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A 3-decade advancements in prediction of tropical cyclones and other severe weather over India: a recap

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सार – भारत हाल के वर्षों में लगातार और घातक चरम मौसम की घटनाओं का सामना कर रहा है। जलवायु परिवर्तन, शहरीकरण और भूमि-आवरण में बदलाव के संयुक्त प्रभावों के कारण ये घटनाएँ लगातार जटिल होती जा रही हैं, जिससे इनका सटीक पूर्वानुमान लगाना अनुसंधान और संचालन समुदायों, दोनों के लिए एक बड़ी चुनौती बन गया है। संख्यात्मक मौसम पूर्वानुमान (NWP) प्रारंभिक चेतावनियाँ प्रदान करने में एक महत्वपूर्ण उपकरण रहा है, जिससे संपत्ति को होने वाले नुकसान को कम करने, मानव जीवन पर प्रतिकूल प्रभाव को न्यूनतम करने और देश के आर्थिक नुकसान को सीमित करने में मदद मिली है। यह समीक्षा पिछले तीन दशकों में NWP अनुसंधान में हुई प्रगति का सारांश प्रस्तुत करती है, जिसका मुख्य उद्देश्य भारत को प्रभावित करने वाले मौसम की प्रचण्ड स्थितियों (उष्णकटिबंधीय चक्रवात और उससे जुड़ी तूफ़ानी लहरें, गरज के साथ छिंटे, लू और शहरी वर्षा) के पूर्वानुमानों को बेहतर बनाना है। यह प्रगति निरंतर अनुसंधान एवं विकास के प्रयासों और भारत मौसम विज्ञान विभाग (IMD) के सहयोग से संभव हुई, जिससे प्रेक्षण नेटवर्क का विस्तार हुआ, प्रचण्ड मौसम की निगरानी की गई और NWP क्षमताओं को उन्नत करने में अनुसंधान समुदाय को समय पर सहायता प्रदान की गई तथा संतोषजनक पूर्वानुमान कौशल प्राप्त हुए, जिससे निर्णय समर्थन प्रणालियों की विश्वसनीयता बढ़ी है।

ABSTRACT. India has been witnessing frequent and deadly extreme weather events in recent years. These events are becoming increasingly complex due to the compound effects of climate change, urbanization, and land-use land-cover changes, making their accurate prediction a major challenge for both research and operational communities. Numerical Weather Prediction (NWP) has been a vital tool in providing the early warnings, thereby helping to reduce the damage to properties, minimize adverse impact on human life, and limits the country's economic losses. This review summarizes progress in NWP research over the past three decades, with a focus on improving forecasts of weather extremes (tropical cyclones and associated storm surge, thunderstorms, heatwaves, and urban rainfall) affecting India. These advancements have been made possible through continuous R&D efforts and the support of India Meteorological Department (IMD) in increasing the observational network, severe weather monitoring, and providing timely assistance to the research community in advancing NWP capabilities and reached satisfactory prediction skills that enhanced the reliability in the decision support systems.

Key words – Weather forecasting, Machine learning, Deep learning, Neural networks, Polar weather data, Data science.

1. Introduction

The extreme weather events, such as tropical cyclones (TCs), severe thunderstorms, monsoonal heavy rains, temperature extremes, etc. are seasonal over the Indian monsoon region (IMR). Tropical cyclones (TCs) over the North Indian Ocean (NIO), encompassing the Bay of Bengal (BoB) and the Arabian Sea (AS), rank among the most devastating hydro-meteorological phenomena on Earth. Their impact on the densely populated and low-lying coastlines of surrounding nations is catastrophic, resulting in immense loss of life and widespread destruction of property and infrastructure. The vulnerability of the region is starkly highlighted by historical records; according to the World Meteorological Organization (WMO), TCs in this basin have been responsible for between 5,000 and well over 300,000 fatalities in the last 300 years alone, with the BoB and AS contributing approximately 75% of the global total of storm-related deaths (WMO, 2008). This disproportionate toll is attributed to the unique physiography of the region, particularly the BoB, which features shallow bathymetry and a funnel-shaped coastline that amplifies the most lethal TC hazard: the storm surge. These surges inundate coastal belts entrenched with large river delta systems, such as those along the east coast of India and Bangladesh, leading to catastrophic flooding (Dube *et al.*, 2009; Priya *et al.*, 2021). Severe thunderstorms are vigorous localized convective activity, posing devastating weather through thunder, lighting, heavy rain, hail, and squalls. They sometimes also result in tornadoes causing massive destruction. Over the IMR, the eastern parts of India and Bangladesh are prone to severe thunderstorms (~28 numbers) in pre-monsoon months (*i.e.*, April and May). They generally move from northwest to southeast. These are often poorly forecasted due to their small spatial and temporal scales. To improve the knowledge and prediction of these systems, the Department of Science and Technology (DST), and the Ministry of Earth Sciences (MoES), Government of India, executed a research program called the severe thunderstorms-observations and regional modeling (STORM; Das *et al.* 2014). The southwest monsoon receives heavy to very heavy rainfall due to organized meso-convective systems such as monsoon depressions (MDs), lows, and mid-tropospheric circulations over significant parts of India (Nayak *et al.*, 2025). Full details can be found in the previous studies related to MDs (Hunt & Fletcher, 2019; Sikka, 1977; Osuri *et al.*, 2020), mid-tropospheric circulations (Benson and Rao, 1987; Sikka and Gadgil, 1980; Mohanty *et al.*, 2012).

Moreover, in the recent decade urbanization also plays a significant role to the increase the strength of extreme weather events such as extreme rainfall and heatwaves. A city-specific modeling framework is essential to accurately represent urban morphology, land use, and anthropogenic heat emissions that influence local thermal dynamics over Indian cities (Nayak *et al.*, 2023). The realistic representation of urban morphology such as building density, land use types and vegetation distribution and the thermal exchange processes between the building structure and street canopy is important in a city specific modelling framework. In addition, extreme weather simulation is sensitive to the choice of physical parameterization schemes, such as urban physics, land surface, radiation and boundary layer schemes (Giannaros *et al.*, 2019; Silva *et al.*, 2021; Patel *et al.*, 2022; Boyaj *et al.*, 2024; Karrevula *et al.*, 2024).

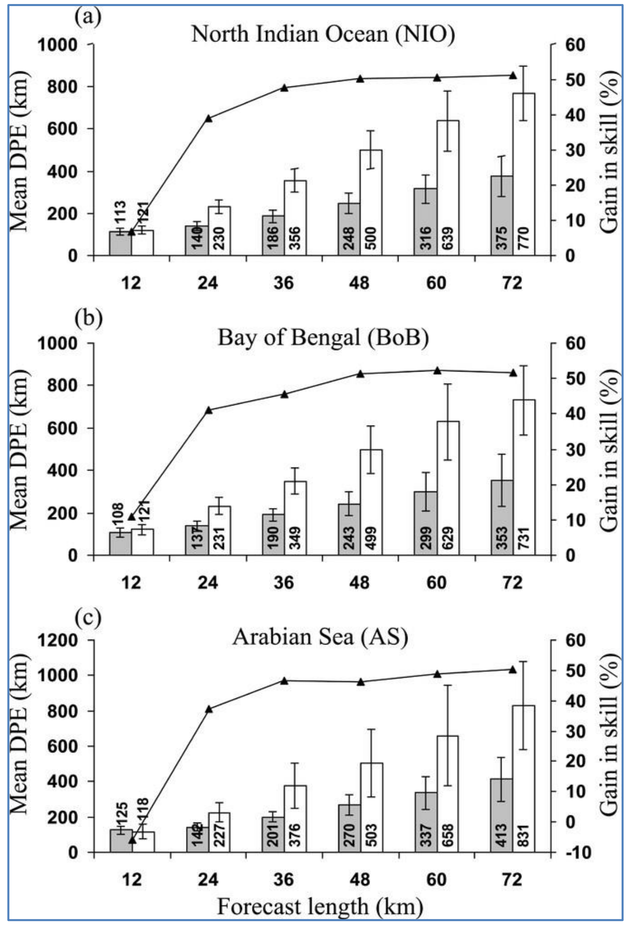
Given this extreme vulnerability, accurate prediction of these systems, and associated hazards is not merely a scientific endeavour but a critical socio-economic imperative for disaster risk reduction. The evolution of Numerical Weather Prediction (NWP) models has been the cornerstone of this effort, transforming extreme weather forecasting from a largely subjective exercise to a sophisticated, physics-based deterministic and probabilistic system. The present paper illustrates the recent developments in numerical modelling systems used for the improvement in understanding and prediction of Tropical cyclones with associated storm surges, Thunderstorms and accompanied lightening, urban heavy rainfall and heatwaves. The detailed discussion including model, data assimilation, simulation results and broad discussion are presented in subsequent sections. A broad conclusions and future strategies are highlighted in the section 5.

2. Tropical cyclones and coastal hazard

The limitations of global models in resolving the inner-core dynamics of TCs led to the adoption of high-resolution, non-hydrostatic mesoscale models. Pioneering work over the North Indian Ocean (NIO) began with the Penn State University (PSU) Mesoscale Model version 5 (MM5). A key innovation was the development of an in-house "bogus vortex" scheme. This technique involved inserting a physically consistent, model-friendly vortex into the initial conditions to compensate for the poor initial representation of the storm due to sparse oceanic data, thereby accelerating model spin-up and improving forecast skill (Prasad and Rama Rao, 2003).

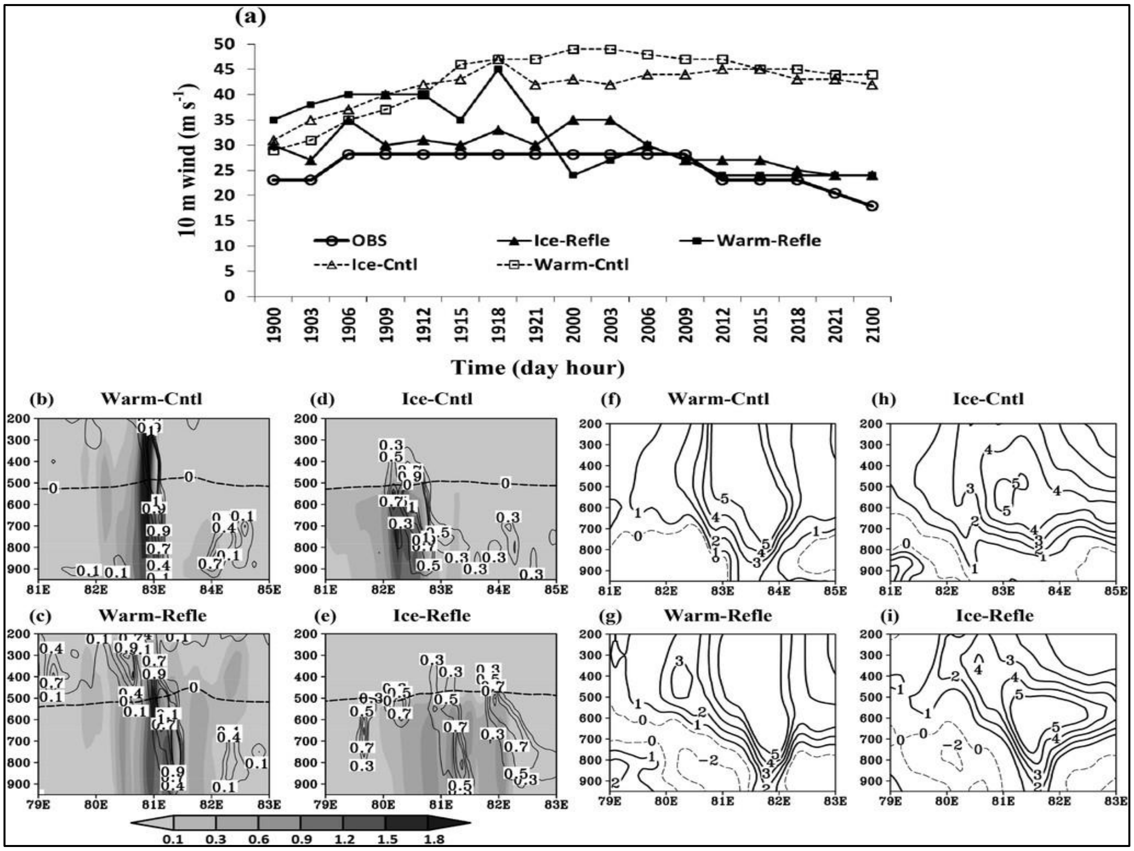
This era was soon revolutionized by the next-generation Weather Research and Forecasting (WRF) model, particularly its Advanced Research WRF (ARW) dynamic core (Skamarock *et al.,* 2008). Extensive research with the WRF-ARW model has demonstrated its significant skill in predicting TC tracks over the NIO. Primarily, Osuri *et al.* (2012) customized the model for the predictions of TCs over the NIO region using numerous combinations of physical parameterizations. Studies have shown that the model can effectively capture the re-curving nature of storms and provide reliable real-time track guidance, with errors reducing with increasing lead time up to 72 hours (Osuri *et al.,* 2012a, 2013). The 9 km horizontal grid spacing experiments have exhibited the least error in track position for all the forecast compared to the 18 and 27 km horizontal resolution experiments (Fig. 1a). The error ranges from 106-329 km for forecast period of 24-72 hours, while 18 km and 27 km experiments range from 106-329 km and 113-375 km respectively for same forecast lengths (Fig. 1b-c). A major challenge, however, has been the accurate prediction of tropical cyclone rainfall (TCR), which is crucial for inland flood forecasting. Research has systematically characterized these errors, finding that the model tends to overestimate light rain and underestimate heavy rain, with errors being more pronounced for higher-intensity storms and over land regions post-landfall (Osuri *et al.,* 2020a). Successful real-time prediction of the movement, intensity, and associated storm surge for devastating cyclones like Hudhud (2014) has showcased the operational utility of these high-resolution modeling systems (Nadimpalli *et al.,* 2016).

The real breakthrough in enhancing the predictive skill of these events came from the assimilation of diverse observations to better define the initial state of the atmosphere. Key advancements include assimilation of remote sensing data (satellite and Doppler Weather Radar,



Figs. 1(a-c). Mean DPE (km; shaded bars) and gain in skill (%; line) of the model with 27-km resolution for the TCs over the (a) NIO, (b) BoB, and (c) AS. Open bars give mean DPE of persistence tracks. (source: Osuri *et al*. 2013)

etc). Assimilating satellite-derived atmospheric motion vectors and scatterometer ocean surface winds has been proven to significantly improve the analysis of a cyclone's initial position, intensity, and large-scale structure, leading to reduced track and intensity forecast errors (Osuri *et al.,* 2012b and cross-references). The assimilation of Indian ground based Doppler Weather Radar (DWR) observations (radial velocity and reflectivity) represents a quantum leap. This provides high-resolution data on the inner-core dynamics, leading to a more accurate analysis of the vortex structure, which in turn drastically improves predictions of track, intensity, and the spatial distribution of convective rainfall (Osuri *et al.,* 2015). Further, they have highlighted the interplay of rainfall process and radar data assimilation for the better predictability over the region (Fig. 2). Improved initialization of land surface states, particularly soil moisture and temperature, has been shown to enhance the simulation of boundary layer processes. This not only improves the prediction of monsoon depressions and associated heavy rainfall but



Figs. 2(a-i). (a) The 3-hourly simulated 10-m wind (m s−1) of TC Laila from warm-rain and ice-phase microphysics along with IMD observations with and without reflectivity assimilation. Vertical cross section of rain (shaded) and cloud (contours) mixing ratio (g kg−1) from (b) Warm-Cntl, (c) Warm-Refle, (d) Ice-Cntl, and (e) Ice-Refle. (f)–(i) As in (b)–(e), but for temperature anomaly. The thick dashed line in (b)–(e) represents the 0°C isotherm. (source: Osuri et al. 2015)

also contributes to better forecasting of TCs during their landfall and post-landfall stages by more accurately simulating land-atmosphere interactions (Niyogi *et al.*, 2016; Osuri *et al.* 2020).

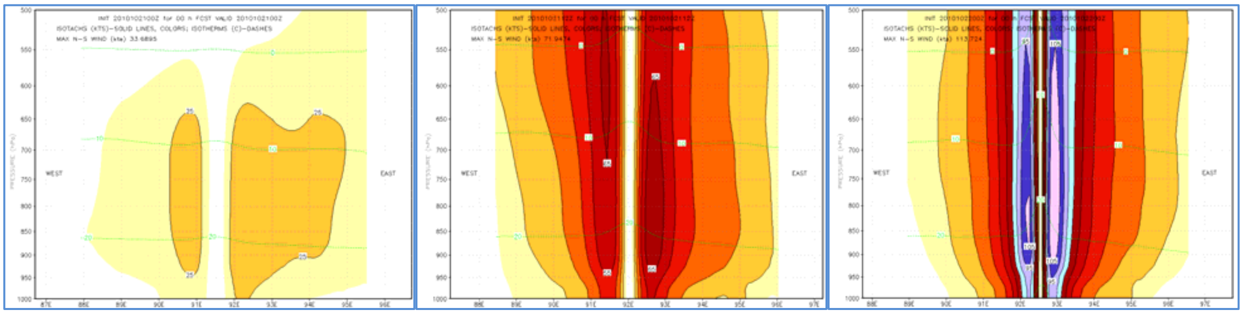
2.1. *The operational leap: the HWRF system, ocean coupling, and India-specific advancements*

A significant milestone was the operational implementation of the specialized Hurricane Weather Research and Forecasting (HWRF) system for the NIO basin. HWRF, built on the NMM dynamic core, is a coupled atmosphere-ocean model designed specifically for TC prediction. Its advanced features include moving nested grids (with inner domains down to 1-2 km), coupling with the Princeton Ocean Model (POM) to account for ocean feedback, and sophisticated hybrid ensemble-variational data assimilation (Gopalakrishnan *et al.*, 2011; Mohanty *et al.* 2013; Osuri *et al.* 2017a). Comparative assessment studies between the WRF and HWRF systems have demonstrated HWRF's superior performance for TC-specific forecasting over the BoB (by 29% in Track and 73% in Intensity), particularly for intensity prediction, owing to its specialized physics, moving nest, and most importantly, its coupled ocean - atmosphere dynamics (Nadimpalli *et al.*, 2020a; Mohanty *et al.*, 2021). Research in the Indian context has focused on refining key components of the HWRF system to address regional forecasting challenges:

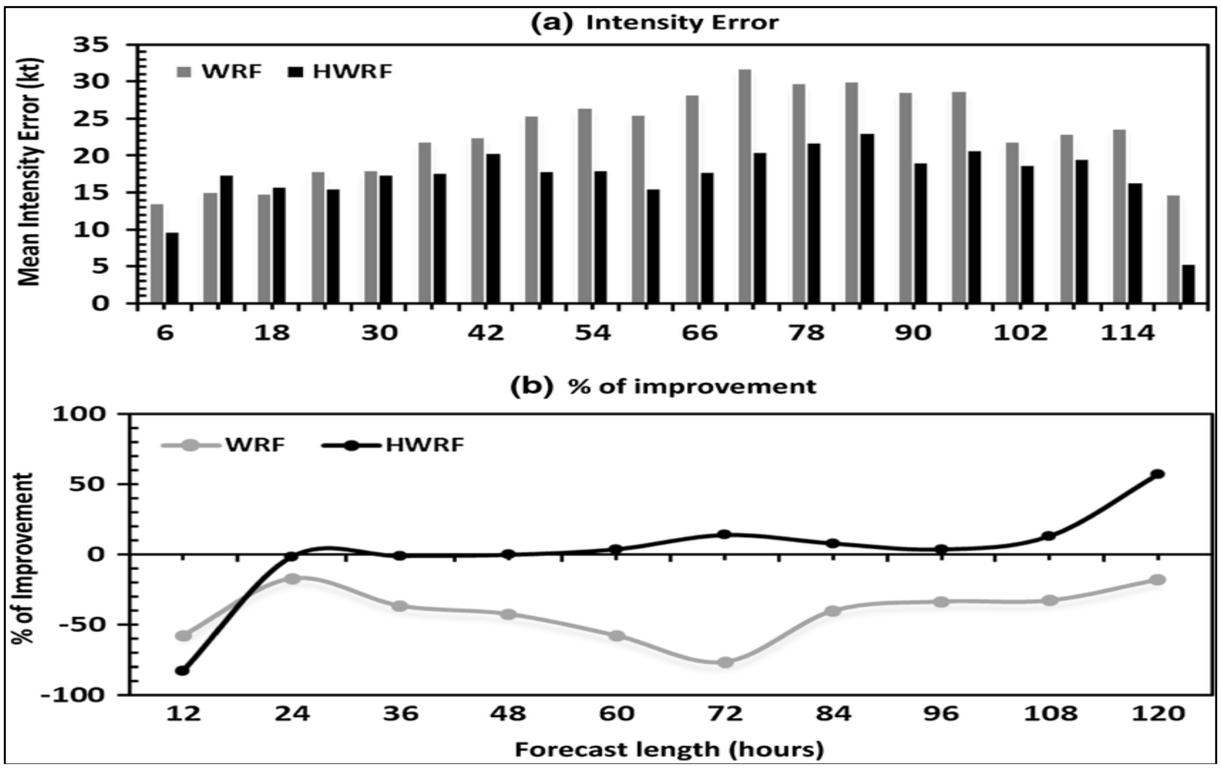
2.2. *Vortex initialization and relocation*

The accurate initial representation of the cyclone vortex is paramount. Studies have shown that the method of vortex initialization and relocation significantly impacts both track and intensity forecasts (Nadimpalli *et al.* 2021). Optimized techniques that create a model-compatible, balanced initial vortex have been proven to reduce initial spindown/spinup issues and lead to a substantial reduction in forecast errors for both parameters over the BoB (Nadimpalli *et al.*, 2021). Fig. 3 shows differences in vortex structures generated through advanced initialization procedures when TC Giri is at the DD stage, the CS stage, and the SCS stages. During these stages, the TC GIRI

(a) DD stage valid at 00UTC 21 Oct 2010 (b) CS stage valid at 12UTC 21 Oct 2010 (c) SCS stage valid at 00UTC 22 Oct 2010



Figs. 3(a-c). The initial vortex created through improved vortex initialization and relocation method of HWRF at (a) depression stage, 0000 UTC 21 Oct (b) cyclonic storm stage at 1200 UTC 21 Oct c) severe cyclonic storm, 0000 UTC 22 Oct 2010 (Source: Mohanty *et al*. 2013)

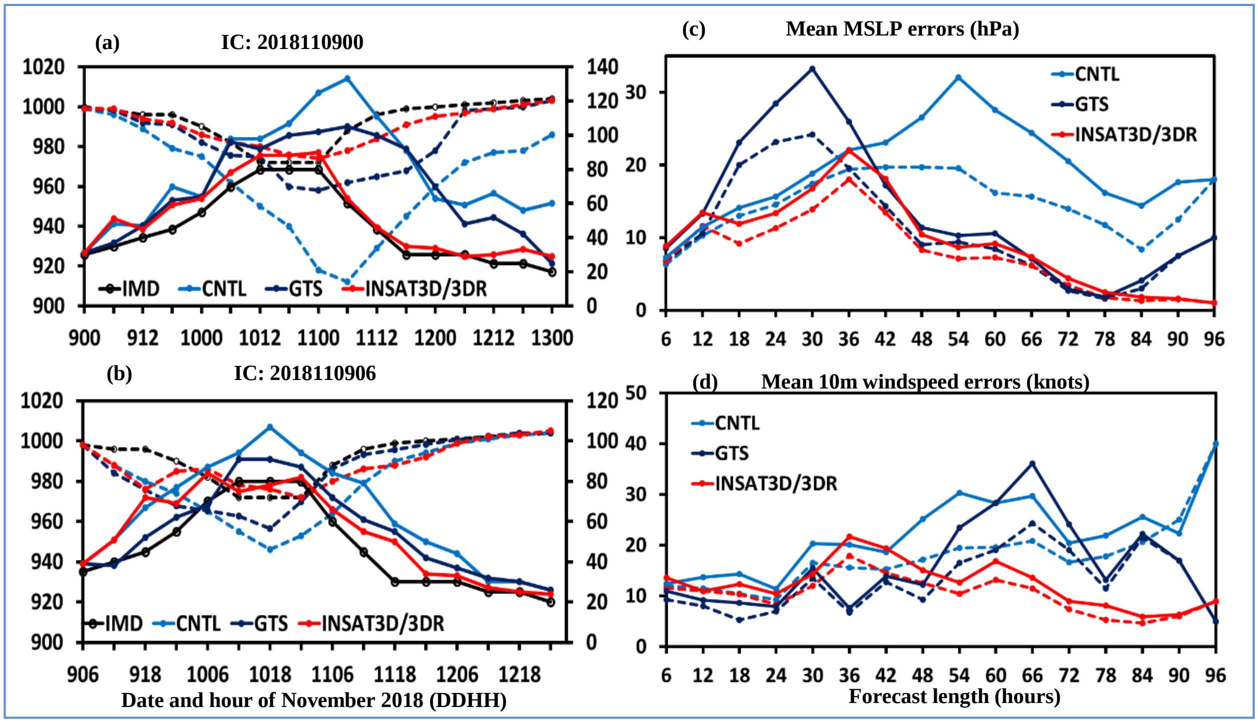


Figs. 4(a&b). (a) Mean RMSE of intensity forecast (knots) for all 62 forecast cases from WRF and HWRF calculated against IMD best estimations. (b) % gain of model intensity with respect to IMD long-term average error (2003–2017) (source: Nadimpalli *et al*. 2020a)

exhibited shallow, medium, and deep convective structures and is well represented in the initial vortex (Fig. 3). Full details of vortex initialization and relocation method can be found in Gopalakrishnan *et al.*, (2011); Mohanty *et al.* (2013); Osuri *et al.* (2017a). Nadimpalli *et al.* (2020a) showed superiority of the cyclone-specific model in predicting the TCs over the NIO region. They further showed the HWRF performance in predicting the better intensity in terms of wind speed compared to the existing mechanisms of IMD (Fig. 4). The operational run of HWRF by the India Meteorological Department (IMD) and its continuous refinement through these research efforts have led to a quantum leap in forecast skill, with documented substantial reductions in track errors (8-24%) and intensity errors (15-40%) for forecasts up to 72 hours (Nadimpalli *et al.*, 2020a; IMD, 2020).

2.3. *Assimilation of indigenous satellite data*

A major advancement has been the effective assimilation of data from Indian satellites. The assimilation of clear-sky radiances from the INSAT-3D/3DR satellites has a positive impact on defining the large-scale environmental conditions-such as moisture, temperature, and wind fields-surrounding the TC. This improves the model's initial analysis, leading to better



Figs. 5(a-d). (a) Intensity (10m wind speed in knots [solid line] and Mean Sea level pressure [Dashed line]) prediction from CNTL, GTS and INSAT3D/3DR experiments along with the IMD best estimation for IC: 00 UTC 09 November 2018. (b) same as (a) but for IC: 06 UTC 09 November 2018. (c) Mean Absolute Error (solid line) and RMSE (dashed line) of MSLP from all the 7 cases of CNTL, GTS and INSAT3D/3DR experiments calculated against IMD best estimations. (d) same as (c) but for 10m wind speed (Source: Nadimpalli *et al*. 2020b)

predictions of the storm's track and intensity, as demonstrated during cyclones like Titli (Nadimpalli *et al.*, 2020b). Especially, the intensity prediction (rapidly intensified phase) has been captured very well with less error by the INSAT-3S/3DR experiments (Fig. 5).

A significant improvement in annual average skill of official track forecast of IMD from 2003-2024. The skill is noticeably high from 2009 onwards, compared to 2003-2008. The skill may be attributed to the modernization programme of IMD in 2009 with respect to observation, analysis and prediction tools & techniques. The research and development activities including enhanced data assimilation, higher resolution, improved physics etc. have been advanced with the help of improved network of in-situ observations and mainly from DWR and satellites observations (Fig. 6). Noticeable improvements in TC track and intensity forecasts have been achieved in recent years. For instance, the IMD track forecast errors for BoB TC DANA were 32, 24, and 29 km for the 24, 48 and 72-hour lead periods, respectively, as against the recent five-year (2019-2023) average errors of 72, 112, and 156 km (ESSO/MoES/IMD/RSMC-Tropical Cyclone Report/01 (2025)/15). The track forecast skill for TC DANA has also shown a marked improvement relative to the 2019–2023 baseline. Similarly, the absolute errors (AE) in wind forecasts for TC DANA were 2.7, 5.0, and 3.8 knots at the 24-, 48- and 72-hour lead periods, compared with the corresponding five-year average errors of 7.1, 10.3, and 13.8 knots. Moreover, IMD's track forecast accuracy has been continuously improving since 2003, with track forecast errors decreasing at a rate of 5.2 km per year (52 km per decade) for the 24-hour lead period, and forecast skill increasing at a rate of 2.8% per year (28% per decade) (ESSO/MoES/IMD/RSMC-Tropical Cyclone Report/01 (2025)/15).

2.4. *Understanding and predicting rapid intensification (RI)*

The HWRF system has been proved superior in studying and predicting the challenging phenomenon of RI over the NIO. Detailed analyses have identified key atmospheric and oceanic precursors-such as low vertical wind shear, high ocean heat content, and the presence of a pre-existing upper-level outflow channel-that the model can capture to anticipate RI events (Nekkali *et al.* 2024; Nadimpalli *et al.*, 2021; Mohanty *et al.* 2021; Vinodhkumar *et al.* 2021).

High-Resolution Ocean State: The critical role of ocean coupling has been emphasized through studies using high-resolution Regional Ocean Modeling System (ROMS) Sea Surface Temperature (SST) fields. Replacing

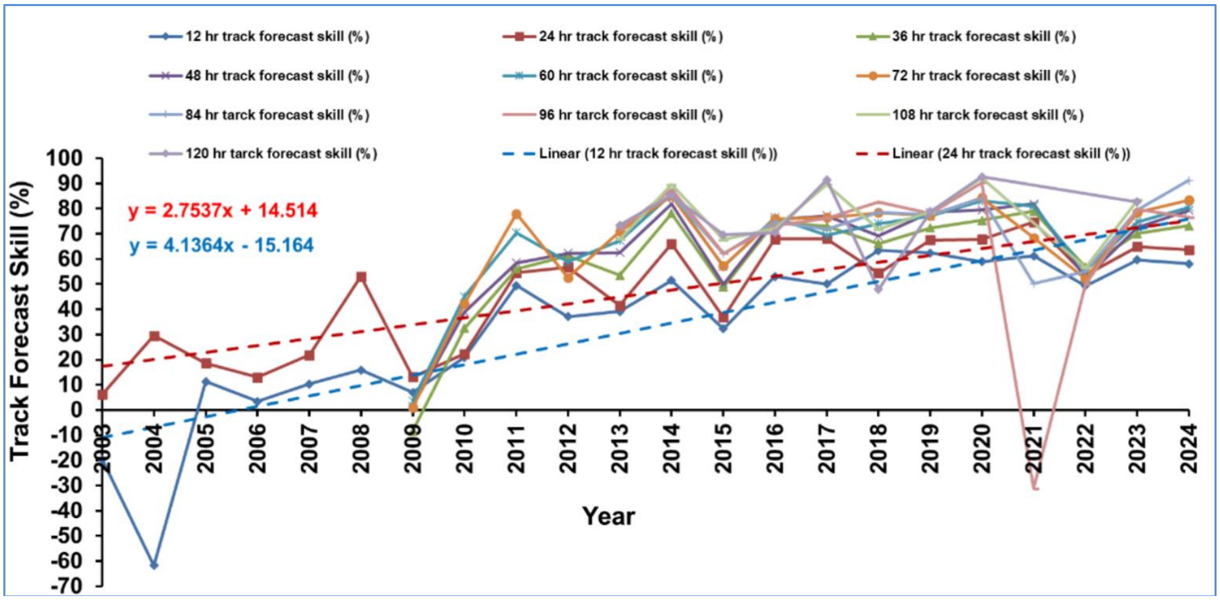


Fig. 6. Average percentage improvement of operational track forecast from IMD in the past 2 decades (adopted from RSMC report of 2024 available at https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=Mjc=

coarser SST analyses with these high-resolution fields in the WRF/HWRF modeling systems has been shown to improve the simulation of cyclone intensity and inner-core structure by more accurately representing the ocean's energy potential and the cold wake generated by the storm's passage (Nadimpalli *et al.*, 2023; Mohanty *et al.* 2019; Busireddy *et al.* 2022). Busireddy *et al.* (2022) showed how the size and intensity of TCs would increase in a hypothetical study with different SST inputs, which was proved in a later study by Nekkali et al. (2022).

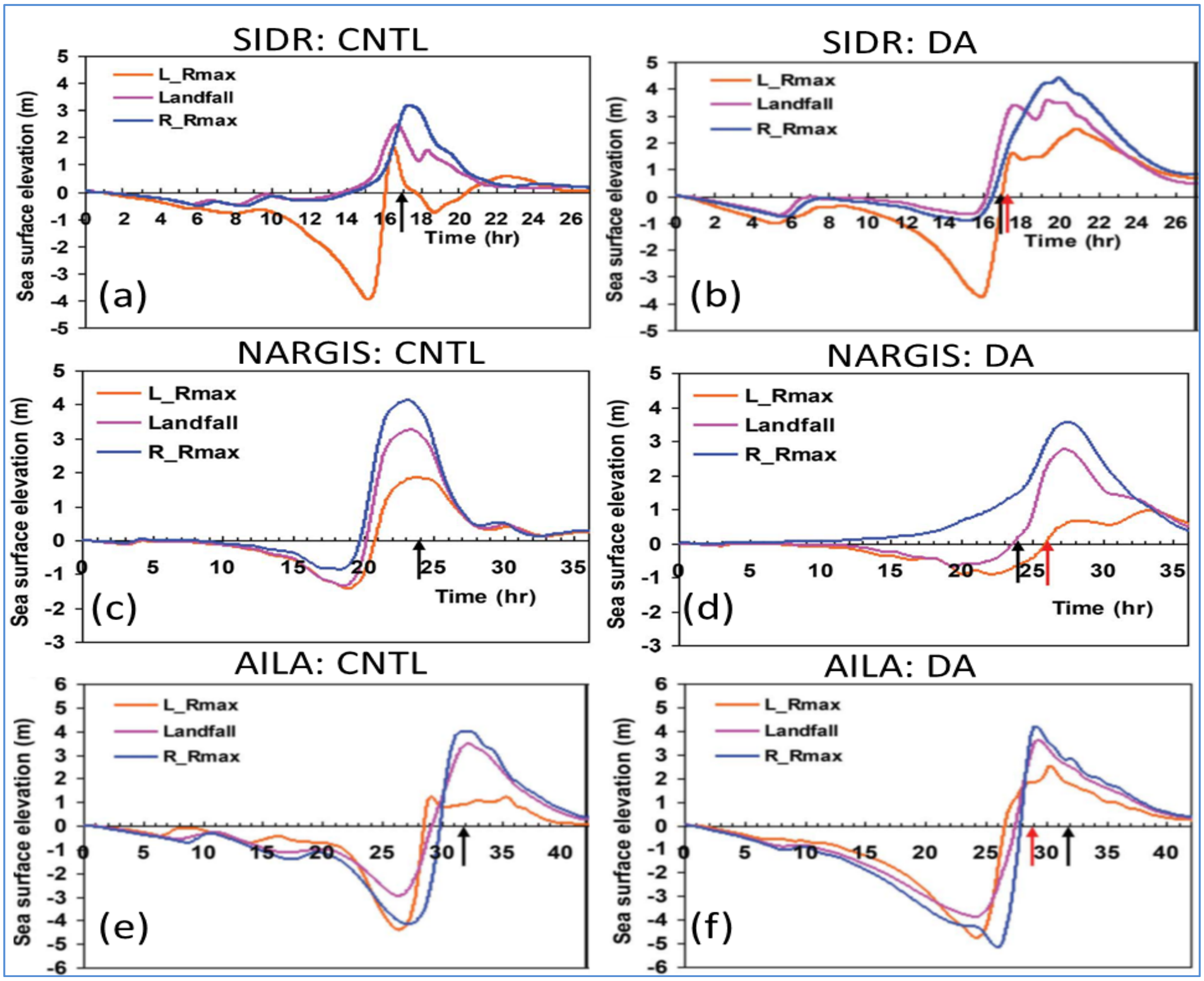
The ocean coupling component is particularly critical for intensity forecasting. TCs are heat engines that derive their energy from the warm ocean surface. However, the cyclone's strong winds also induce vertical mixing and upwelling, which bring cooler water from the subsurface to the surface, a phenomenon known as sea surface temperature (SST) cooling**.** This cold wake left behind the storm can act as a negative feedback mechanism, limiting the storm's potential intensity or even causing weakening. Case studies of intense cyclones like Fani (2019) and Ockhi (2017) have demonstrated that high-resolution coupled models (HWRF) are far superior to their uncoupled counterparts in simulating this crucial air-sea interaction. They accurately capture the magnitude and spatial distribution of SST cooling, which is directly linked to improved intensity forecasts, including the prediction of rapid intensification (RI) phases and the timing of intensity peaks (Mohanty *et al.,* 2021; Mohanty *et al.,* 2022).

The role of the pre-storm oceanic thermal structure, particularly the Ocean Heat Content (OHC) and the depth of the warm upper-ocean layer (26 °C isotherm depth), is now well-established as a key modulator of cyclone life cycles over the BoB. High OHC provides a large reservoir of energy, preventing significant surface cooling and thus sustaining or promoting intensification. Conversely, low OHC or a shallow warm layer can lead to rapid cooling and quick weakening of a storm. High-resolution coupled modeling systems are essential for initializing and simulating these ocean parameters accurately, making them indispensable for reliable operational forecast guidance (Mohanty *et al.,* 2019).

2.5. *Integrated impact - based forecasting: advancements in storm surge prediction*

Early pioneering work by Das (1972) and Murty & Henry (1983) laid the critical foundation in storm surge modeling, identifying key challenges and recommendations for improving surge modeling in the complex bathymetry of the BoB. Mesoscale forcing plays a crucial role in determining storm surge amplitude, and improvements in meteorological inputs are hypothesized to lead to better surge predictions. High-resolution mesoscale models, (WRF, HWRF systems), have substantially improved the TC track forecasts for 3-5 days (Pattanayak *et al.*, 2012) and thus the challenge has been taken up to step forward in storm surge prediction in a similar level of accuracy with the lead time of at least two days for effective evacuation.

To address this challenge, a novel research work has been initiated to simulate storm surges associated with

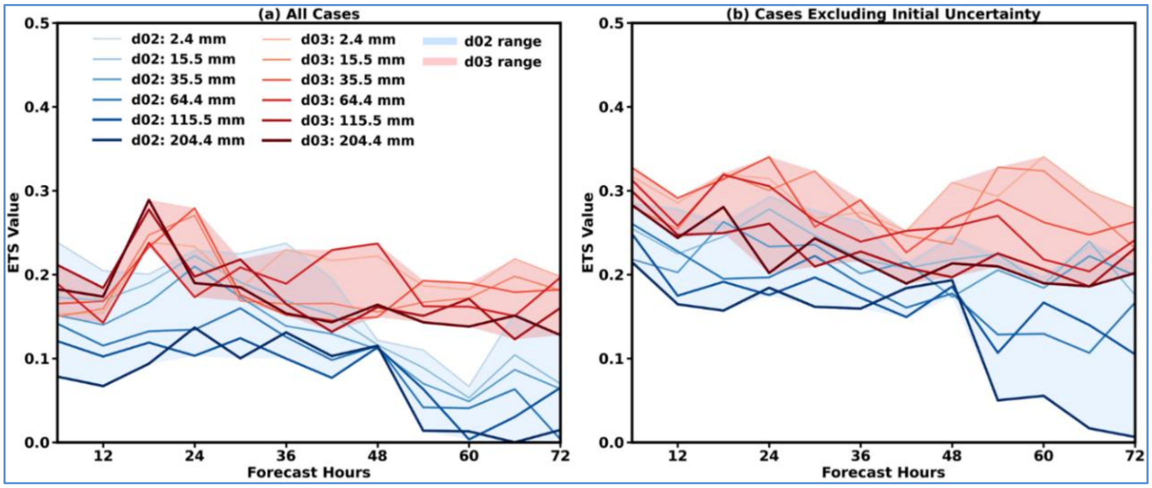


Figs. 7(a-f). Time evolution of storm surges as predicted at left (L_Rmax), Landfall, and right (R_Rmax) points for TC Sidr, Nargis and Aila (Source: Pattanayak *et a*l. 2016)

severe TCs over the BoB using a one-way coupling approach between the Non-hydrostatic Mesoscale Model-WRF and with the two-dimensional finite-difference storm surge model (Pattanayak *et al.*, 2016). By leveraging the strengths of both models, this study seeks to enhance the predictability of storm surges and support the development of effective early warning systems, enabling rapid evacuation and relocation of people in vulnerable coastal regions. Fig. 7 illustrates the time evolution of storm surges at left (L_Rmax), landfall and right (R_Rmax) points of the cyclones Sidr, Nargis and Aila. This study suggests that the real-time storm surge prediction is possible using the high-resolution mesoscale model products and is communicated to IMD through FDP programme of landfalling TC over BoB and to the rim countries of BoB and AS for their operational use.

The modern paradigm for operational storm surge forecasting involves a seamless one-way coupling chain: (*i*) atmospheric Forcing**:** High-resolution surface wind and pressure fields from operational NWP models (*e.g.*, WRF, HWRF) provide the primary driving force. (*ii*) hydrodynamic Modeling**:** These meteorological fields are used to force sophisticated hydrodynamic models (e.g., the ADCIRC model coupled with the SWAN wave model) that solve the shallow water equations. (*iii*) **i**nput Factors: The models simulate water elevation by factoring in the cyclone's winds, atmospheric pressure, astronomical tides, wave setup, and the region's intricate bathymetry and coastline geometry.

As an extension of the previous study, WRF and HWRF have been used to simulate 8 TCs over BoB and the model track and intensity both in terms of pressure drop and 10 m maximum wind speed have been provided as input to produce surge height using IIT Delhi dynamical storm surge model (Mohanty *et al.*, 2024). The models' reliability has been verified by analysing different



Figs. 9(a&b). Equitable Threat Score (ETS) for different rainfall thresholds along the forecast length for (a) all the cases considered, and (b) for the cases excluding initial uncertainty in Domain 2 (3 km horizontal resolution; Blue color) and Domain 3 (1 km horizontal resolution; Red color) (Adopted from Gopalakrishnana *et al*. 2025)

initial condition simulations of all TCs selected for 96-24 h forecast length with 12 h interval, prior to landfall of the system and presented in Fig. 8. HWRF shows better overall predictability for the track, intensity as well as landfall; however, both models are capable of producing reliable results with 3-4 days of lead time.

This integrated system has been successfully implemented for real-time forecasting. A landmark demonstration was during Very Severe Cyclonic Storm Hudhud (2014), where a coupled modeling system provided accurate real-time forecasts of surge heights and coastal inundation extents. This capability proved crucial for emergency preparedness and highlighted the importance of using high-resolution, accurate cyclone forecasts to drive the surge models (Murty *et al.*, 2017).

2.6. *Advancement in extreme weather events and costal processes prediction*

Recently, Indian Ocean-Land-Atmosphere (IOLA) Coupled Mesoscale Prediction system has been developed to enhance the predictability of severe weather over the ocean, coastal, and inland regions of the Indian Monsoon region (Gopalakrishnana *et al.*, 2025). The IOLA model is based on the NMM dynamical core and improved physical and microphysical parameterization processes from the Hurricane Weather Research and Forecast (HWRF) system, including ocean coupling from HWRF. Moreover, the nesting capabilities have been further advanced to represent the first-ever coupled modeling system explicitly focused to tackle "all-purpose" severe weather across multiple domains and scales. Fig. 9 presents the skill of IOLA model for rainfall prediction in terms of Equitable Threat Score (ETS). ETS values around 0.12 typically indicate skilful predictions (Krishnamurti *et al.*, 2009) and serves as a benchmark in evaluating forecast accuracy. In the low-resolution (3-km) simulation, lighter rainfall (0.15 to 0.25) is skilful but heavy rainfall skill dropped to 0.08 to 0.15, with a marked decline in skill (ETS < 0.1) beyond 48 hours (Fig. 9a). On the other hand, the high-resolution simulation (D03), with a 1 km grid spacing, demonstrates high skill score 0.15 and ~0.3 across various rainfall categories up to 72-hour forecasts. Comparing with existing models such as WRF and COAWST models whose ETS values below 0.18 (Osuri *et al.*, 2020; Chakraborty *et al.*, 2023), the IOLA simulations demonstrated better skill.

3. Thunderstorms and associated lightning

Thunderstorms are global phenomenon, with an estimated 40,000 occurring daily around the Earth (NWS, 2024). Over the Indian subcontinent, the pre-monsoon (March-May) Thunderstorms are often more intense convective storms compared to the monsoon season (STORM Science Plan, 2005; Tyagi, 2007; Ray *et al.*, 2016). These severe thunderstorms, accompanied by squalls, hail, torrential rain, and lightning, pose a grave threat to life, property, and the socio-economy, damaging infrastructure, agriculture, and livelihoods (Priya *et al.*, 2021).

3.1. *Traditional prediction methods: thermodynamic indices*

The prediction of thunderstorms has historically relied on the use of thermodynamic stability indices derived from radiosonde (weather balloon) observations. These indices, which quantify the energy and moisture available in the atmosphere, provide a snapshot of its potential for convective development. Widely used indices include the Convective Available Potential Energy (CAPE), Lifted Index (LI), K-Index, SWEAT index and Total Totals Index. Several studies have established correlations between high values of these indices and the likelihood of thunderstorm occurrence over India, offering a valuable first-guess tool for forecasters (Mukhopadhyay *et al.*, 2003; Tyagi *et al.*, 2011; Nayak *et al.*, 2014). While these indices are useful indicators of convective instability, none of the thermodynamic indices alone is adequate for predicting thunderstorms. To address this issue, combinations of these thermodynamic indices have been used, but their predictive skill remains limited (Tyagi *et al.*, 2011; Chakraborty *et al.*, 2013). The work of Chakraborty *et al.* (2013) refined the use of these indices for the Northeast Indian region, identifying specific threshold combinations most predictive of severe weather. However, these indices are limited by their point-based nature and their inability to capture the dynamic triggers, such as wind shear and lifting mechanisms, required to initiate convection. Furthermore, prediction of these storms requires an understanding of their thermodynamic structure and genesis, as well as their movement; point-based observations alone are insufficient, necessitating comprehensive observational networks and advanced modeling approaches.

3.2. *Understanding severe thunderstorms: STORM program*

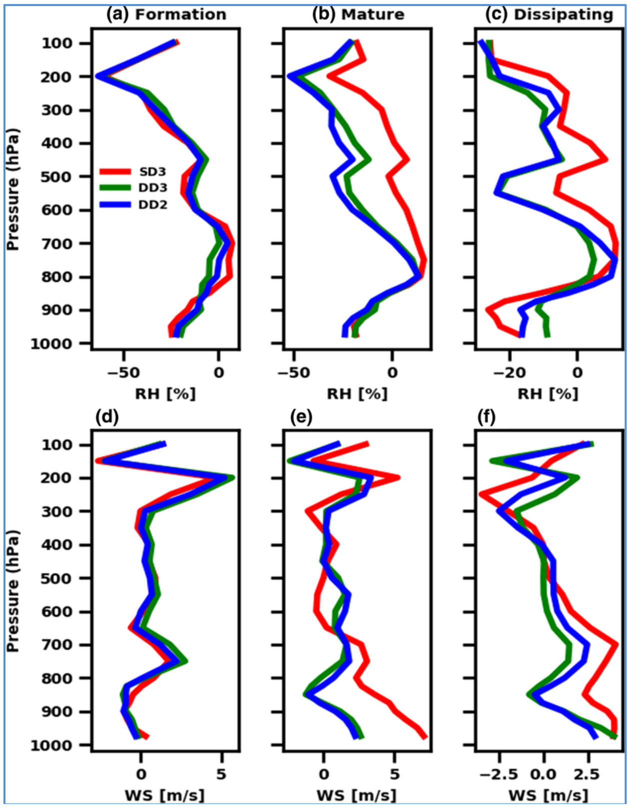
The *Severe Thunderstorm Observations and Regional Modeling (STORM)* program was initiated by Department of Science and Technology, Govt of India, to improve the understanding and prediction of pre-monsoon severe thunderstorms, with particularly focus on the northeastern region of India (STORM, 2005). The program was subsequently expanded to encompass a wider range of convective systems across South Asia, including dust storms and deep convection over the western region, as well as maritime and continental thunderstorms in the south. Recognizing the similar challenges faced across the region, the South Asian SAARC countries also joined this effort, after which it is known as the *SAARC STORM* program (Das *et al.*, 2014). Implemented in three phases, Phase I focused on deep moist convection, nor'westers, and severe thunderstorms; Phase II emphasized dry convection, dust storms, and western disturbances; while Phase III addressed maritime convection. These initiatives employ a comprehensive suite of observational platforms-surface stations, upper-air soundings, radars, satellites, and mobile systems-integrated with regional modeling to investigate storm life cycles, structural characteristics, and the interplay of dynamics, cloud microphysics, and electrical processes. By combining observations with modeling approaches, the program aims to advance scientific understanding and enhance operational forecasting and nowcasting capabilities for severe convective weather across South Asia.

Findings from SAARC STORM program pilot studies have revealed key features of storm systems in the region. Squall lines typically extend 150-250 km in length, occasionally exceeding 300 km, with lifetimes of 8-10 hours and average propagation speeds of 50-60 km/h. Cloud tops usually rise to 10-12 km but sometimes penetrate the tropopause, reaching up to 18 km, with temperatures as low as -80 °C. Most squalls develop in the afternoon and evening, predominantly from the northwest, with preferred storm tracks from northwest to southeast and west to east. While the majority of squalls are of moderate intensity, a significant fraction (~12%) are intense, producing damaging winds over 100 km/h (Das *et al.*, 2014). The merging of squall lines, particularly over eastern India, is a recurring feature of severe weather days. These insights highlight the importance of SAARC STORM in improving the understanding of severe convective systems and in building the foundation for more reliable forecasting and nowcasting capabilities.

3.3. *Numerical modeling of thunderstorms and data assimilation*

High-resolution mesoscale models such as WRF model are extensively used to simulate and predict the initiation, evolution, and dissipation of thunderstorm systems (Dodla & Ratna, 2010; Litta *et al.*, 2012; Priya *et al.*, 2021; Stensrud, 2007; Osuri *et al.*, 2017). Study by Routray *et al.* (2010) demonstrated the critical importance of choosing appropriate cloud microphysics and cumulus parameterization schemes for accurately simulating the structure and rainfall patterns of thunderstorms over the Indian region. Priya *et al.*, 2021 verified the importance of very high-resolution modeling to resolve the convective scale processes especially at various stages during pre-monsoon thunderstorm evolution (Fig. 10).

The NWP models have been proven to be effective in simulating thunderstorms, but its accuracy is highly sensitive to choice of physical parametrization, initial, lateral boundary conditions and model grid resolutions (Kiranprasad *et al.*, 2014). A pivotal advancement in enhancing model initial conditions is data assimilation (DA), which integrates heterogeneous observations into the model to create a more accurate and physically consistent analysis of the atmospheric state. The assimilation of Doppler Weather Radar (DWR) data is particularly transformative for thunderstorm prediction.



Figs. 10(a-f). Vertical profiles of mean errors of model simulated relative humidity [RH] (%) (a–c) and wind speed [WS] (ms^{-1}) (d–f) from all the experiments. Note that all 14 cases of TS stages are considered in this analysis (Source: Priya *et al.* 2022)

Fig. 11 shows assimilation of DWR radar radial velocity and reflectivity in WRF model results better representation of pre-convective environment, including moisture convergence, wind shear, and the location of convective cells, leading to improved simulation of storm timing, location, and intensity (Kiranprasad *et al.*, 2014). Further, these results have been supported by the Abhilash *et al.*, (2012) with assimilation of DWR derived products within WRF framework. Srivastava *et al.*, 2024 used rapid update cyclic DA framework of DWR products over India for prediction the severe convective activity over India, which is now operational at IMD. Similarly, the assimilation of land surface variables (soil moisture and temperature) has been shown to significantly improve the prediction of severe thunderstorms by creating a more realistic representation of the boundary layer, which governs the initiation of convection. Accurate initial soil conditions modulate heat and moisture fluxes, thereby improving the forecast of convective initiation and subsequent storm evolution (Nayak *et al.*, 2018; 2021; Osuri *et al.*, 2017b; Vaidya *et al.*, 2004; Rajesh *et al.*, 2016). Osuri *et al.* 2017b clearly brought out the necessity of high-resolution land data initialization in the model especially for these types of convective storms (Fig. 11). Furthermore, studies by Kulkarni *et al.* (2020) have shown the positive impact of assimilating satellite-derived atmospheric motion vectors on capturing the mesoscale environment conducive to convection. These DA techniques are essential for overcoming the inherent limitations of model spin-up and capturing the fast-evolving nature of severe convective storms.

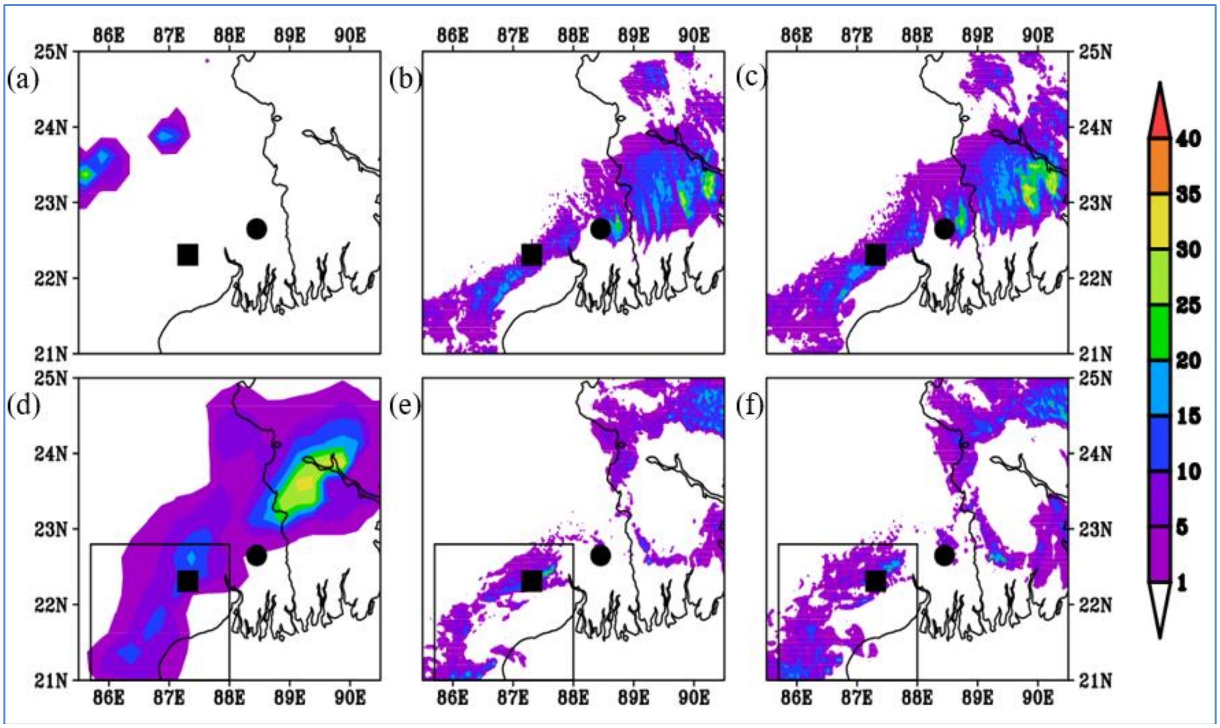
3.4. *Physics of Lightning Generation*

In severe convective clouds, the lightning generation is a complex microphysical process. The ice particles (like snow and ice crystals) in convective cloud grow by consuming super-cooled water droplets and are carried aloft by powerful updrafts. These particles collide with falling graupel (soft hail). Through this collision process, a charge separation occurs: the smaller ice particles tend to become positively charged and accumulate in the upper reaches of the cloud, while the larger graupel particles acquire a negative charge in the middle and lower portions. This massive charge separation generates a powerful electric field. When the electric field strength exceeds the dielectric breakdown capacity of air, it results in a giant spark-lightning (Cooray, 2003).

Lightning over the Indian subcontinent is predominantly associated with deep convective activity (Barthe *et al.*, 2010). Recent research has provided new insights, revealing that approximately 25% of all cloud-to-ground (CG) lightning during the break periods of the Indian summer monsoon has positive polarity (+CG). The work of Ranalkar and Chaudhari (2009) and Pawar *et al.* (2012) has been instrumental in establishing climatology of lightning activity over different Indian regions and correlating flash rates with convective available potential energy (CAPE) and cloud top height. The study by Ghosh *et al.* (2024) highlights that the microphysical and dynamical characteristics within the cloud, specifically a larger mixed-phase cloud liquid water content, are key factors supporting the production of +CG lightning during these break days. Building on this physical understanding, efforts are now underway to develop lightning prediction schemes within NWP models. These schemes typically parameterize lightning flash rates based on model-predicted microphysical quantities, such as graupel mass, ice water content, and updraft volume (McCaul *et al.*, 2009; Yair *et al.*, 2010; Mohan *et al.*, 2022; Nadimpalli *et al.* 2025), providing a crucial link between simulated storm dynamics and the resulting electrical activity.

4. **Urban extreme weather**

As cities expand, surface and atmospheric dynamics alterations elevate risks to urban populations and infrastructure by increasing extreme weather events (Liu

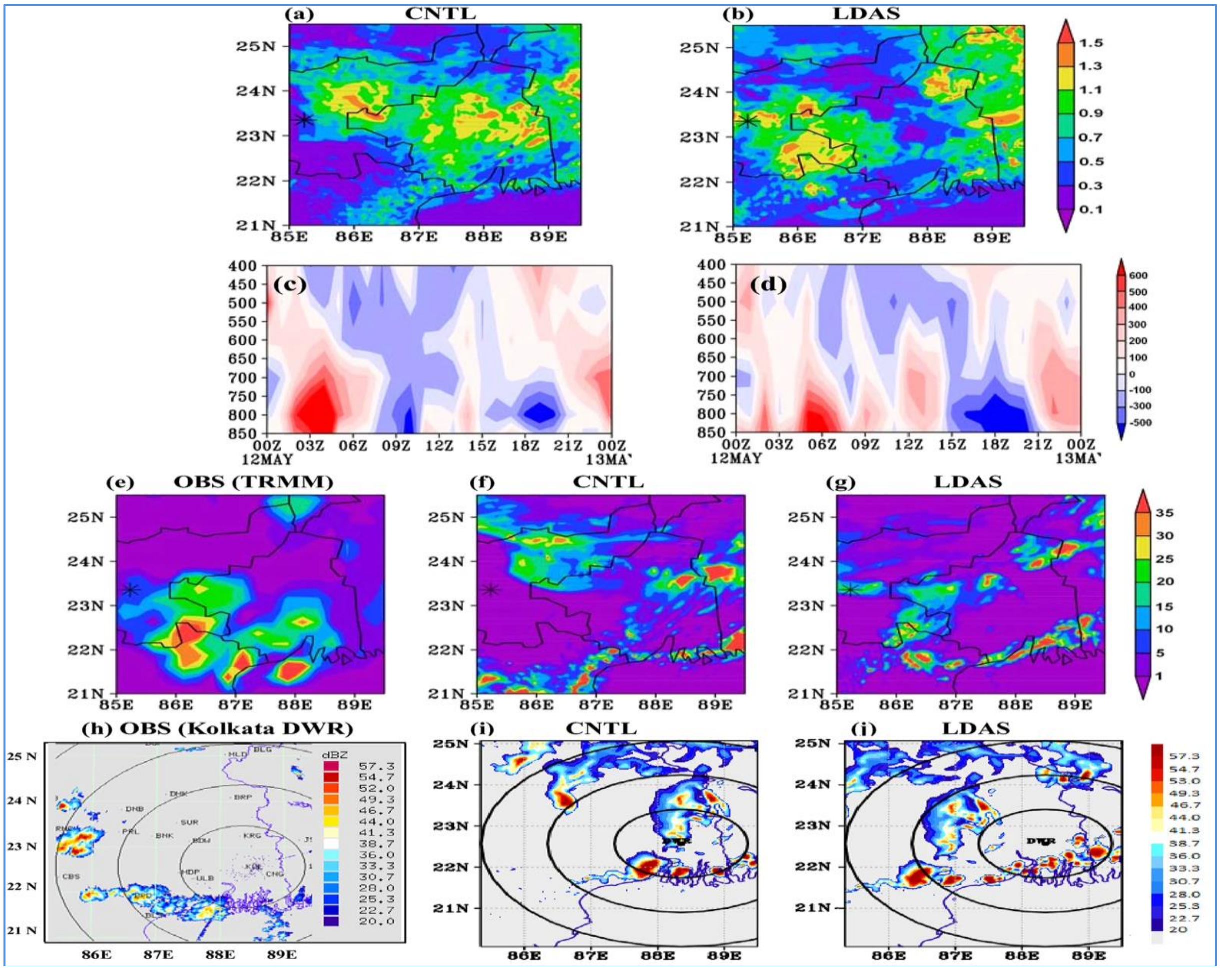


Figs.11(a-f). Model-simulated 3 hr accumulated rainfall (mm) for Case 1 during 06 to 09 UTC for (a) TRMM, (b) CNTL, and (c) 3DV. (d-f) is same as (a-b) but during 09 to 12 UTC 11 May 2009. The location of Kolkata and Kharagpur are marked with a black dot and black square respectively (Source: Kiran Prasad *et al.* 2014)

& Niyogi, 2019). Accurate representation of urban landscapes and their associated physical processes is increasingly recognized as a critical factor for successfully modeling convective systems over and downwind of cities. The growth of cities alters the surface energy balance, creating Urban Heat Islands (UHIs), modifying boundary layer dynamics, and increasing surface roughness, all of which can initiate, enhance, or alter the trajectory of thunderstorms. The major extreme events having frequence occurrence are mainly confined to urban heavy rainfall and urban heatwaves.

4.1. *Urban rainfall*

A seminal study by Patel *et al.* (2023) provided a comprehensive analysis of how urbanization impacts hurricane rainfall, revealing significantly altered spatial rainfall patterns due to urban land use. Their high-resolution simulations demonstrated that urban areas can enhance convective activity and reorganize precipitation distribution, leading to localized extremes that pose a severe flood risk. This work underscores the necessity of incorporating detailed urban representations for predicting rainfall in landfalling systems. Complementing this, research on monsoon systems by Swain *et al.* (2023) documented the delayed timing and spatial reorganization of rainfall due to urban sprawl in Bhubaneswar. Karrevula *et al.* (2024) conducted 32 sensitivity experiments involving land surface, microphysics, and cumulus physics schemes to identify the 8 best configurations for simulating heavy rainfall events over Bhubaneswar city. Subsequently, Boyaj *et al.* (2025) performed additional experiments with a larger number of rainfall events to further improve the model performance and finalized the best four combinations of physical parameterization schemes. Using these optimized configurations, semi–real-time simulations of the 2022 monsoonal heavy rainfall events were carried out over Bhubaneswar (Fig. 13). The results show that the optimized WRF model effectively captured both the occurrence and intensity of heavy rainfall events, achieving an overall success rate of 64% compared to 16% for the IMD-GFS at the station level. For different lead times, the WRF (IMD-GFS) exhibited success rates of 45% (8%), 40% (8%), and 46% (4%) for day-1, day-2, and day-3 forecasts, respectively. In terms of rainfall magnitude, the WRF model showed a 30% overestimation, whereas the IMD-GFS demonstrated a 65% underestimation (Boyaj *et al.*, 2025). These studies collectively show that urban landscapes do not merely increase rainfall totals but fundamentally reshape its spatiotemporal characteristics.



Figs. 12(a-J). Model simulated surface moisture flux (kg m−2 s−1) from (a) CNTL and (b) LDAS averaged for 9–12 UTC 12 May 2009 (case-2). (c,d) Are same (a,b) but time-vertical cross section of diabatic heating (K/h) averaged over the region 86°–88.5°E and 21.5°–24°N. 3 hr (9–12 UTC) accumulated rainfall in mm from (e) TRMM (f) CNTL and (g) LDAS. (h–j) Are, respectively, the Kolkata DWR observed reflectivity, CNTL and LDAS simulated reflectivity (dBZ) at 11 UTC. The star in (a,b,e–g) represents the Ranchi station. (Source: Osuri *et al*. 2017b)

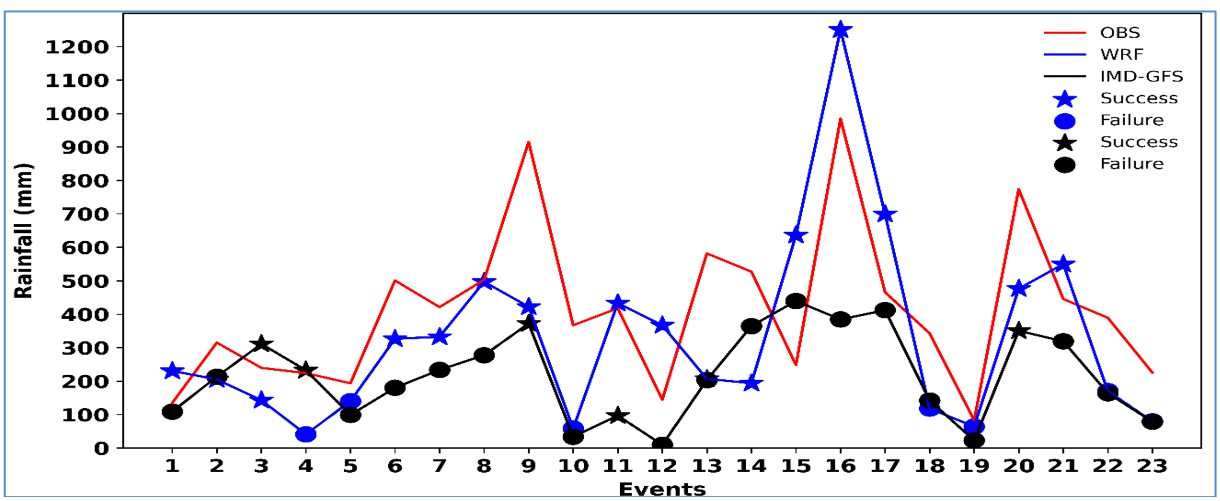
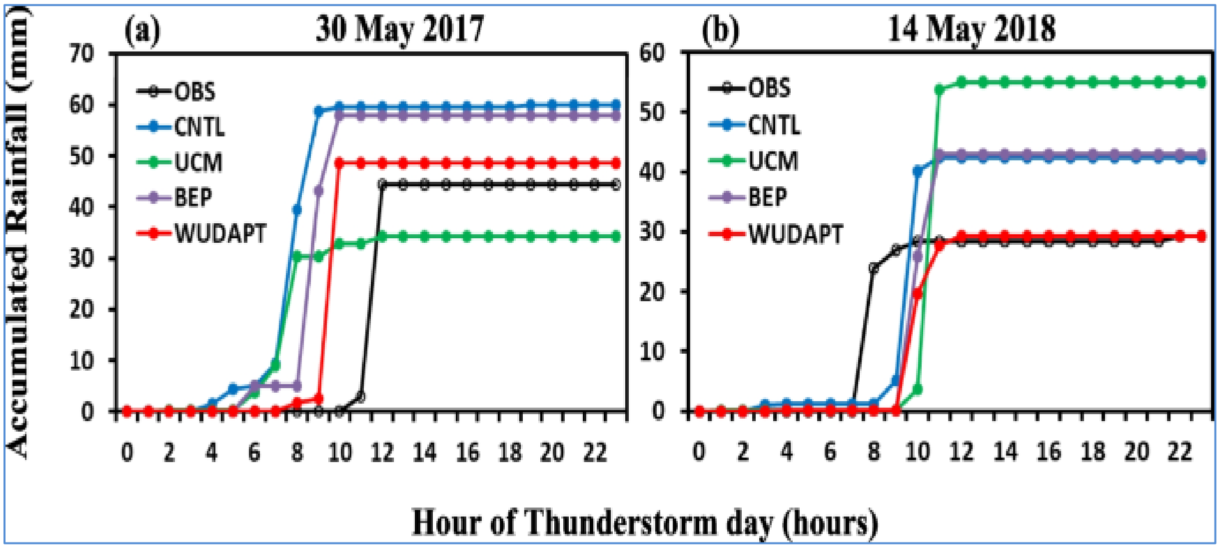


Fig. 13. The line diagram shows the sum of all stations (within the analysis domain) rainfall (mm/day) for each heavy rainfall event. The red, blue, and black lines represent rainfall observations, WRF, and IMD-GFS, respectively. Star and closed circle symbols denote success and failure, respectively, for each event considering the 'event captured at the same station' method (Boyaj *et al*., 2025)



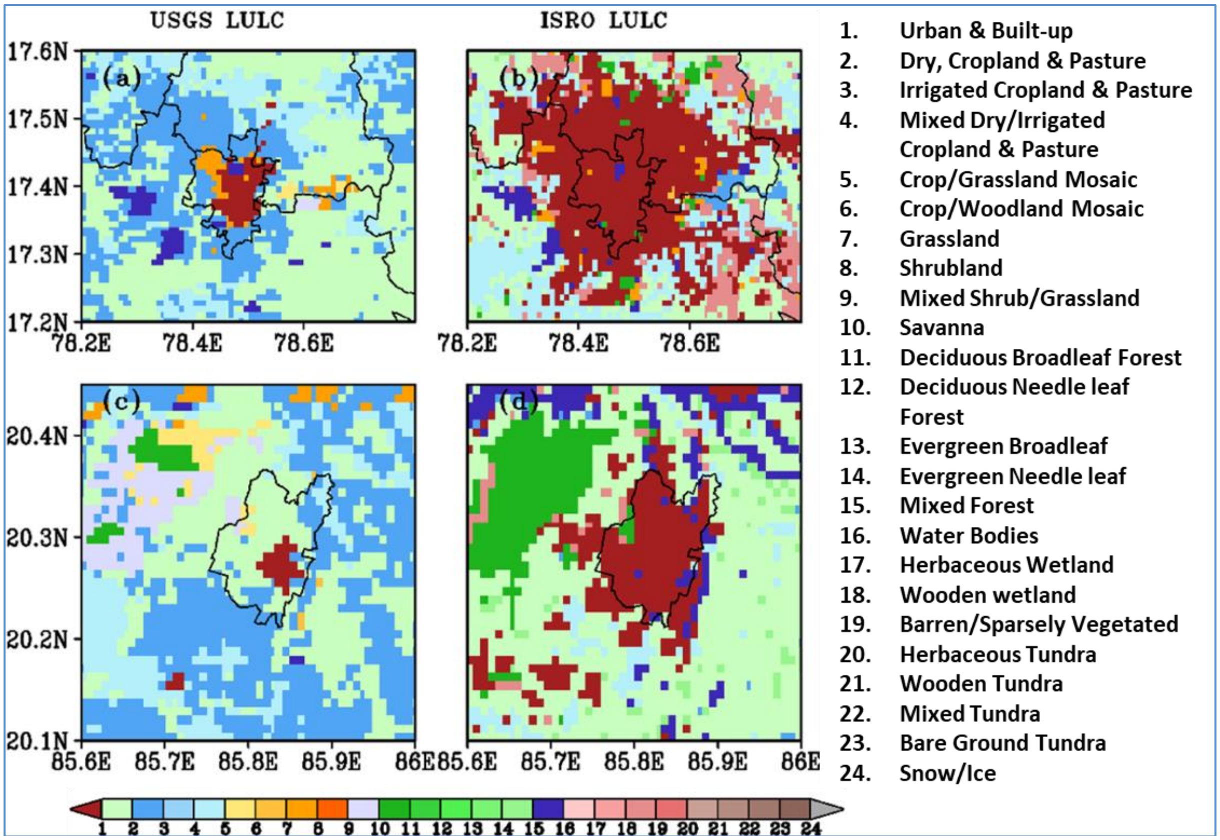
Figs. 14(a&b). a) Hourly accumulated rainfall (mm) from all the experiments along with the Bhubaneswar meteorological station observation (OBS) for 30 May 2017 case. b) Same as (a) but for 14 May 2018 case (Source: Nadimpalli *et al*., 2023)

Although studies from Bhubaneswar and Mumbai provide important insights into extreme rainfall episodes in coastal megacities, a more systematic discussion across diverse Indian urban centres reveals that the problem is both widespread and escalating. Delhi, Hyderabad, and Bengaluru have increasingly reported short-duration, high-intensity rainfall events that overwhelm stormwater drainage systems and amplify pluvial flood risks. In Chennai, the 2015 flood highlighted how rapid urban expansion, encroachment of natural wetlands, and inadequate urban planning exacerbate the impacts of extreme precipitation. Similarly, Kolkata and Guwahati face compound risks where high population density and aging drainage infrastructure combine with intensifying monsoon bursts to produce recurrent urban flooding. Medium-sized cities such as Surat, Indore, and Lucknow are increasingly vulnerable, as they often lack the adaptive infrastructure and institutional capacity of megacities, yet are exposed to similar or higher rainfall extremes under changing monsoon dynamics. These patterns highlight the need for kilometre-scale modelling and ensemble-based NWP frameworks that integrate land-use data, hydrological models, and high-resolution rainfall forecasts.

To address this modeling challenge, significant advancements have been made in integrating high-resolution urban data. Nadimpalli *et al.* (2022) demonstrated a marked improvement in short-term rainfall forecasting for urban regions by integrating a high-resolution urban-scale model, highlighting the value of city-specific information. This effort was expanded upon by Nadimpalli *et al.* (2023), who integrated the World Urban Database and Access Portal Tools (WUDAPT) into the WRF model for severe convection modeling. The WUDAPT framework provides a standardized method for representing urban morphology (*e.g.*, building height, street width) globally, allowing for a more physical representation of drag and turbulence effects from buildings in Planetary Boundary Layer (PBL) schemes. Their results showed that this integration led to a more accurate simulation of storm evolution and associated precipitation patterns over urban corridors (Fig. 14).

Beyond direct urban effects, the preconditioning of the land surface is a key modulator of convection. This is encapsulated in the concept of the "Brown Ocean Effect" (BOE). The BOE describes a phenomenon where saturated soils (acting as a "brown ocean") can sustain or even intensify convective systems, including cyclones, after landfall by providing ample latent heat flux that replaces the energy source lost from the ocean. This research links antecedent soil moisture states to post-landfall cyclone intensification and the maintenance of severe convective systems, demonstrating that land-atmosphere interactions are as crucial as urban effects in determining convective behavior.

Emerging frameworks, such as the integrated urban "systems of systems" approach outlined by Patel *et al.* (2023), offer a holistic perspective for developing weather-ready cities. This approach aligns with findings that urban sprawl alters rainfall timing and intensity and emphasizes the need for coupled modeling that integrates built-environment data, hydrological models, and infrastructure networks to fully assess urban vulnerability



Figs. 15(a-d). Spatial distributions of the land-use and land-cover (LULC) classes over the study regions as obtained from the USGS and ISRO datasets. The first (a, b) and second rows (c, d) show the LULC of Hyderabad and Bhubaneswar, respectively. The first (a, c) and second columns (b, d) display the 1993 (USGS) and 2019 (ISRO) LULC datasets. The table on the left side of the figure represents the names of the LULC categories (Source: Boyaj *et al*., 2024)

to convective extremes. This growing body of work unequivocally underscores that high-resolution urban data and advanced urban canopy parameterizations are no longer optional but are essential components for accurately predicting and managing weather extremes in the world's rapidly urbanizing regions.

4.2. *Urban heatwaves*

Although casualties from severe weather events have generally declined, the mortality rate associated with heatwaves has remained largely unchanged, averaging about 25 deaths per event. Moreover, the temperature extremes continue to increase and intensify (Ray *et al.,* 2021). This is a serious concern in the recent decade, particularly in the context of global warming. Heatwaves are further exacerbated by land-use and land-cover changes, particularly the conversion of vegetation or agricultural land into built-up areas. Such urbanization leads to increased surface temperatures, which, in turn, amplify the occurrence and intensity of heatwaves. For example, built-up areas have increased 11-fold in Bhubaneswar and 13-fold in Hyderabad (Fig. 15) and heat extremes are increasing 2days/decade (Boyaj *et al.,* 2024; Karrevula *et al.,* 2025). Nearly two-thirds of the world’s population is projected to live in urban areas by 2050 (Department of Economic and Social Affairs, 2018; Song *et al.,* 2020). Urbanization-amplified compound heatwaves are expected to elevate heat exposure risks in more than 90% of cities, with stronger amplification observed in highly urbanized regions (Gao *et al.,* 2024). While urbanization drives economic growth, it also significantly alters local weather and climate systems (*e.g*., Chai *et al.,* 2022; Qian *et al.,* 2022). Despite these alarming projections, detailed studies addressing the impacts of urbanization on heatwaves are still limited in Indian cities, with only a few observational and modeling studies available.

There are only a few studies that emphasize the modeling of heatwaves in the context of urbanization and the improvement of maximum temperature prediction over cities such as Ahmedabad, Hyderabad, and Bhubaneswar (Boyaj *et al.,* 2023; Jaiswal *et al.,* 2023;

daytime spatial distribution of temperature revealed that the ACM2 scheme simulated maximum temperatures in close agreement with IMDAA, with the lowest absolute error of 1.28 °C. However, further experiments are needed to understand the influence of urbanization over the different geoclimatic conditions to optimize the WRF model configuration for the operational use.

Boyaj *et al.* (2024) examined how updated land use land cover characteristics affect the representation of heatwaves over Bhubaneswar and Hyderabad, highlighting the importance of realistic urban surface representation in improving heatwave simulations. For the HW cases considered over both cities, air and surface temperatures increased due to urbanization by approximately 4-5 °C and 5-6 °C, respectively (Fig. 16). Furthermore, urbanization had a stronger impact on surface temperature (~1–2 °C) than on air temperature during the nighttime. Such studies are lacking for other Indian cities, particularly state capitals and industrial hubs where major GDP growth is occurring and SDGs are improving. Conducting these studies is crucial to customize model setups for providing early predictions to various sectors such as health, energy, agriculture, water resources, and urban planning, thereby minimizing losses and saving lives.

The above mentioned reported studies from Bhubaneswar and Mumbai provide useful insights into the localized manifestation of heat stress, a broader and systematic perspective across Indian urban centres is also essential to contextualize the increasing risks of heatwaves. Indian cities experience diverse climatological and socio-economic conditions that modulate heatwave impacts. It is seen that Delhi and Ahmedabad have consistently recorded some of the highest urban heat stress indices, with mortality and morbidity linked to both daytime maximum temperatures and elevated night-time minimums (Azhar *et al.,* 2014; Rohini et al., 2016). Hyderabad and Chennai, though traditionally influenced by maritime proximity, have shown increasing frequency of heatwave events due to rapid land-use change, rising urban heat island (UHI) intensity, and compounding air quality deterioration (Mazdiyasni *et al.,* 2017; Mishra *et al.,* 2020). Cities in eastern and central India, including Kolkata and Nagpur, are witnessing more persistent hot nights, which exacerbate public health risks even when daytime maxima remain moderate (Im *et al.,* 2017). Furthermore, smaller urban centres such as Raipur and Jaipur are emerging as new hotspots, where expanding built-up areas, limited green infrastructure, and insufficient adaptation planning amplify exposure. These trends indicating the urgent need for integrated modelling that couples high-resolution climate projections, UHI quantification, and socio - economic vulnerability assessments. Systematic inter - city comparisons, supported by ensemble-based NWP and machine learning frameworks, can provide probabilistic guidance to policymakers for designing urban heat action plans, thereby moving beyond isolated case studies to a nationally coherent adaptation strategy.

5. Conclusions

Numerical Weather Prediction (NWP) models have significantly enhanced the prediction of extreme weather events and the efficiency of early warning systems across the Indian region. The NWP system has contributed to a deeper understanding of atmospheric processes, integration of diverse datasets, and the development of impact-based forecasting, ultimately benefiting society at large. The advancements in predicting extreme weather events-including tropical cyclones, storm surges, thunderstorms, urban rainfall, and urban heatwaves-along with the future roadmap for further improvements, are summarized below.

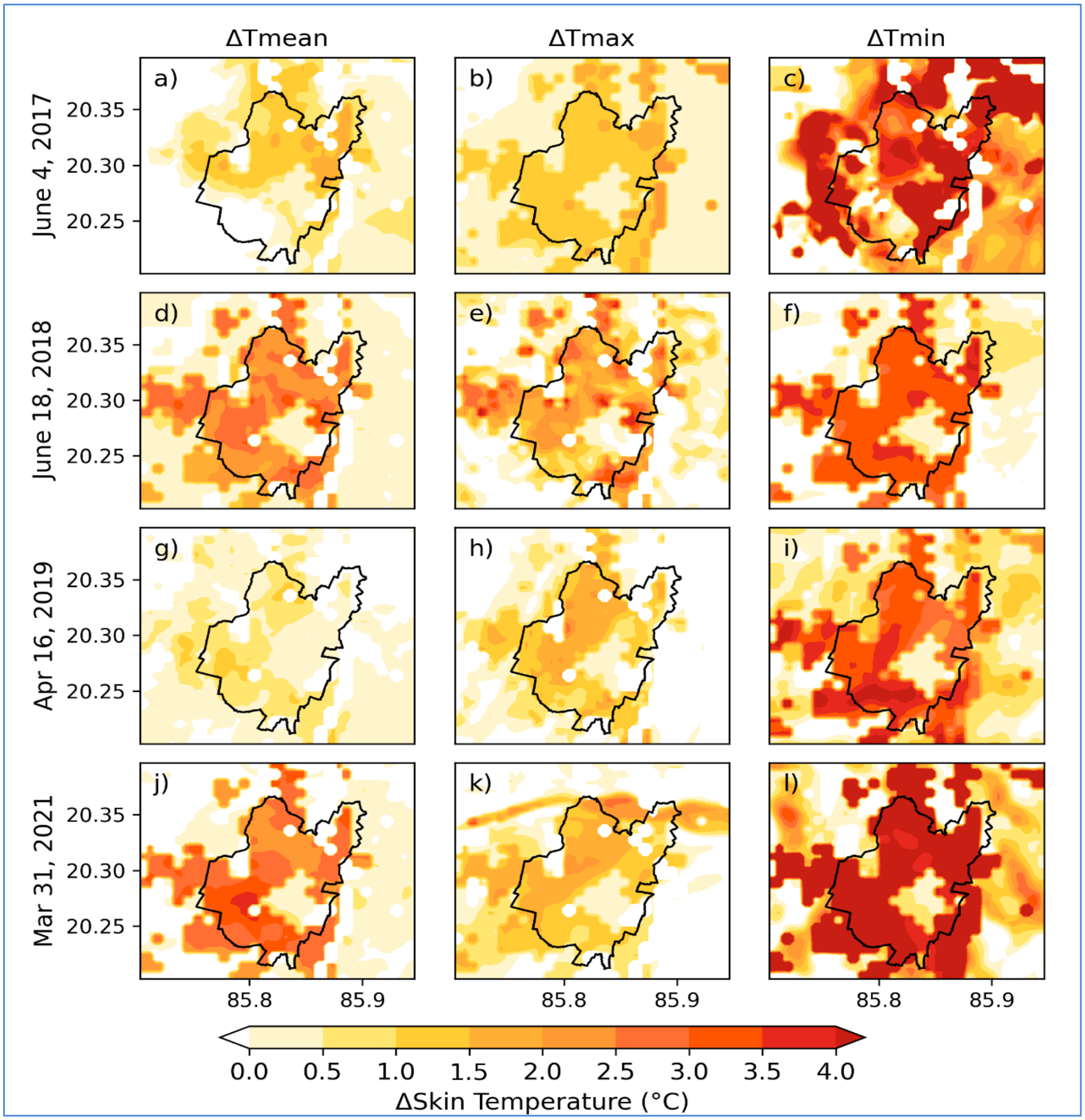
(*i*) The TC prediction system has achieved remarkable success, including zero casualties in recent years. This success is attributed to advancements in observational infrastructure and continual improvements in NWP models, particularly the implementation of coupled land-ocean-atmosphere systems.

(*ii*) The incorporation of non-conventional observational data, particularly Doppler Weather Radar (DWR) and satellite observations, into mesoscale modeling systems has further improved TC forecasting accuracy.

(*iii*) Significant improvements have been made in storm surge modeling by utilizing model-generated surface fields, as opposed to relying on synthetic surface winds generated using idealized TC vortices.

(*iv*) Development of Indian Ocean-Land-Atmosphere (IOLA) coupled mesoscale prediction system **is a** first-ever coupled modeling system explicitly focused to tackle "all-purpose" severe weather across multiple domains and scales over the Indian Monsoon region.

(*v*) The SAARC STORM initiative has played a vital role in enhancing the understanding of thunderstorm characteristics and improving their prediction. Through pilot studies, mesoscale modeling, and data assimilation, improved accuracy in thunderstorm forecasting has been achieved. However, lightning prediction remains a challenge. Ongoing efforts to improve lightning forecasts include the installation of a comprehensive sensor network, such as deployment of extensive lightning detection sensors. In addition, continuous monitoring via Karrevula *et al.,* 2024). A recent study by Boyaj *et al.,* (2023) conducted a series of



Figs. 16(a-l). Spatial distributions of skin temperature (°C) differences between the 1993 and 2019 LULC simulations over Bhubaneswar for the four heatwave events. The first (a–c), second (d–f), third (g–i) and fourth (j–l) rows represent the temperature difference for 4 June 2017, 18 June 2018, 16 April 2019 and 31 March 2021 heatwave cases, respectively. The first, second and third columns show the temperature differences for the day mean (average of 24 h), at 0900 UTC (daytime) and 0000 UTC (nighttime), respectively (Boyaj *et al*., 2024)

sensitivity experiments with radiation (RRTM, CAM, and RRTMG) and urban (NoUCM, Single-Layer UCM, and BEP) physics schemes at 500 m resolution using the WRF model for different lead times during various heatwave events. Their findings suggested that the WRF model effectively captured the spatial distribution and timing of HWs up to two days in advance, particularly when using the CAM radiation scheme in combination with the Single-Layer UCM over the Bhubaneswar urban region.

Another study by Karrevula *et al.* (2024) assessed the role of PBL schemes in predicting heatwave events over Bhubaneswar city using a very high-resolution (500 m horizontal resolution) WRF model. The analysis of the geostationary satellites (*e.g.*, INSAT-3D/3DR) are underway to improve nowcasting capabilities.

(*vi*) Recently, initiatives have been undertaken to enhance urban-scale rainfall and heat stress forecasts. Traditional

NWP models often lack the resolution to accurately represent urban meteorological processes. New developments include incorporation of urban parameterization schemes, integration of high-resolution urban morphology, building geometry, and street canyon effects into urban modeling systems. These enhancements enable realistic simulation of heat transfer between walls, streets, and rooftops, improving surface energy balance modeling. As a result, forecasts of heavy rainfall and heatwaves over urban regions have become more realistic.

(*vii*) Despite the substantial progress in NWP demonstrated in recent years, several outstanding challenges must be addressed to further improve predictive capability and societal resilience against high-impact weather events. The integration of artificial intelligence (AI) and machine learning (ML) into NWP systems represents a transformative opportunity. While physics-based models capture fundamental dynamical processes, they remain computationally expensive and prone to biases arising from imperfect parameterizations. AI/ML techniques, when embedded into the forecast pipeline, can address systematic errors, provide rapid post-processing, and exploit the deluge of satellite, radar, and in-situ observations for data-driven model augmentation (Reichstein *et al.*, 2019; Schultz *et al.*, 2021). Hybrid approaches that couple dynamical cores with AI-driven emulators are likely to accelerate forecast cycles without compromising physical fidelity, thereby improving early warning systems for hazards such as tropical cyclones and localized extreme rainfall (Rasp and Thuerey, 2021).

(*viii*) Advancing kilometre-scale coupled data assimilation remains a critical priority. Accurate prediction of convective systems, urban hydrometeorological extremes, and storm surges requires resolving interactions across atmosphere, ocean, and land interfaces at high resolution (Bauer *et al.*, 2015). With the launch of the ambitious Mission Mausam program by the Ministry of Earth Sciences (MoES), and the upcoming Indo-US collaborative satellite NISER, India's observational capabilities are expected to be significantly enhanced. However, the emerging challenge for the modeling community lies in effectively integrating these high-resolution datasets into a coupled land-ocean-atmosphere data assimilation system to provide initial value in the coupled model such as IOLA. Successes in such endeavour is crucial for enhanced accuracy track, intensity, and rapid intensification forecasts of cyclones, improve urban flood modelling under heavy rainfall, and better characterize land–atmosphere feedbacks driving heatwaves (Janjić *et al.*, 2018).

(*ix*) The implementation of ensemble-based uncertainty quantification is essential for providing probabilistic forecasts that are both scientifically robust and decision-relevant. Deterministic forecasts alone are insufficient for risk management, particularly in densely populated and vulnerable regions (Palmer, 2019). Ensemble prediction systems, when designed to account for model physics uncertainties, observational errors, and initial condition spread, can generate a range of plausible outcomes (Leutbecher and Palmer, 2008). The resulting probabilistic guidance enables more informed decision-making for disaster preparedness, infrastructure planning, and emergency response (Buizza, 2018). The challenge, however, lies in balancing ensemble size with computational feasibility, while developing frameworks that effectively communicate uncertainty to end users.

(*x*) Development of comprehensive decision support system based on GIS, data mining, various vulnerability indies (physical, social, economic, infrastructure etc) and NWP products, as guiding tool for the disaster managers at local scale will further enhance the capabilities of common people towards appropriate and timely action to face the vagaries of the extreme events.

Therefore, the forward-looking trajectory for weather and climate prediction lies in the synergistic integration of AI/ML methodologies, kilometre-scale coupled assimilation, and ensemble-based uncertainty quantification within the broader NWP framework. By anchoring these scientific challenges within national missions and research ecosystems, it will be possible to deliver high-resolution, impact-oriented, and probabilistic forecasts that directly benefit society. Such a holistic approach is not only essential for safeguarding populations against extreme weather but also for advancing the frontier of predictive sciences in the coming decades.

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