical thermodynamic changes.

The 2-hourly precipitation accumulation indicates that during the storm's mature phase, total rainfall around 20:00 IST ranges between 33.84 mm and 40 mm, indicating the peak convective intensity of the event. A more detailed thermodynamic perspective is shown in Figure 3, which present Skew-T log-P diagrams derived from radiosonde observations on the storm day and preceding days. These profiles indicate greater atmospheric instability on the storm day. While the Level of Free Convection (LFC) typically located near 800 hPa on previous days, it shifted to around 900 hPa on the storm day, i.e. on 10 May 2025, indicating that less energy was required to lift air parcels to the LFC, thereby enhancing convective potential. The Equilibrium Level (EL) extended up to the 200-300 hPa range, indicating the development of deep convective cloud tops. Notably, cloud tops reached the -10/^{0}C level near 300 hPa, a threshold generally associated with thunderstorm development and increased lightning activity (Taszarek *et al*., 2017). Additionally, the early morning radiosonde sounding on 10 May at 05:30 IST shows strong vertical wind shear between 800 hPa and 250 hPa, a condition conductive to the maintenance of deep convection and organized propagation of the storm system.

Thunderstorm indices

To better understand the high-resolution thermodynamic environment, the spatial distribution of CAPE was analyzed using the model's inner domain (3 km resolution) of WRF model, as shown in Figure 4.

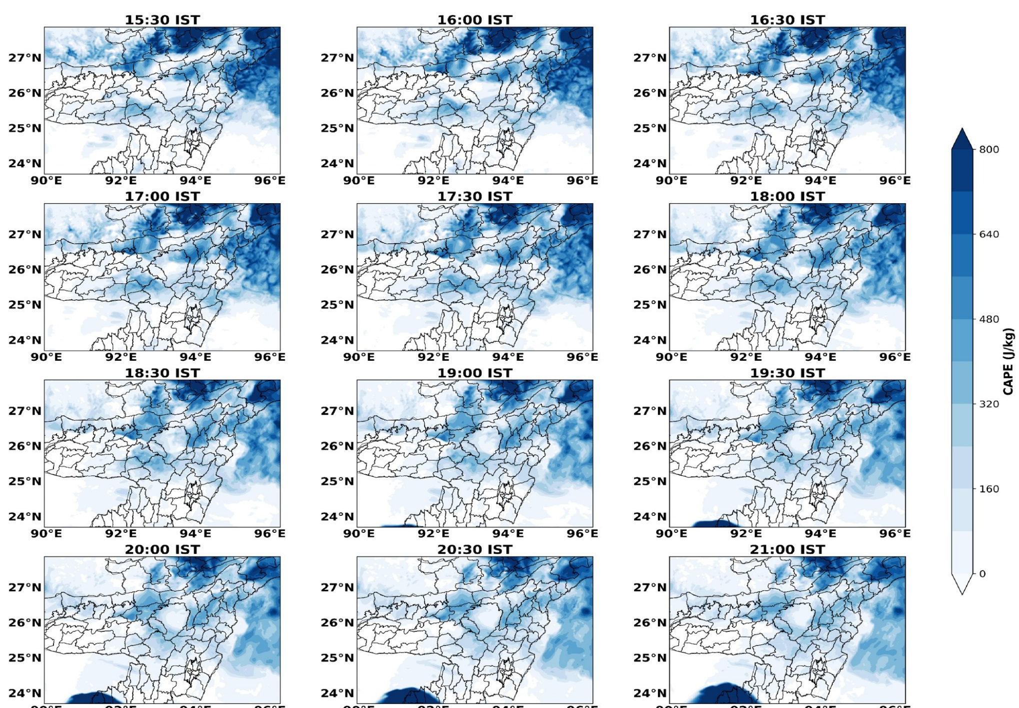

Fig. 4. Spatial distribution of CAPE at multiple time steps within the 3 km model domain.

Since CAPE represents the conversion of potential energy into kinetic energy during convective development (Mondal *et al*., 2022), it plays a crucial role in thunderstorm forecasting and dynamic interpretation (Rastogi *et al*., 2024). The model-simulated Maximum CAPE (MCAPE) values indicate that during the storm's formation and evolution, the domain exhibited regions highly susceptible to convection. Specially, the area between 26 ^{o}N-28 ^{o}N and 94 ^{o}E-96 ^{o}E recorded CAPE values ranging from 640 to 800 J/kg, signifying a moderately unstable atmosphere conducive to thunderstorm development. However, comparison with radiosonde observations reveals a systematic underestimate of CAPE by the model, particularly evident from the LFC and Equilibrium Level (EL) values derived from the storm day sounding. Figure 5 illustrates the spatial distribution of the K Index during the evolution of the storm. Typically, K Index values above 30 indicate a favorable environment for the severe thunderstorm occurrence. Across the region, K values remained above 30, with localized maxima exceeding 39 observed during the initial stages of storm development. As the system progressed and followed its trajectory, the K Index values gradually decreased, indicating a diminishing level of atmospheric instability in the region. The presence of such elevated K Index values during the initial phase suggests that the thunderstorm on 10 May was primarily driven by local atmospheric instability, characteristic of airmass thunderstorms (Umakanth *et al*., 2021).

Vertical Profiles

Figure 6 presents the vertical velocity cross-sections along a latitudinal belt at a fixed longitude intersecting through the city of Guwahati, effectively capturing the storm's vertical evolution and associated precipitation intensity. When overlaid with topographic data, the figure illustrates strong updraft velocities during the early development phase of the storm (15:30 to 19:30 IST), indicating significant atmospheric instability over the region. As the storm progresses and precipitation begins, the updrafts strength diminishes, reflecting atmospheric cooling and surface stabilization. During the initial phase, a distinct updraft-downdraft couplet is observed in the vertical velocity field, a signature feature of organized convection. However, in the later hours, this pattern transitions into a dominant low-level updraft, suggesting sustained surface based convective activity.

The corresponding vertical relative humidity pro-

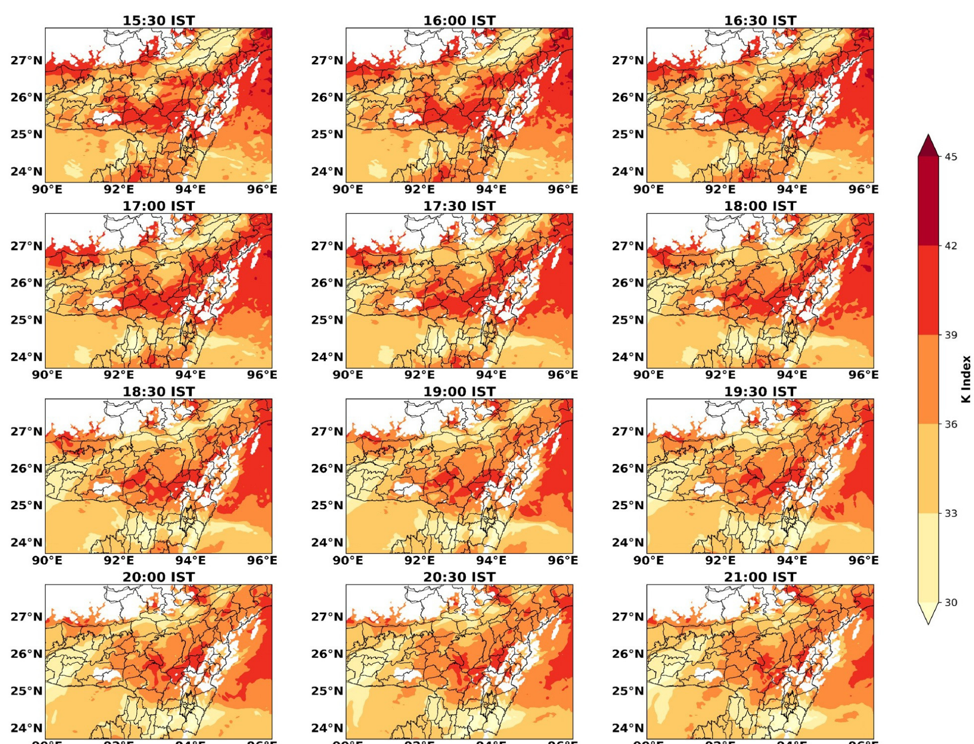

Fig. 5. K-Index spatial patterns across different time steps over the 3 km model domain.

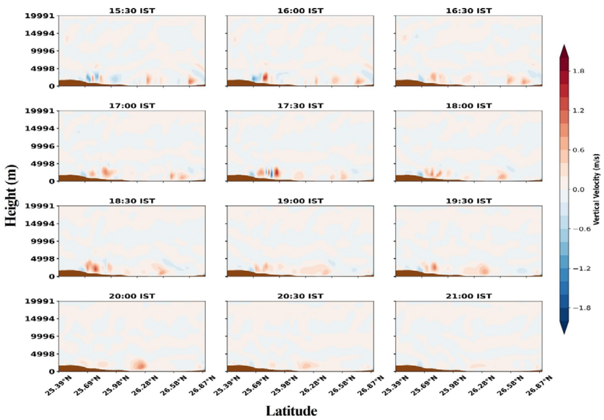

Fig. 6. Vertical cross-sections of vertical velocity along a fixed longitude (91.6°E) across a latitudinal belt over Guwahati from the 3 km model domain at different time steps.

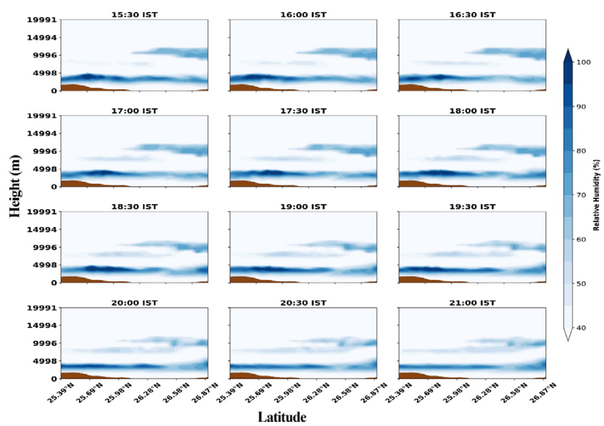

Fig. 7. Vertical cross-sections of relative humidity along a fixed longitude (91.6°E) across a latitudinal belt over Guwahati from the 3 km model domain at different time steps.

files, shown in Figure 7, along the same cross-section, reveal humidity levels of 90-100% up to approximately 5000 meters, especially near the hilly terrain. This indicates the availability of substantial moisture to support thunderstorm development. It is well established that an increase in relative humidity from 60% to 90% enhances vertical development by promoting stronger updrafts and the formation of hydrometeors within the cloud, which, in turn, supports deeper convection and increase the potential for lightning activity (Mondal *et al.*, 2023; Shi *et al.*, 2018).

Surface parameters

Figure 8 illustrates the diurnal variation of relative humidity, temperature, and wind speed over Guwahati on 10 May, comparing observational data with WRF model outputs from both the outer (9 km) and inner (3 km) domains.

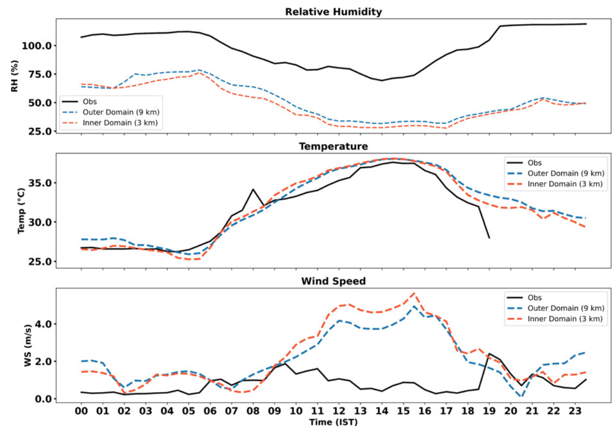

Fig. 8. Comparison of surface meteorological parameters from model output and ground-based observations at Guwahati.

The observed relative humidity remained consistently high throughout the day, fluctuating between 75% and 100%, with peak values occurring during the late evening hours. However, both WRF model domains significantly underestimated RH, indicating a dry bias near the surface in the model simulation. In contrast, temperature trends were more accurately captured by the model, with both domains showing the morning increase and early afternoon peak. The inner domain slightly overestimated midday temperatures but overall aligned more closely with observations than the outer domain. For wind speed, simulations diverged notably from observations. While observed winds remained light and relatively steady, the model produced higher wind speeds, especially in the afternoon, with the inner domain exceeding 4/m/s. This overestimation suggests that the model have represented low-level wind flow too vigorously, particularly during periods of convective development. Overall, the model effectively captured the diurnal temperature cycle, but demonstrated limitations in simulating surface moisture and wind conditions, factors that are critical for storm forecasting.

Conclusion

This study presents a high-resolution analysis of a severe nocturnal thunderstorm event that occurred over Guwahati on 10 May 2025, using the WRF model in conjunction with multiple observational datasets. The results highlight the model's capability to capture the overall storm evolution, including key synoptic and mesoscale features such as the cloud cluster extent, wind flow patterns, thermodynamic instability, and convective indices like CAPE and the K Index. The storm exhibited classical Nor'wester behaviour, with strong moisture-laden winds from the Bay of Bengal and significant vertical development, supported by high CAPE values and elevated K Index readings. Radiosonde data confirmed the presence of deep convective layers and favourable vertical wind shear, both essential for sustaining organized convection. Vertical cross-sections further revealed intense updrafts and high relative humidity in the lower and mid-troposphere, further validating the presence of conducive thermodynamic environment for storm intensification. However, the model tended to underestimate near-surface humidity and CAPE, indicating that further parameter tuning or the assimilation of high-resolution observations could improve simulation accuracy. Despite these limitations, the WRF model effectively captured the storm's structure and dynamics, demonstrating its utility in understanding and forecasting severe convective events over the complex terrain of Northeast India. Such high-resolution simulation studies are essential in enhancing regional forecasting capabilities and in the development of effective early warning systems, which are vital for mitigating the societal impacts of severe weather.

Acknowledgements

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Conflict of interest

The authors declare there is no conflict of interest.

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