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Performance evaluation of WRF model in simulating a thundershower event of March 2025 in Bhubaneswar, Odisha, India

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सार– यह अध्ययन भुवनेश्वर, ओडिशा में 22 मार्च को 18 UTC से 23 मार्च 2025 को 00 UTC तक गरज के साथ छिंटे की घटना के अनुकरण में मौसम अनुसंधान एवं पूर्वानुमान (WRF) मॉडल के प्रदर्शन का मूल्यांकन करता है। तूफान की संरचना, वर्षण और गतिशीलता का अध्ययन करने के लिए WRF सिंगल मोमेंट सिक्स-क्लास (WSM6) सूक्ष्मभौतिकी, योनसेई विश्वविद्यालय ग्रहीय सीमा परत पैरामीटरीकरण का उपयोग करके अनुकरण आयोजित किया गया था। मॉडल द्वारा अनुकरणीय आउटपुट की तुलना वैश्विक वर्षा मापन (GPM) वर्षा आंकडों सहित प्रेक्षणों से की जाती है। परिणाम दर्शाते हैं कि मॉडल गरज के साथ छिंटे के स्थानिक वितरण और कालिक विकास को प्रभावी ढंग से दर्शाता है, हालाँकि वर्षा की तीव्रता और समय में कुछ पूर्वाग्रह हैं। क्षैतिज विचलन और सापेक्ष भ्रमिलता विशेषताओं का विश्लेषण संख्यात्मक मौसम पूर्वानुमान मॉडल में बेहतर सूक्ष्मभौतिकीय अभ्यावेदन की आवश्यकता को रेखांकित करता है ताकि उष्णकटिबंधीय और उपोष्णकटिबंधीय क्षेत्रों में गरज/तूफान से जुड़ी संवहनीय घटनाओं के लिए पूर्वानुमान की सटीकता को बढ़ाया जा सके।

ABSTRACT. This study evaluates the performance of Weather Research and Forecasting (WRF) model in simulating a thundershower event that occurred in Bhubaneswar, Odisha valid 18 UTC on 22 March to 00 UTC on 23 March 2025. Simulation was conducted using WRF single moment six-class (WSM6) microphysics, Yonsei University Planetary boundary layer parameterizations to study the storm structure, precipitation, and dynamics. Model simulated outputs are compared with observations including Global Precipitation Measurement (GPM) rainfall data. Results indicate that the model effectively captures the spatial distribution and temporal evolution of the thundershower, although with certain biases in rainfall intensity and timing. The analysis of horizontal divergence and relative vorticity features underscore the necessity for improved microphysical representations in numerical weather prediction models to enhance forecasting accuracy for convective events associated with thundershowers/thunderstorms in tropical and subtropical regions.

Key words– WRF model; Microphysics; Thundershower; Stratiform clouds

1. Introduction

Severe convective weather phenomena-particularly thunderstorms, thundershowers, and intense short-duration rainfall, represent some of the most hazardous atmospheric events, posing serious risks to life and property due to their rapid development and inherent unpredictability (Huo *et al.*,, 2024). Understanding and accurately simulating these events is therefore crucial for effective forecasting and disaster preparedness (Prasad *et al.*,, 2014). In April, the eastern and northeastern regions of India-particularly Gangetic West Bengal, Jharkhand, Bihar, Odisha, Assam, and parts of the other northeastern states - are frequently impacted by severe thunderstorms, locally referred to as *Kalbaishakhi*. These events are mesoscale convective systems that often develop within the large-scale envelope of the seasonal low-level trough over West Bengal, Bihar, and Jharkhand, sometimes accompanied by an embedded low-pressure area (Sharma 2022). Thundershowers are localized convective weather phenomena characterized by intense rainfall, thunder, lightning, and occasionally hail or gusty winds. These events are typically short-lived but can make significant damage to urban infrastructure, agriculture, aviation, and public safety. The state of Odisha, located on the eastern coast of India, frequently experiences such convective episodes during the pre-monsoon months of March to May, with Bhubaneswar—the capital city—being particularly vulnerable due to its geographical location and rapid urbanization in the last two decades (Nayak *et al.,* 2021). Considering their highly localized and transient nature, the forecasting of such events remains a challenge for meteorologists. In this context, high-resolution numerical weather prediction (NWP) models like the Weather Research and Forecasting (WRF) model have emerged as essential tools for simulating and understanding mesoscale atmospheric processes responsible for thundershowers. Among various physics parameterizations, microphysics schemes play a vital role in resolving cloud and precipitation processes. The microphysics scheme governs cloud formation processes, hydrometeor interactions, and precipitation production (Hong and Lim 2006; Thompson *et al.,* 2008; Kumar *et al.,* 2022). Thundershowers are mesoscale phenomena (~1-10 km) and require high spatial and temporal resolution to simulate convection accurately (Bryan *et al.,* 2003). Thundershowers involve complex interactions between cloud droplets, ice, hail, and rain, which are difficult to model. Microphysics schemes often use simplified assumptions, leading to uncertainties in storm intensity and structure (Morrison *et al.,* 2009). Processes like entrainment and turbulence occur at scales smaller than the grid size and must be parameterized. Inaccurate turbulence modeling can alter convective initiation and storm morphology (Petch *et al.,* 2002). However, the performance of WRF model in simulating localized events like thundershowers is sensitive to the choice of model configuration, initial and boundary conditions, and physical parameterization schemes - particularly those governing convection, microphysics, and planetary boundary layer processes (Jankov *et al.,* 2005; Miao *et al.,* 2009). Simulating thundershowers is a complex task due to the multiscale nature of the processes involved, the need for high-resolution models, and the sensitivity of storm behavior to initial conditions.

This study focuses on simulating a severe thundershower event that occurred in Bhubaneswar, Odisha valid 18 UTC on 22 March to 00 UTC on 23 March 2025 using WRF model and assessing its ability to replicate observed features such as rainfall intensity, cloud structure, and storm dynamics.

TABLE 1

Customization of the simulation domain

Configuration	Customization		
	Domain1	Domain2	Domain3
Horizontal grids (staggered)	111x111	181x181	238x238
Horizontal resolution (km)	15	5	1.66
Time step (seconds)	45	15	5
Vertical levels	45	45	45
Microphysics	WSM6		
Cumulus physics	Kain-Fritsch	off	off
Planetary boundary layer	Yonsei University (YSU)		
Surface physics	Noah-MP land-surface model		
dzstretch_s (surface stretch factor)	1.1		

2. Data and methodology

2.1. *Study area and event description*

IMD had predicted light to moderate rainfall accompanied with thunderstorm, lightning and gusty winds (speed 40-50 kmph) likely over East Madhya Pradesh, Chhattisgarh, Madhya Maharashtra, Marathwada, Vidarbha, West Bengal, Sikkim, Bihar, Jharkhand and Odisha on 21st & 22nd March 2025 and reduction in intensity thereafter (https://internal.imd.gov.in/press_release/20250322_pr_3823.pdf) due to an upper air cyclonic circulation laying over central parts of Madhya Pradesh and wind confluence over east and adjoining central India accompanied with an anticyclonic wind circulation over northwest Bay of Bengal at lower tropospheric levels. A thundershower event that occurred in Bhubaneswar, Odisha valid 18 UTC on 22 March to 00 UTC on 23 March 2025, was selected for the current study. The event was characterized by moderate convection and precipitation, and was well-documented by satellite and surface observations, making it suitable for model evaluation.

2.2. *Model configuration*

The WRF-ARW version (4.6.1) was configured with a high resolution of 1.66 km in horizontal along with other features as depicted in Table 1. The initial and boundary conditions were obtained from the National centre for environmental prediction (NCEP) final (https://rda.ucar.edu/datasets/d083003/). These data are operational global analysis and forecast data on 0.25° × 0.25° grids prepared

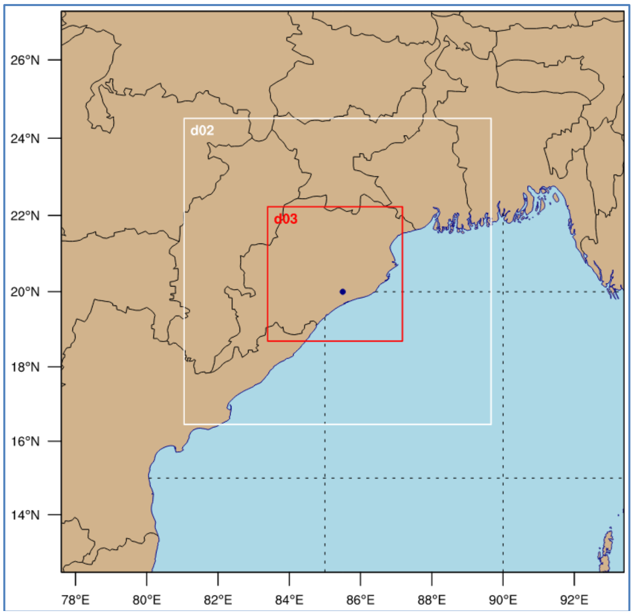
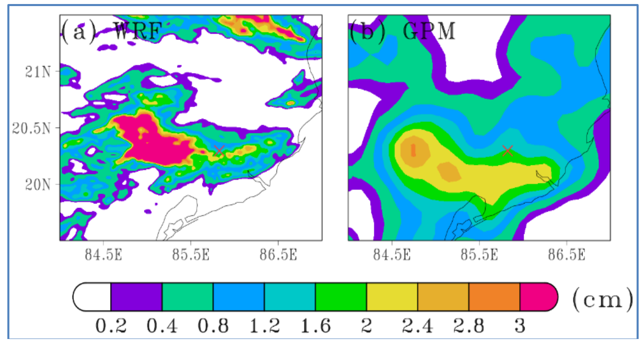


Fig. 1. WRF nested domains

operationally every six hours. The finals data are delayed so that more observational data can be used.

Rapid Radiative Transfer Model (RRTM) scheme for long waves and Dudhia scheme for the short waves are used for simulation of severe weather events such as tropical cyclones in the past studies (Mahala *et al.,* 2021; Xalxo *et al.,* 2022). WSM6 predicts the mass mixing ratios of six hydrometeor species *viz*., cloud water, rainwater, cloud ice, snow, graupel, and water vapour. The limitations of the WSM6 scheme in predicting the rainfall, its duration and spread, with a lag of approximately 30 min in predicting precipitation onset. Also, it exhibits a tendency to forecast peak rainfall events slightly after their occurrence (Huo *et al.,* 2024). The study by Rahimian *et al.*, (2022) suggests that WSM6 microphysics produced slightly stronger reflectivity. Furthermore, the study by Hong *et al.,* (2009) suggested that the rainfall intensity becomes stronger with an increase in number of hydrometeors. The YSU scheme exhibits the least bias with respect to surface temperature and moisture. The study by Boadh *et al.*, (2016) suggests that YSU scheme could capture the characteristic variation of surface meteorological variables and the atmospheric structure. In the current study, YSU scheme has been used anticipating better representation of boundary-layer parameters (Boadh *et al.,* 2016; Potvin *et al.,* 2020). The simulation domain is shown in Fig. 1. The centre is chosen nearest the Bhubaneswar city (20.2 °N latitude and 85.8 °E longitude) in Odisha. The rainfall distribution was validated both qualitatively and quantitatively using the observation data (https://daac.gsfc.nasa.gov/datasets/GPM_3IMERGDL_07/summary) and the model evaluation tool (version 10).



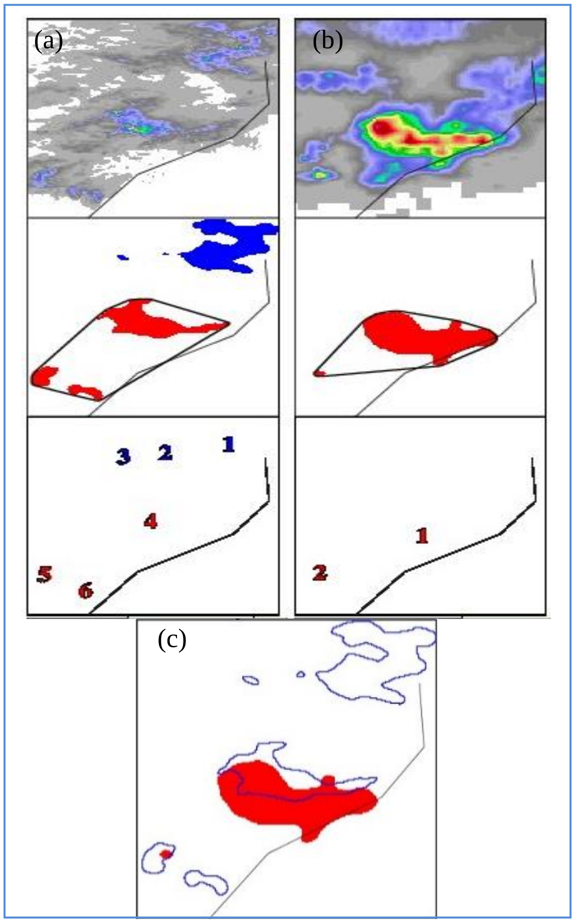
Figs. 2(a & b). 24-h accumulation by a) WRF model, b) GPM observation valid 00 UTC 23 March 2025

3. Results and analysis

3.1. *Rainfall distribution*

The intensity of precipitation is a reflection of the convective systems (Nolan *et al.,* 2007; Houze 2010). Fig. 2 presents the 24-h accumulation by the WRF model valid at 00 UTC on 23 May (Fig. 2a) against the GPM observation (Fig. 2b). Therefore, 24-h accumulation and its spatial distribution by the simulation indicate the efficacy of the model in predicting the intensity of thundershower. WRF model could simulate rainfall varying from 0.2 to 3 cm against the GPM observation of 0.2 to 2.8 cm. The WRF model captured the core intensity and spatial distribution of rainfall over the region of interest, aligning well with observed data from GPM satellite measurements, albeit the model overestimated the 24-h accumulation.

The Method for Object-based Diagnostic Evaluation (MODE) tool is an efficient tool for the verification of 24-h accumulated precipitation. The quality of the forecast is quantified by matching the forecast and observed objects (Davis *et al.,* 2009). The intensity of the objects is captured in a 2-dimensional field using a convolution operator, governed by a convolution radius (R in grid units) and a convolution threshold (CT in mm). The Global Precipitation Measurement (GPM) data is interpolated to WRF model domain grids using budget interpolation method. The performance can be evaluated by clustering the objects between forecast and observation along with using variety of verification statistics such as critical success index (CSI), equitable threat score (ETS), false-alarm-ratio (FAR), and the intersection area (Davis *et al.,* 2009; Routray *et al.,* 2017; Omranian and Sharif 2018; Mahala *et al.,* 2019, 2021) computed by MODE. In the current study, we have considered the clustering of the objects, False Alarm Ratio (FAR), and intersection area between forecast and observation for the performance of the model in simulating the thundershower event. The detail on MODE attributes is depicted in Table 2.



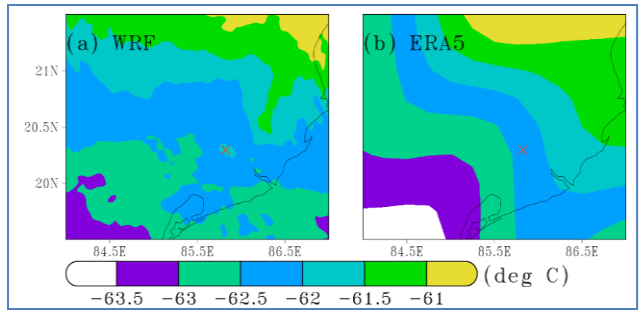
Figs. 3(a-c). Clustering the objects for a) forecast b) observation, &c)Observation objects (red) with forecast outlines (blue)

TABLE 2

MODE configuration

Mode attributes	Option
Convolution radius (grid units)	5
Convolution threshold (mm)	15
Merge threshold	1.25
Centroid distance	2
Boundary distance	2

Fig. 3 shows the matching of the forecast (blue) against the observation (red). The matching pairs were performed by clustering the region using MODE attributes as mentioned in Table 2. There were 6(2) clusters for the forecast (observation) objects, Figs. 3(a & b). Fourth cluster of the forecast matches the first cluster of the observation at an interest of 0.9075, while the matching interest between the fifth cluster of the forecast and the second cluster of the observation was 0.8401. The forecast area was 6436 square kilometers while it is 4292 square kilometres by GPM out of which 3030 (4292) square kilometres of area



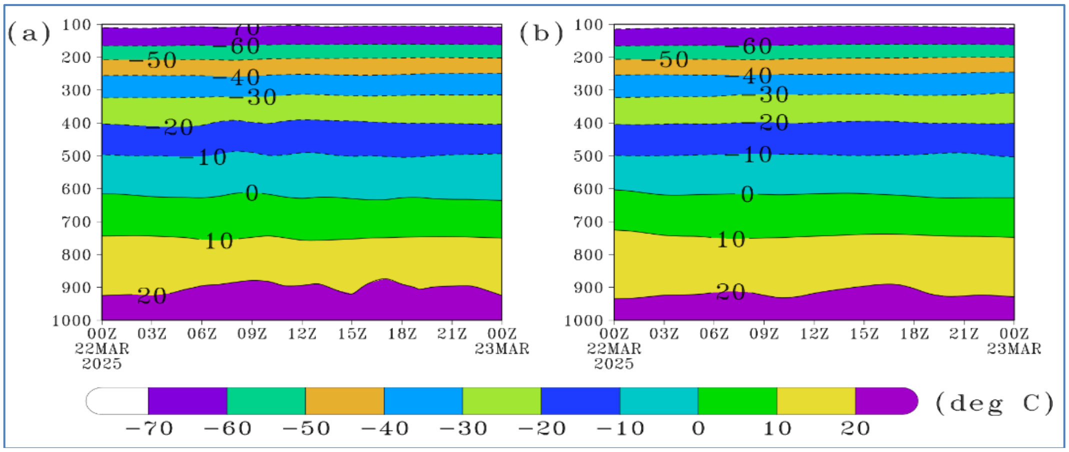
Figs. 4(a & b). Cloud top temperature at 150 hPa valid 18 UTC 22 March 2025 for a) WRF, b) ERA5

was matched by WRF (GPM) with the MODE attributes. Furthermore, the intersection area between WRF and GPM was 1328 square kilometers. The statistical index, total interest, was calculated by MET as 0.9096 which is close to unity suggesting better forecast skill of the model. However, the FAR value of 0.7934 suggests an over-forecast tendency by the model (Fig. 3c).

3.2. *Storm structure and dynamics*

3.2.1. *Cloud top temperature*

Lightning and thunder are the result of cloud electrification, which occurs as a result of collisions between charged water droplets, graupel, and ice crystal particles in mature cumulonimbus clouds, a thunderstorm that produces heavy rain. (https://www.weather.gov). Anvil clouds associated with cumulonimbus tops are a strong indicator of a mature thundershower and deep convection (Stolzenburg *et al.*, 2010). The cloud top temperature in a cumulonimbus cloud is typically less than -60 °C. Fig. 4 shows the spatial distribution of cloud top temperature at the 150 hPa level by the WRF model and ERA-5 data valid at 18 UTC on 22 March 2025. The analysis suggested that the region is surrounded by temperatures ranging -63.5 °C to -61.0 °C. Fig. 5 presents the diurnal temperature profile at the location 85.8246° E and 20.2960° N. This indicates deep convection during the event and suggests the formation of anvil clouds due to advection of ice crystals from the upper portion of the convective cells. Furthermore, this may result in electrically charged ice crystals within the convection and further carry their charge with them. Our results corroborate with the study by Stolzenburg *et al.*, (2010) which states that hazardous electric fields are associated with the anvil and spread over at least 220 square kilometres. The area average of maximum sustained surface wind speed was simulated as 8.81 km/h against the observed value of 6 km/h valid 18 UTC 22 March 2025 while the area average simulated sea level pressure was1015.11 hPa against the observed value of 1016 hPa (https://www.timeanddate.com/weather/india/bhubaneshwar).



Figs. 5(a&b). Diurnal temperature profile by a) WRF, b) ERA5 valid 00 UTC 22 March 2025 to 00 UTC 23 March 2025

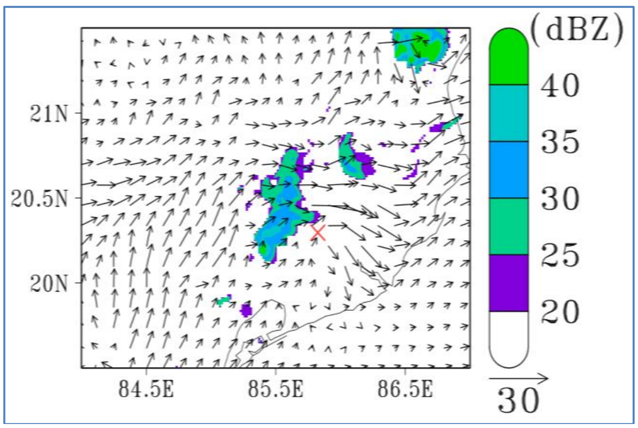


Fig. 6. Stratiform clouds at 500 hPa level with wind vector at 850 hPa level valid 15 UTC 22 March 2025

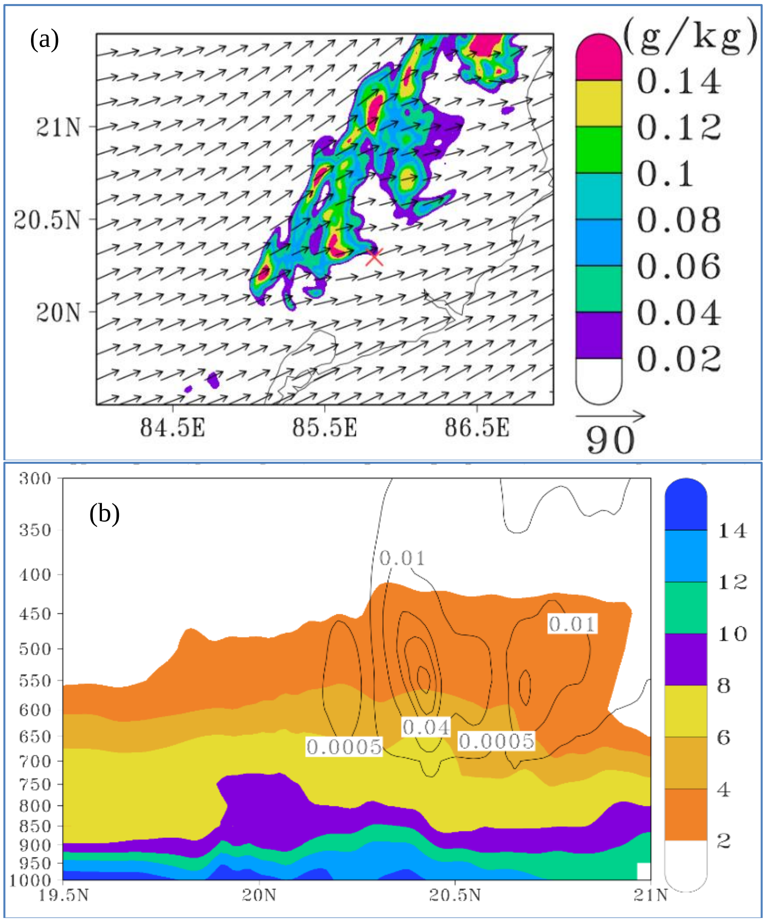
The greatest instability occurs in the late afternoon due to maximum surface heating. This favors the deep convection in land areas. Diurnal warming near the surface and relatively cooler temperatures aloft increase convective available potential energy (CAPE), leading to strong updrafts (Dai, 2001). The diurnal cycle is strong, with sharp heating and cooling transition over land. The analysis of temperature profile (Fig. 5) suggests that the temperature is at least 20 °C near the surface (1000-900 hPa) typically, the altitude is at its peak during 15-18 UTC of 22 March 2025. And the lowest temperature of -60 to -70 °C is simulated between 150-100 hPa level, and the results match well with ERA5 data, suggesting a deep convection during 15-18 UTC of 22 March 2025.

3.2.2. *Stratiform clouds*

The charge separation in thundershowers involves a collision between graupel and ice crystals in the presence of supercooled water. During these collisions, graupel becomes negatively charged and ice crystals become positively charged. Furthermore, these particles move to different regions by updrafts. Lighter ice crystals move upward & heavier graupel falls or remains in the mid-levels. The hydrometeors such as supercooled water, graupel, and ice crystals are crucial in the thundershower events (Takahashi *et al.*, 2019; Liu *et al.*, 2024). Stratiform clouds at 500 hPa level play a vital role in redistributing latent heat. The stratiform heating profile affects local and mesoscale circulation around the thundershower (Mapes and Houze 1995). The stratiform cloud often contains supercooled water & ice, which helps in the charge separation process that drives lightning (Rutledge & MacGorman 1988). Fig. 6 shows the typical 500 hPa level stratiform region between 20–40 dBZ along with wind vectors at 850 hPa level valid at 15 UTC 22 March 2025. The reflectivity values (20–40 dBZ) are optimal for mixed phase microphysics, a phase in which supercooled water and ice co-exist, stimulating charge separation & lightning production. The reflectivity values suggest a well-developed shield, often found in thunder-showers which transition from their initial convective phase. Strong low-level convergence of winds at 850 hPa helps in transportation of warm, moist air into the storm system, modulating the lift and convection & determining the orientation of the stratiform region (Saulo *et al.*, 2007). Analysis of Fig. 6 suggests that there is a strong convergence near 85.5° E & 20.5° N situated northwest of the Bhubaneswar city and characterized by a stratiform region due to the mature stage of the system. The deep convection during event may be attributed to presence of strong stratiform clouds at 500 hPa level prior to the event. Our results agree with the previous studies (Mapes and Houze 1995; Tao *et al.*, 2003; Houze Jr. 2004).

3.2.3. Cloud ice

The intensity and depth of the convection associated with thundershower/ convective systems is indicated by

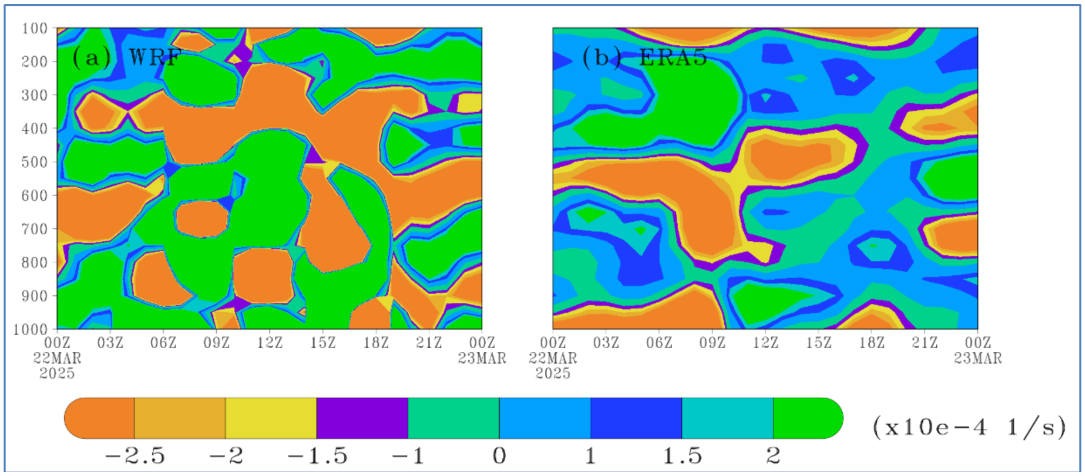


Figs. 7(a&b). Model simulated a) cloud ice with wind vectors at 350 hPa level, b) total mixing ratio (shaded), graupel (contour) valid 15 UTC 22 March 2025

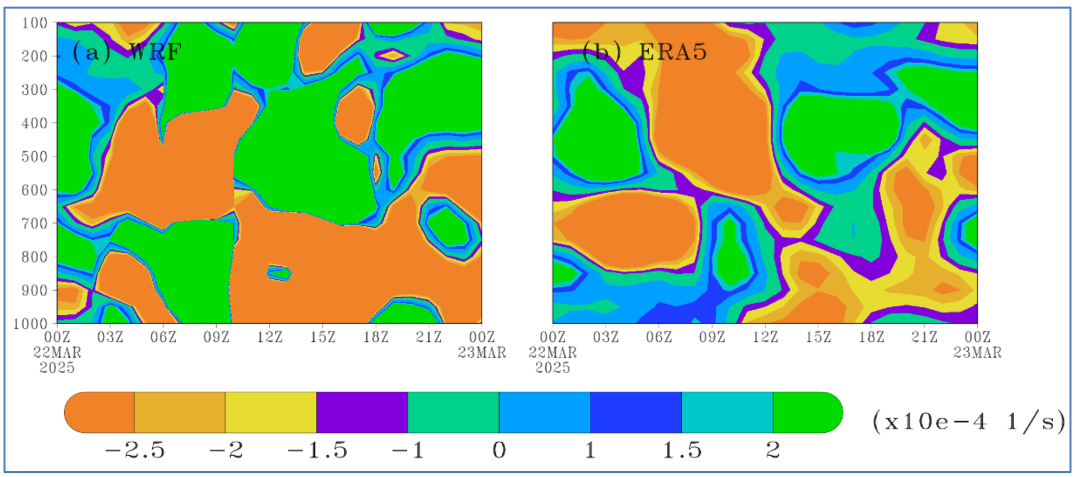
350 hPa cloud ice contents (Tao *et al.,* 2003). The cloud ice values varying from 0.01 to 0.1 g/kg are interpreted as moderate convection, while it is considered as strong with the values in the range of more than 0.1 g/kg. Fig. 7 (a) shows the model simulated cloud ice with wind vector at 350 hPa level valid 15 UTC 22 March 2025. WSM6 microphysics is a mixed-phase scheme, allowing the existence of supercooled water (Park *et al.,* 2020). Cloud ice values more than 0.1 g kg^{-1} are estimated in the northern and north-western sector of the city. Furthermore, the wind vectors at 350 hPa level are south westerlies. The analysis of distribution of cloud ice and wind vectors suggests the existence of warm core in the north and north-west sector of the city prior to the formation of the thundershower. Furthermore, high total mixing ratio in the boundary layer indicates ample moisture that favours the convection and cloud formation. Boundary layer total mixing ratios fuel the thunderstorm development. Graupel reflects the strength and maturity of the storm and plays a key role in lightning and severe weather events. In particular, the microphysical properties related to graupel are closely related to lightning flash rate (Calhoun *et al.,* 2013; Carey *et al.,* 2019; Wang *et al.,* 2024). Fig. 7 (b) shows the total mixing ratios (shaded) and graupel (contour) valid 15 UTC 22 March 2025. Total mixing ratios varying from 8 to 14 g kg^{-1} are simulated in the boundary layer from 1000 - 800 hPa levels. This would help convection and cloud formation. Graupels varying 0.0005 to 0.8 g kg^{-1} are spread from 750 - 400 hPa. Graupel mixing ratios less than 0.05 g kg^{-1} at mid-levels and sharp gradients in vertical direction help transition between warm-rain and cold-phase precipitation regimes, pertinent to thunderstorm structure. Our results corroborate the study by Rajput *et al.,* (2024).

3.2.4. *Horizontal divergence*

Fig. 8 shows WRF model simulated horizontal divergence (x $10^{-3}s^{-1}$) against ERA5 reanalysis data over pressure levels (y-axis, from 1000hPa to 100hPa) and time (x-axis, 00UTC 22 March 2025 to 00UTC 23 March 2025). Positive (negative) values indicate



Figs. 8(a&b) Time-pressure cross section of horizontal divergence ($\times 10^{-4}s^{-1}$) at Bhubaneswar (20.323 °N and 85.815 °E)



Figs. 9(a&b). Time-pressure cross section of relative vorticity ($\times 10^{-4}s^{-1}$) at Bhubaneswar (20.323 °N and 85.815 °E)

divergence (convergence). The analysis suggests that a strong convergence ($-2.5 \times 10^{-3}s^{-1}$) zone spreading 900-200 hPa pressure levels is simulated during 00UTC 22 March to 15 UTC 22 March 2025 while the ERA5 data shows values of $-2.5 \times 10^{-3}s^{-1}$ to $-1.5 \times 10^{-3}s^{-1}$ from 1000-400 hPa pressure levels. Notably, divergence cores appear more vertically extended and spatially broader in WRF than in ERA5. Below 800hPa, convergence (divergence) dominates in ERA5 (WRF) data, especially during early hours (00-10 UTC). Compared to ERA5 reanalysis, the WRF simulation shows more frequent alternations between convergence and divergence, especially in the mid-troposphere (500-700hPa). The convergence dominates during the developing stage from 03 UTC to 12 UTC in the 800-500 hPa levels. This may indicate more intense or vertically dynamic convective activity captured by the model. The convergence in the mid-troposphere during 18 UTC-00 UTC 23 March 2025 is simulated by WRF, while the observed values are slightly less and prominent in the upper troposphere and lower troposphere. Our analysis corroborates the study by Mohanty *et al.*, (2012) who conducted a study on the simulation of heavy rainfall events over Indian regions using the WRF model. Overall, the WRF model captures stronger and more variable divergence signatures than ERA5 which needs further investigation by considering more cases as well as microphysics/boundary layer parameterizations. Fig. 9 shows the time-pressure cross-section of relative vorticity (x $10^{-3}s^{-1}$) by WRF simulation along with ERA5 reanalysis from 00UTC 22 March to 00 UTC 23 March 2025. Positive (negative) values represent cyclonic (anticyclonic) vorticity. In the WRF simulation, alternating layers of positive and negative vorticity are observed throughout the troposphere, with strong cyclonic zones ($> 2 * 10^{-3}s^{-1}$) appearing mainly between 300hPa and 600 hPa around 09 UTC to 21 UTC. These vorticity patterns are vertically extended and more irregular in shape. ERA5 shows more layered and smoother vorticity structures. Cyclonic regions appear more organized, especially near 300hPa-500hPa between 00-06 UTC and 12-18 UTC (Fig. 9b). Anticyclonic patches are seen mostly below 700 hPa. Overall, WRF captures stronger and more frequent shifts in vorticity compared to ERA5, indicating the model’s ability to represent finer-scale rotational features.

4. Conclusions

This study evaluates the Weather Research and Forecasting (WRF) model's performance in simulating a thundershower event that occurred in Bhubaneswar, Odisha, from 18 UTC on March 22 to 00 UTC on March 23, 2025. The simulation utilized the WRF single moment six-class (WSM6) microphysics scheme and Yonsei University Planetary boundary layer parameterizations. The model's outputs were compared with Global Precipitation Measurement (GPM) rainfall data. Results indicated that while the WRF model effectively captured the spatial distribution and temporal evolution of the thundershower, it exhibited biases in rainfall intensity and timing. The study highlights the complexities of simulating convective systems and emphasizes the importance of microphysics schemes in accurately representing storm dynamics. The validation against observational data reveals insights into rainfall distribution, storm structure, and dynamics. The analysis of horizontal divergence and relative vorticity features underscores the necessity for improved microphysical representations in numerical weather prediction models to enhance forecasting accuracy for convective events in tropical and subtropical regions. However, future studies will include more cases using different parameterization schemes to address the complexities in the parameterization schemes.

Data availability

The datasets and materials used in this study were obtained from publicly accessible repositories: (*i*) .https://rda.ucar.edu/datasets/ds083.3/.(*ii*) https://daac.gsfc .nasa.gov/datasets/GPM_3IMERGDL_07/summary (*iii*). The source code for the WRF model utilzed in this study is available at https://www2.mmm.ucar.edu/wrf/users /download/get_source.html.

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Authors' Contributions

All authors contributed to the study design and concept as:
Susmita Samantara: Source code compilation, Methodology, experiments, visualization, and Writing-original draft,
Biranchi Kumar Mahala: Methodology, conceptualization, Writing-reviewing and editing.
Ashish Routray: Methodology, conceptualization, Writing-reviewing and editing.
Rohan Kumar: Read and approved the manuscript.

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