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A journey through time: the history of mesoscale severe weather monitoring and forecasting in India

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सार – मौसम की घटनाओं की भविष्यवाणी में सुधार करना हमेशा से ही मौसम विज्ञानियों के लिए एक महत्वपूर्ण शोध क्षेत्र और चुनौतीपूर्ण कार्य रहा है क्योंकि यह मानव जीवन, संपत्तियों और देश की अर्थव्यवस्था पर बड़ा प्रभाव डालता है। दुनिया भर के परिचालन और अनुसंधान केंद्र उष्णकटिबंधीय चक्रवातों और आंधी-तूफान की भविष्यवाणियों सहित गंभीर मौसम को आगे बढ़ाने में शामिल बहुस्तरीय अंतःक्रियाओं को बेहतर ढंग से समझने के लिए काम कर रहे हैं। वर्तमान समीक्षा लेख संख्यात्मक मौसम पूर्वानुमान (NWP) विधियों पर विशेष जोर देने के साथ अनुसंधान गतिविधियों पर केंद्रित है, जिसके कारण पिछले तीन दशकों के दौरान भारत में गंभीर मौसम की भविष्यवाणी में सुधार हुआ है। यह कार्य अवलोकन नेटवर्क और गंभीर मौसम की निगरानी बढ़ाने में भारत मौसम विज्ञान विभाग (IMD) के निरंतर प्रयासों पर भी प्रकाश डालता है। NWP मॉडल के विकास और इन मॉडलों द्वारा चरम घटनाओं की उत्पत्ति, गति और वर्षा के पूर्वानुमान में संबंधित प्रगति पर चर्चा की गई है।

ABSTRACT. Improving the prediction of weather events is always an important research area and challenging task for meteorologists since it can minimize the damage, adverse impact on human life, properties, and the country's economy. The operational and research centers around the globe have been working to better understand the multiscale interactions involved in advancing severe weather, including Tropical Cyclones and thunderstorm predictions. The present review article focuses on research activities with a specific emphasis on Numerical Weather Prediction (NWP) methods that led to improvements in severe weather prediction over India during the last three decades. This work also highlights the continuous efforts of the India Meteorological Department (IMD) in increasing the observational network and severe weather monitoring. The evolution of NWP models and associated advancements in genesis, movement, and precipitation forecasts of extreme events by these models are discussed.

Key words – Severe weather, numerical models, India

1. Introduction

Severe weather and associated heavy rainfall events have been attributed to large-scale floods in major cities, landslides, crop damages, and fatalities. The losses due to extreme rainfall and floods in India are considered to be \$3 billion per year, which is 10% of the global economic loss (Roxy *et al.*, 2017). Since the 1950s, the heavy rainfall activity (rainfall$\geq$ 100 mm/day) has increased by 10% per decade and the number of very heavy events (rainfall$\geq$ 150 mm/day) has more than doubled, indicating a large increase in disaster potential. The tropical and warm northern Indian Ocean, consisting of the Bay of Bengal and the Arabian Sea, is known for being a favorable environment for the formation of devastating tropical cyclones. Throughout history, a significant majority (over 75%) of global tropical cyclones that have resulted in 5,000 or more human casualties in the past 300 years have originated from the Bay of Bengal (Dube *et al.*, 2013). The occurrence of tropical cyclones is particularly high along the east and west coasts of India, and the vulnerability to such hazards has been examined on a district level by Mohapatra *et al.* (2012). Coastal regions in India, Bangladesh, Myanmar, Pakistan, Sri Lanka, and Oman are particularly vulnerable to the destructive impact of storm surge flooding. This phenomenon results in substantial loss of life, damages to coastal structures, and significant agricultural losses, leading to annual economic setbacks in these nations. One of the most devastating examples occurred in November 1970 when a severe cyclone struck Bangladesh (then East Pakistan), claiming approximately 300,000 lives. In November 1977, the Andhra Cyclone wreaked havoc on the eastern coast of India, resulting in the loss of around 10,000 lives. The Chittagong cyclone in April 1991 claimed the lives of 140,000 people in Bangladesh, and the severe cyclonic storm that hit the Odisha coast of India in October 1999 resulted in the deaths of over 15,000 people, along with significant property damage in the region. These catastrophic events, along with numerous other major natural disasters worldwide linked to tropical cyclones, are directly attributed to the impact of storm surges.

Thunderstorms are one of the deadliest natural hazards associated with heavy rainfall, thunder, gusty wind and lightning. These thunderstorms are very devastating in nature, causing destruction to property and loss of lives, particularly due to lightning that lead to ~350 casualties every year (IMD annual report, 2022). The violent weather conditions associated with thunderstorms are heavy rainfall, lightning, hail, gust winds, squall lines, and sometimes even tornados (Mohanty *et al.*, 2007; American Meteorological Society, 2022). The pre-monsoon season (March to May) in India is one of the global hotspots for thunderstorms (Sasanka *et al.*, 2023; Tyagi 2007; Zipser *et al.*, 2006). In the recent era, the frequency and intensity of these storms have varied rapidly with an increase in urban land (Sultana *et al.*, 2022; Nadimpalli *et al.*, 2023) posing a severe threat to mankind. The Indian subcontinent is one of the fastest-growing economies in the world. India’s economic development is intimately tied to the ability to predict and respond to heavy rainfall events associated with severe weather across the country.

2. Evolution of observation network for severe weather monitoring

Mesoscale severe weather events are typically known to cause a lot of damage in different temporal& spatial scales. In addition, their characteristics also evolve with varying paces in different spatial-temporal and spatial dimensions. Thereby making their monitoring and forecasting a big challenge. Monitoring severe mesoscale events in real-time at high temporal and spatial resolution provides beneficial inputs to the disaster response, making them more focused on the most affected regions. The monitoring platforms also support the nowcast activities with respect to severe weather events, considering the efficiency of the persistence method of forecasting in nowcast to a very short range apart from providing information regarding synoptic features. However, at present, Numerical weather prediction (NWP) is the best tool to capture the evolution and impact of these severe mesoscale weather events for better preparedness and mitigation measures in all spatial and temporal scales. These NWP models, in turn, are again dependent on the observational network for better initial conditions leading to improved numerical guidance.

IMD maintains a dense network of surface and upper air observatories all over the country to support monitoring, forecasting, and NWP activities. In addition, IMD also maintains a network of radars to detect & monitor storms, tropical cyclones, and different severe weather events along with ozone and radiation observatories. Prior to the formation of IMD in 1875, the British East India Company had 77 meteorological observatories whose number grew to 200 in 1900. IMD has progressively expanded its infrastructure for meteorological observations and has achieved significant scientific growth by using contemporary technology. IMD started automation of its surface observational network in the 1960s and installed about 100 Automatic Weather Stations in the 1980s along the country's coastal districts. Currently, IMD maintains more than 2000 AWS and Automatic Rain Guage stations. IMD also maintains a dense network of upper-air observatories, with 56 operational Radiosonde radio wind stations apart from 62 pilot balloon observatories, which have rapidly been transitioned to GPS-based observing platforms (IMD annual report, 2022).

To further support & improve the observational aspects, IMD has also made a lot of progress in remote sensing platforms. The first meteorological radar was commissioned by IMD in 1954 at Calcutta airport. The first cyclone detection radar was commissioned at Visakhapatnam in 1970. IMD currently operates and maintains a Doppler Weather Radar network consisting of a total of 37 DWRs (22 S-band, 02 Polarimetric C-band DWRs, and 13 X-band) all over India. In addition, IMD also utilizes the DWRs installed by ISRO at

Thiruvananthapuram (C-Band), Cherapunji (S-Band) and Sriharikota (C-Band). Work is also in progress for the installation of several C-Band radars over the Indian mainland and X-Band radars over the Himalayan regions and Northeastern parts of the country. With respect to the satellite observations in the beginning IMD was utilizing the satellite imageries provided by foreign satellites and a big breakthrough happened in the 1980s with the launch of INSAT-1A on 10th April, 1982. It was the first operational multi-purpose geostationary satellite followed by INSAT-1B in 1983, INSAT-1C in 1988, and INSAT-1D in 1990. The second generation of satellites carrying meteorological payload was INSAT-2A launched in 1992, INSAT-2B launched in 1993, and INSAT-2E in 1999. The resolution of these satellites was 2.75 km (Visible) and 11 km (Infrared) for the INSAT 1 series and 2 km (Visible) and 8 km (Infrared) for the INSAT 2 series. INSAT-2E also provided additional information on the Water vapor channel which was not available in its predecessors and also carried a charge-coupled device having a resolution of 1 km. At the beginning of the 21st century, Kalpana-1 was launched in 2002 followed by INSAT-3A in 2003, INSAT 3D in 2013, and INSAT 3DR in 2016. Currently, IMD uses INSAT 3D/3DR, Polar satellites, Oceansat, etc. for monitoring severe weather events like Tropical Cyclones, Local severe storms, Dust Storms, sea breeze fronts, mountain waves, etc. (IMD annual report, 2022). Further, various field experiments were conducted to understand the atmospheric processes such as BoBMEx, ARMEx, MonEx, MonBlEx, LaspEx etc. associated with the severe weather over NIO region. Eight significant field experiments have been conducted thus far concerning the Indian summer monsoon. Although these experiments had international participation and were initially driven by external motivations until 1980, India has since developed its own monsoon programs. As per Bhat and Narasimha (2007) and Turner *et al*. 2020, four monsoon experiments were conducted prior to 1980, including the International Indian Ocean Expedition (IIOE) from 1960 to 1965, the 1973 Indian Summer Monsoon Experiment (ISMEX), the Indo-Soviet monsoon experiment of 1977 (MONSOON77), and MONEX-79 performed in 1979. After 1980,there were experiments such as the Monsoon Trough Boundary Layer Experiment (MONTBLEX) in 1990, the Land Surface Processes Experiment (LASPEX) from 1997 to 1998, the Bay of Bengal Monsoon Experiment (BOBMEX) in 1999 (Bhat *et al.*, 2001), and the Arabian Sea Monsoon Experiment (ARMEX) that spanned 2002 to 2005. Furthermore, an international collaboration called 'Joint Air–Sea Monsoon Interaction Experiment' (JASMINE) took place in 1999 across the tropical Indian Ocean during both the pre-monsoon period (7–22 April, 1 May–8 June) and the ending phase of the monsoon (Webster *et al.*, 2022). The observational data collected during these expeditions have been utilized by various researchers to generate the high resolution analysis, and developing/upgrading the physical parameterisation suits in the NWP models (Krishnamuriand Subrahmanyam, 1982; Rao and Kumar, 1991; Bhat *et al.*, 2001; Das *et al.*, 2001 & 2003; Routray *et al.*, 2005).

It is also to be taken in to account that monitoring of events associated with convective events especially lightning. Atmospheric lightning is a type of static electrical discharge that occurs within a cloud (IC), between clouds (CC), or from a cloud to the ground (CG). Lightning is commonly linked with mesoscale convective systems and exhibits significant temporal and spatial variations. Therefore, it is advisable to investigate this phenomenon with greater spatial precision. CG lightning has been observed using ground-based optical cameras (Velde *et al.*, 2020) and electric field mills (Pawar and Kamra, 2004; Mkrtchyan, 2018). In India, Khandalgaonkar *et al.*, (2003) analyzed LIS data for a region ranging from 8° to 33° N in latitude and 73° to 86° E in longitude between 1998 and 2001. They observed that the highest occurrences of lightning were in the pre-monsoon season and the lowest in the post-monsoon season, with a noticeable peak in lightning activity around 10:00 UTC. In a recent study, Unnikrishnan *et al.*, (2021) utilized ground-based lightning data and LIS data to identify lightning hotspots across India. They observed a wide distribution in peak lightning occurrences and diurnal amplitude of approximately 15% in central and southwest India. Additionally, they found a significant increase in annual lightning occurrences over Southwestern India from 1998 to 2014. The National Remote Sensing Centre (NRSC) of the Indian Space Research Organization (ISRO) recently established the Lightning Detection Sensor Network (LDSN) over India. Taori *et al.*, (2021, 2022) utilized LDSN data to demonstrate that CG lightning occurrences peaked during August-September 2019-2020, with Odisha, Chhattisgarh, and West Bengal emerging as the lightning hotspots. They also compared the LDSN data with other networks and found correlations ranging from 0.82 to 0.96. Additionally, they compared the data with the World Wide Lightning Location Network (WWLLN) and found a significant correlation. Notably, the WWLLN data underestimated the number of lightning occurrences. This study focuses on CG lightning occurrence data from 2019 to 2021 across India, investigating the seasonal variability and diurnal variations over the six homogeneous monsoon regions for the first time.

3. Forecasting using NWP models:

NWP models are powerful tools for forecasting the atmosphere, but they have certain limitations *viz.*

initialization, resolution, parameterization and assimilation; that are important to consider. Bormann and Bauer, 2010 a&b argued that NWP models rely on accurate and comprehensive observational data for their initial conditions. Gaps in data or errors in assimilation can lead to inaccuracies in forecasts. Further, Skamarock and Klemp, 2008 reported NWP models are limited by their spatial and temporal resolution. Fine-scale weather features, such as thunderstorms and local wind patterns, may not be well-represented in coarser-resolution models. It is also to be remembered that sub-grid scale processes, like cloud microphysics and turbulence, require parameterization in NWP models. The accuracy of these schemes can impact the model's ability to simulate certain weather phenomena. High-resolution models demand significant computational power and resources. Limited computing capabilities can restrict the spatial and temporal resolution of NWP models (Laprise, 2008). Some of the weather systems, especially at local scales have limited predictability, and NWP models are sensitive to initial conditions. Predictability decreases with time, making long-range forecasts less reliable. Some processes, such as convection and boundary layer interactions, are complex and may not be fully represented in NWP models (Arakawa and Schubert, 1974). Improper specification of local topography or land use characteristics could be another reason for the poor performance of NWP models, particularly for regional/local scale weather conditions (Niyogi *et al.*, 2020; Priya *et al.*, 2023). Tyagi, (2007) studied the climatology of thunderstorms in India using 30 years (1951-1980) of in situ station data. Zipser *et al.*, (2006) examined severe thunderstorm climatology across the globe using the topical rainfall measurement mission (TRMM) data from 1998-2004. Sansanka *et al.*, (2023) updated the climatology based on 2001-2021 using GPM rainfall. All these studies have presented similar characteristics. The highest frequency is observed in the western foothills of the Himalayas (Jammu sub-division), the northeast part of India, and the west coast of Kerala, while the lowest frequency over Gujarat, Rajasthan, West Madhya Pradesh and north Maharashtra. However, the thunderstorms over East Madhya Pradesh, Chhattisgarh, Odisha, adjoining parts of Andhra Pradesh, West Bengal and adjoining Jharkhand experience higher rainfall than that of in other parts of India (Sasanka *et al.*, 2023).

It is observed that in most parts of India, the average thunderstorm duration lies between 1.5 h to 3 h. Longer duration (> 3 hours) thunderstorms are observed in North East India and the Western foothills of Himalaya (Jammu and Kashmir, Himachal Pradesh), with maximum duration (>4.5 hours) observed in eastern Assam and eastern Arunachal Pradesh. Fig. 1(c) illustrates the mean precipitation intensity of the detected thunderstorms. Highest intensity (>9 mm hour-1) thunderstorms are observed in the northeastern region (western and southern Assam, Meghalaya, Tripura, and Mizoram), northern West Bengal, and the southwestern coast of India (similar to Zisper *et al.*, 2006). Overall, high-intensity thunderstorms (5-9 mm hour-1) are observed over the eastern (West Bengal, Odisha, Bihar, Jharkhand) and southern (Andhra Pradesh, Tamil Nadu, Kerala, Karnataka) parts of India. On the contrary, the few thunderstorms observed over mid and western India (Madhya Pradesh, North Maharashtra, South Rajasthan, Gujrat) have very low-intensity precipitation (<3 mm hour-1). Fig. 1(d) exhibits the peak hours of pre-monsoon thunderstorms in India. It can be noticed that the majority of India experiences thunderstorms in the evening hours - between 16 IST (10:30 UTC) to 20 IST (14:30 UTC). However, the foothills of the Himalayas and NE regions receive thunderstorms from midnight (0 IST, 18.30 UTC) to early morning (8 IST, 02:30 UTC). Fig. 1(e) overlaps the climatology prepared using GPM rainfall (2001-2021) and that of Tyagi *et al.*, (2007). The GPM-derived thunderstorm climatology appears to be closely matched with the in-situ data driven climatology by Tyagi *et al.*, (2007).

Under the modernization of IMD, various Forecast Demonstration projects (FDPs) have been initiated especially for severe weather events such as tropical cyclones, heavy rainfall events, and severe thunderstorms. Besides these FDPs, the computational growth of the IMD/MoES has been increased tremendously, to facilitate running NWP models in real time at higher horizontal and vertical resolutions. Many global and regional models have been introduced in the IMD operational model suits after rigorous research to operation (R2O) efforts. Vaidya and Kulkarni, (2006) used the non-hydrostatic Advanced Regional Prediction System (ARPS) mesoscale model with a 40 km grid resolution and studied the impact of domain size and boundary conditions for the prediction of heavy rainfall over Mumbai. It was found that several features of the rainfall event were successfully captured but the model did not simulate the heavy rain amounts over Mumbai. By using the Weather Research Forecasting (WRF) model by Rama Rao *et al.*, (2007) with a 20 km horizontal grid resolution, it is found that the model was able to simulate approximately 250 mm of rain with a location error of 50 km north of Santacruz, Mumbai. Chang *et al.*, (2008) also used the WRF model and concluded that the simulation of heavy rains over Mumbai is highly sensitive to the model resolution (grid size), and the amount and location of the rainfall was modulated by land surface feedback which affected the formation and intensity of rain-producing convection cells.

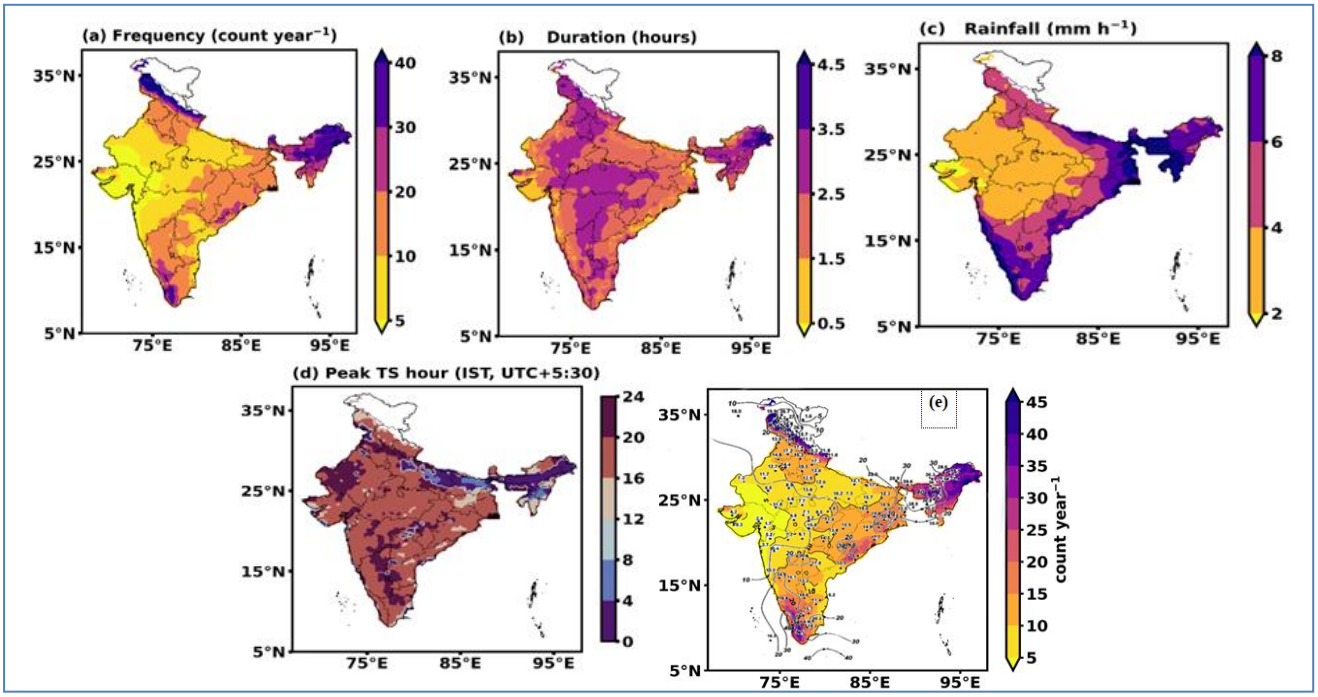


Fig. 1. Climatology of (a) an average number of detected thunderstorm events per year, (b) average thunderstorm duration in hours, (c) average rainfall (mm h-1), and (d) peak time of day of thunderstorm occurrences. Note that the time in (d) is shown in Indian Standard Time (IST, UTC+5.30 h). The climatology is prepared using the detected thunderstorms in the premonsoon season for 2001-2021. (e) The pre-monsoon thunderstorm frequency from Tyagi, (2007) overlaid the results from the current study. Shading indicates the climatology of the present study. Contours indicate the same from Tyagi (2007). (Source: Sasanka *et al.*, 2023)

Priya *et al.*, 2021 performed various domain size and resolution experiments to confirm the high resolution model performance in predicting the pre-monsoon severe convection. Lei *et al.*, (2008) used an explicit urban energy balance model to simulate Mumbai's urban heat island and TRMM-prescribed sea surface temperature (SST) fields in the Regional Atmospheric Modeling System (RAMS). Their results suggest that the heavy rains were a result of a stationary convergence zone caused by SST gradients just off Mumbai and the sensible-heat flux gradients due to the urban heating over Mumbai. The WRFv2 at were tested the Mumbai heavy rainfall event for different sensitivity simulations with different cumulus schemes for 26 July 2005 heavy rainfall at 3.6 km spatial resolution. It is found that with Grell-Devenyi (GD) scheme, the simulated precipitation was closest to the observed rainfall over Mumbai, while the Kain–Fritsch (KF) (Kain and Fritsch, 1990, 1993; Kain, 2004) and Betts–Miller–Janji´c (BMJ) (Janji´c, 1994, 2000) schemes considerably underestimated (by greater than 50%) the rainfall for this case (Kumar *et al.*, 2008). The WRF model with a 3-km resolution simulated the initiation of the isolated thunderstorms, the formation of the convective band, cloud cluster, and squall line in real-time, and the rainfall distribution was reasonably well, but the rainfall amount was less than the observation over Korea (Hong and Lee, 2009). By using a one-way nesting WRF model with horizontal resolutions of 5km and 1km for the outer and inner domains, the sensitivity analyses suggest that the data assimilated initial condition shows more effective results rather than the non-assimilated high-resolution initial condition for heavy rainfall over South Korea (Jee and Kim, 2017). Goswami *et al.*, (2012) showed that domain size is as important as grid spacing and initial conditions for heavy rainfall events. By using high-resolution NWP models such as MM5 and WRF over the Kelantan River basin, it is found that the models have performed quite satisfactory for low and moderate rainfall but not for heavy rainfall (Wardah *et al.*, 2011). Similar results have been identified over Gangetic plain by Chawla *et al.*, (2018).

The NWP models have become more helpful in predicting intense convective activity. Earlier studies demonstrated the value of horizontal resolution and convection treatment in the numerical models. Done *et al.*, (2004) compared convective forecast using 10 km with parameterized convection and a 4 km grid with explicit convection. Their analysis concluded that explicit forecasts predict an identifiable mesoscale convective system. Kain *et al.*, (2008) compared two sets of experiments, 4 km with 35 vertical levels and 2 km with 51 vertical levels with various physical parameterizations. They suggested that the 2 km forecast provides a more detailed representation of convective activity, although the difference in rainfall was negligible between 4 km and 2 km model runs. In the tropical region, Litta *et al.*, (2012) simulated four thunderstorm cases during the pre-monsoon season using a 3 km horizontal resolution with single domain configuration. Priya *et al.*, (2022) revealed an important aspect of resolution treatment in the numerical models. They presented that the thunderstorms predictions can be improved consistently using nested domain configuration than the single domain configuration. The former method downscales the large scale fields smoothly to the thunderstorm region than the single high resolution domain (Priya *et al.*, 2022). Later, Kiran Prasad *et al.*, (2013) revealed that the thunderstorm predictions can be improved from Doppler Weather Radar (DWR) observations. Another major development for improved thunderstorm prediction is the initialization of land surface conditions in the high resolution models (Osuri *et al.*, 2017). The recent studies also highlighted the necessity of accurate definition of land use land cover (LULC) classifications in the models (Priya *et al.*, 2023; Nadimpalli *et al.*, 2023). After considering the severity due to lightning, there is a demand for the forecast of lightning activity using specialized NWP models. In order to exploit the high resolution and independent lightning observations available, lightning parameterization (LPM) and lightning potential indices (FPIs) are being developed for very high resolution numerical models. Historically, lightning potential at a station location has been predicted by computing various static stability parameters derived from radiosonde soundings. (vanDelden 2003; Vuijovic *et al.*, 2015, Kunz, 2007). However, one of the main drawbacks of this methodology is the unrealistic underlying assumption that the atmospheric layers are homogeneous in space and time. In addition, beyond any specific nowcasting potential, the applicability of this method to longer range of prediction is limited due to the inability to take into account the changing synoptic conditions such as large scale flow and convergence zones or synoptic scale lift due to differential vorticity / temperature advection and diabatic heating. Mesoscale models of very high resolution are being used to parameterise highly complex explicit cloud electrification pathways and to generate lightning probability (see Dahl *et al.*, 2011, Lynn *et al.*, 2012, Fierro, 2013). On the other hand, NWP models can also generate diagnostics for total lightning, as a function of ice mass flux, in various convective (predictive and non-predictive) and climate environments (see Deierling, *et al.*, 2008, McCaul, 2009, Yair *et al.*, 2010). The key to the success of explicit electrification methods in convective scale models lies in the precision of the simulation of convective processes and the ability to accurately describe the microphysical characteristics of the clouds. A new parameter, 'Lifting Potential Index', was introduced in Yair *et al.*, (2010), as a threshold value for charge generation, as well as the separation between the cloud's main charging zone (from 0°C to -20°C). Further, Vani *et al.*,(2022) and Mohan *et al.*,(2022) have reported the use of cloud micro-physics and customization of hydro-meteorological distribution in NWP models to forecast the lightning counts over the Maharashtra region. Currently, all over the globe, two approaches are being followed for lightning forecasts in cloud-resolving models. (i) Lightning can either explicitly predicted using anelectrification physics mechanism. (ii) Lightning can be diagnosed via combinations of kinematic and/or microphysical proxy variables known to be well correlated with the occurrence of lightning. Banik *et al.*,(2021) have used the first approach to predict the lightning events over northeast India. They have used a specialized version of WRF for lightning called as Electric WRF (EWRF). The observed flash counts have been nudged into the high-resolution model for the prediction and the same methodology has been adopted for the PAN India level by IMD (NWP annual report 2022).

According to Pattanaik *et al.*, (2013), the heavy rainfall due to a monsoonal low pressure system over Odisha, Chhattisgarh, and Western Himalayas is well captured in the model with Kain-Fritch (KF) cumulus parameterization scheme compared to GD and Betts-Miller-Janjic (BMJ) scheme. BMJ scheme gives better results during the initial period of formation of the low-pressure system while the KF scheme is superior during the intensification of the system. By using the WRF model with three convection schemes, it is found that WRF could simulate low, moderate, and high rainfall reasonably with the BMJ scheme, heavy precipitation with the KF scheme, and low rainfall days alone with the GD scheme over India during summer monsoon season (Srinivas *et al.*, 2013). The spatial occurrence and intensity of heavy rainfall for Hurricane Katrina are better captured by the Hurricane Weather Research Forecasting (HWRF) model compared to WRF and NMM simulations (Rao and Tallapragada, (2011)). However, accurate evaluations of severe rainfall is an area of research. Das *et al.*, 2014 found that the performance evaluation of a high-resolution mesoscale model for heavy rainfall prediction with the standard verification skill scores (continuous and categorical) is not complete, and the representation of forecast error characteristics requires object-oriented verification methods e.g. Contiguous Rain Area (CRA) method (Das *et al.*, 2015; Osuri et al. 2020) and Method for Object-based Diagnostic Evaluation (MODE) technique (Sen Roy *et al.*, 2015). In a study by Das *et al.*, (2019), the comparative verification of 5 different cumulus parameterization schemes in predicting heavy rainfall of monsoon depressions brought out specified separation of total forecast error in terms of displacement, volume, and structure errors.

In this global warming era, extreme weather events (Tropical Cyclones, Monsoonal heavy rainfall, and Severe convection activities, etc.) forecast is a very challenging and demanding task for both operational and research meteorologists. Tropical Cyclones (TCs) over the North Indian Ocean (NIO) region have always caught the attention of all the people from various streams because of their destructive nature and can cause significant loss of lives and property when making landfall due to strong winds, torrential rainfall, and powerful storm surges. Compared to the other basins, the NIO basin, comprising the Bay of Bengal (BoB) and the Arabian Sea (AS) is small in area, but highly vulnerable to TCs and associated storm surges due to its conical shape, bathymetry, and low-lying areas. Of the 23 recorded deadliest storms, 20 are reported in the NIO region (Ramsay, 2017). So, TCs play a crucial role in the county's growth and the economy.

In recent years, various NWP models have been operating in real-time to provide the forecast for the TCs over India. Under the FDP-TC program of the India Meteorological Department, various research and academic institutes are working coherently to provide a realistic forecast over the NIO region. The success story of the TC prediction has also appeared in various international journals (Mohanty *et al.*, 2015 and Nadimpalli *et al.*, 2016. Osuri *et al.*, 2017a). Osuri *et al.*, (2013) performed several simulations to understand the impact of resolution on track prediction of TCs. A study from 100 forecast cases demonstrated that the model at 27-km resolution exhibited the mean track forecast errors varying from 113 to 375 km for a 12–72 h forecast (Osuri *et al.*, 2013). When the model is operated at higher resolution (18 km and 9 km) an improvement in mean track error by ~4%–10% and 8%–24%, respectively has been achieved for the NIO Basin. Interestingly, the high resolution (9 km) predictions could predict the recurving TCs more accurately (Osuri *et al.*, 2013). However, intensity prediction is still a difficult task even at high resolution and needs 1-3 km horizontal grid resolution. The very severe cyclonic storm (VSCS) 'Phailin (2013)' was the strongest cyclone that hit the eastern coast of the India, Odisha state since the super cyclone of 1999. But the same story of casualties was not repeated as that of 1999, where approximately 10,000 fatalities were reported. In the case of Phailin, a record 1 million people were evacuated across 18,000 villages in both Odisha and Andhra Pradesh states to coastal shelters following the improved operational forecast guidance that benefited from highly skillful and accurate numerical model guidance for the movement, intensity, rainfall, and storm surge (Mohanty *et al.*, 2015). The accurate guidance of the cyclone-specific model has been shown in Fig. 2.

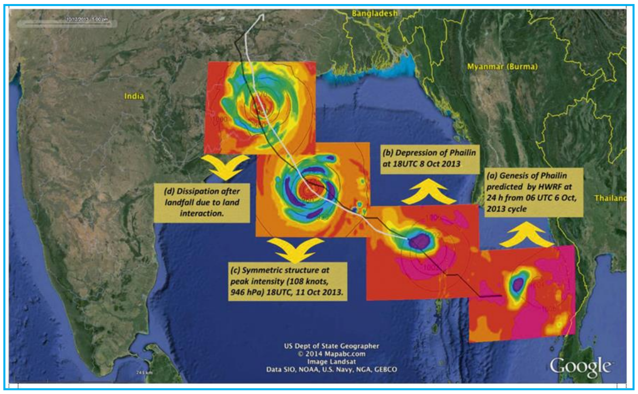


Fig. 2. HWRF forecast of the life cycle of TC Phailin starting from (a) genesis at 0600 UTC 7 Oct 2013, (b) formation of depression on 8 Oct 2013, (c) intensification, and (d) dissipation. Shading depicts the model-simulated microwave satellite imagery at the top of the atmosphere, and contours represent minimum sea level pressure (hPa). The black line represents the best track from JTWC, and the white line is the HWRF predicted track from 0000 UTC 10 Oct 2013. (Source: Mohanty *et al.*, 2015)

Subsequently, Osuri *et al.*, (2017a) showed the credibility of a high-resolution nest (3 km nest) over the coarser (9 km nest) analyzing the Phailin case. The coarser and finer nest experiments have predicted the Phailin movement differently when approaching the land (Osuri *et al.*, 2017a). The coarser resolution nest tracks the Phailin from north-westward to west-northwestward when approaching land and made landfall toward the north Andhra Pradesh coast (near 18° N). The high-resolution nest shows landfall over Chilka (south Odisha coast), north of the observed location (Gopalpur). Similar results were seen in subsequent forecast cycles also. Refer to Fig. 3 obtained from Osuri *et al.*, (2017a). Diagnostic analysis reveals that the two-way interactive high-resolution nest could be able to predict realistically the deep-layer steering and location of upper-level anticyclonic circulations (Osuri *et al.*, 2017a). The same success story was repeated in the case of VSCS Hudhud (2014) which hit the coastal megacity Visakhapatnam (Nadimpalli *et al.*, 2016) and VSCS Fani (2019; Mohanty *et al.*, 2020) that struck Odisha's triplet cities (Cuttack, Bhubaneswar, and Puri). This success is mainly due to the immense R&D efforts in improving predictions of TCs using the cyclone-specific mesoscale modeling system HWRF (Osuri *et al.*, 2017a; Nadimpalli *et al.*, 2020a). Further, the sudden change in movements is investigated, and the role of steering currents along with vortex scale features is explained by Bhattacharya *et al.*, (2015), Osuri *et al.*, (2017a); and Nadimpalli *et al.*, (2020a). In addition, the role of vortex initialization in NWP models was also highlighted by Busireddy *et al.*, 2019 and Nadimpalli *et al.*, 2021. Further, sensitivity experiments proved that the cloud-resolving grid spacing (~3 km) produces better TC sizes than the 6 km resolution (Nekkali *et al.*, 2022 a & b).

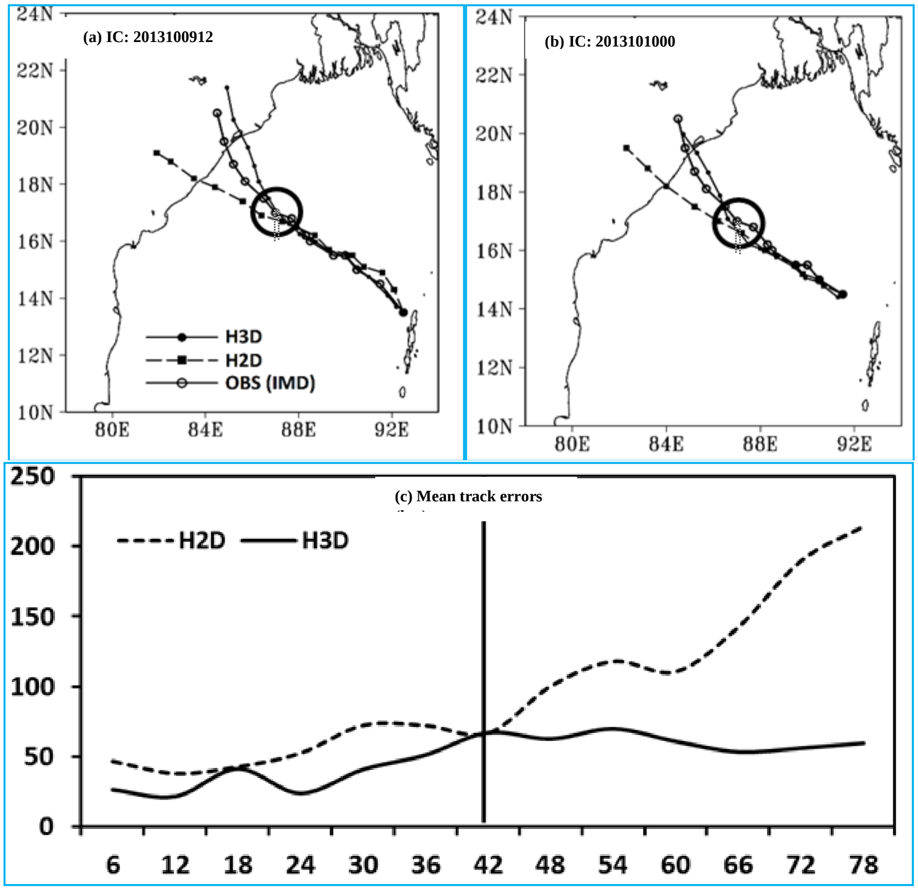


Fig. 3. Predicted tracks from the H2D and H3D model versions initial condition at 12 UTC on 09 October 2013 along with the IMD observed the best track. (b) Same as (a) but for initial conditions at 00 UTC on 10 October 2013. (c) Mean track forecast errors (km) of six runs from both model versions. (Source: Osuri *et al.*, 2017a)

A recent study by Nekkali *et al.*, (2022) demonstrated that TC size is more sensitive to MP schemes. The simple-ice (WSM3) scheme produced smaller and the warm-rain (Kessler) schemes produced larger R34. It is known that the TC size is an important factor in estimating storm surge and coastal evacuation during TC landfall. It is also very important to understand the model biases of torrential rainfall associated with the TCs. Osuri *et al.*, (2020) reported the capability of ARW model in the prediction of tropical cyclone (TC) rainfall and associated uncertainties over the NIO region by considering the large number of TC cases. The model performance in estimating the TC rainfall characteristics on the basis of forecast length, storm intensity, and also with respect to the landfall day is evaluated (Fig. 4). It is also evident that the associated storm surges can cause more casualties when compared to the direct impact of TCs. So, the high population density along the coastal stretch demands a dedicated operational storm surge warning system to predict and evaluate risk due to approaching storms and for the issuance of guidance to the coastal community. In India, the study of numerical storm surge prediction was pioneered by Das (1972). Subsequently, several workers attempted the prediction of storm surges in the Bay of Bengal (Das *et al.*, 1974; Ghosh, 1977; Johns *et al.*, 1981; Murty and Henry, 1983; Dube *et al.*, 1985).

Dube *et al.*, (1994), Dube and Gaur (1995), and Chittibabu *et al.*, (2000) developed a real-time storm surge prediction system for the coastal regions of India. Real-time storm surge prediction systems have also been developed for Bangladesh, Myanmar, Pakistan, Sri Lanka, and Oman (Dube *et al.*, 2004; Chittibabu *et al.*, 2002). The forecasting system created at IIT-D relies on vertically integrated numerical storm surge models previously developed by the group (Johns *et al.*, 1981, 1982; Dube *et al.*, 1985a, b). This model can be executed within a few minutes on a personal computer in an operational office setting. The system is navigated through a terminal menu, producing output in the form of two-dimensional and three-dimensional representations of peak sea surface elevations. A notable aspect of this storm

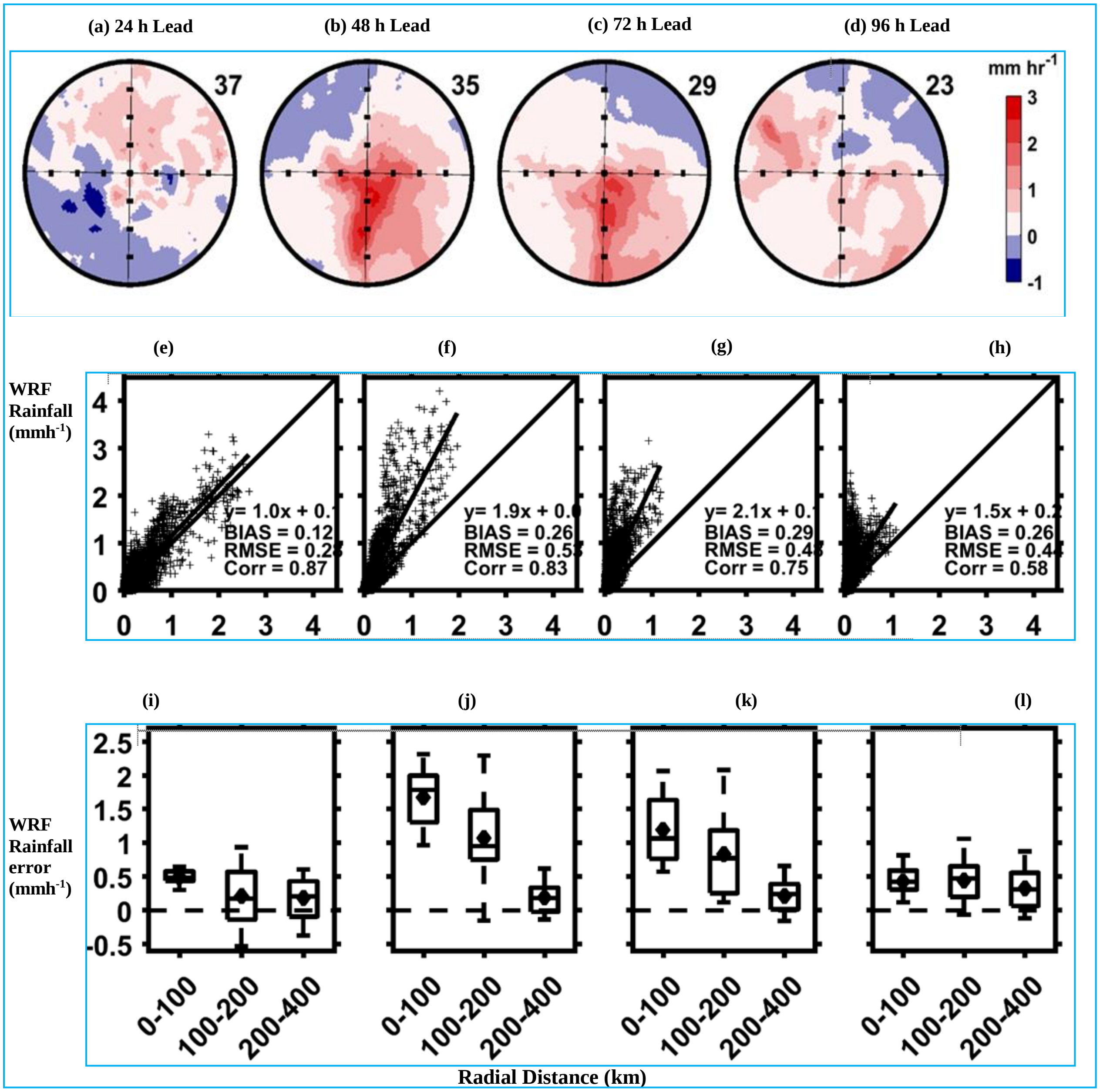
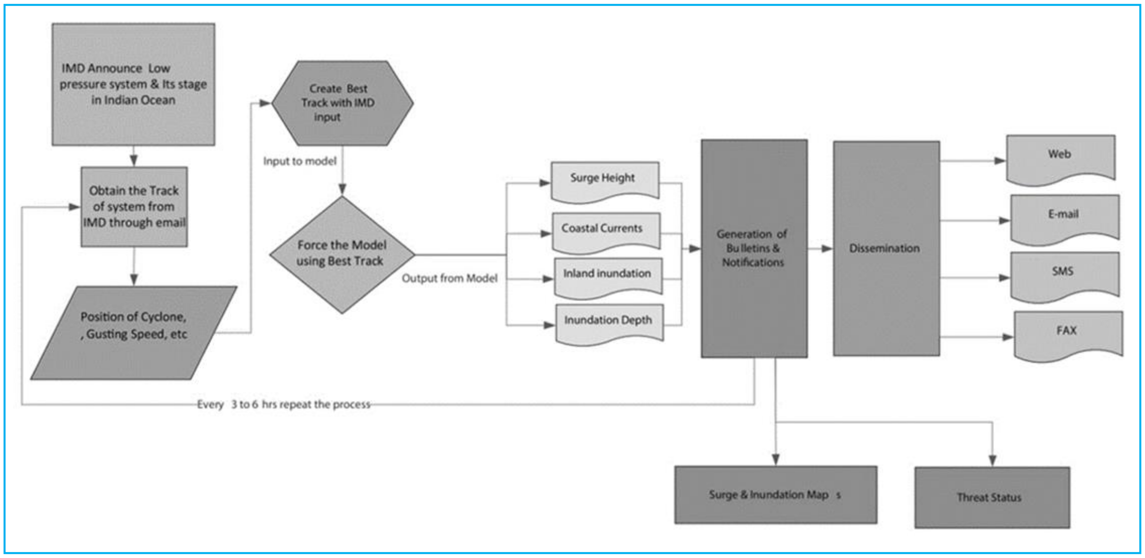


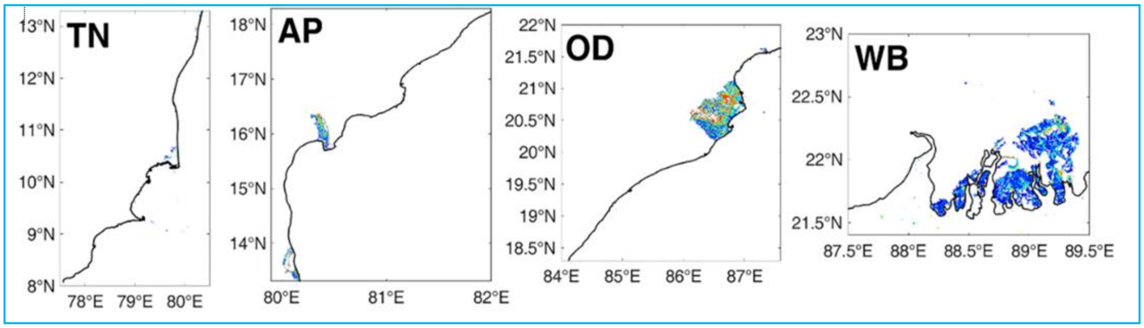
Fig. 4. Spatial distribution of 24 h accumulated model-rainfall error (mm h^{-1}) up to 400 km storm radius against TRMM rainfall valid for the landfall day at (a) 24 h lead (b) 48 h lead (c) 72 h lead and (d) 96 h lead. (e-f) are same as (a-d) but the statistical analysis of the rainfall. The ARW rainfall error (mm h^{-1}) in different annuli of 0-100 km, 100-200 km and 200-400 km for (i) 24 h lead (j) 48 h lead (k) 72 h lead and (l) 96 h lead. Each tick around the storm center and numbers in top right corner in (a-d) denotes the 100 km radius and no. of cases. Note that direction of storm movement is towards the positive y-axis in (a-d). (Source: Osuri *et al.*, 2020)

surge prediction system is its capability to explore multiple forecast scenarios in real-time, allowing for dynamic and adaptable forecasting based on changing conditions. Due to the well-established sensitivity of storm surge evolution near the coast to factors such as coastal geometry and offshore bathymetry at the cyclone's landfall location, it is crucial for operational models to incorporate these elements with utmost precision. Therefore, there is a recognized need for operational centers to utilize high-resolution, location-specific models in addition to large-scale storm surge prediction models for the accurate forecasting of surges. In line with this perspective, the authors mentioned above (Rao *et al.*, 1997; Chittibabu *et al.*, 2000; Dube *et al.*, 2000b, c) have developed location-specific, high-resolution models tailored for the coasts of Andhra, Orissa, Tamil Nadu, and

(a) Storm Surge Warning SOP Flowchart



(b) **State wise coastal inundation maps using historic tracks**



State wise coastal inundation maps using synthetic tracks

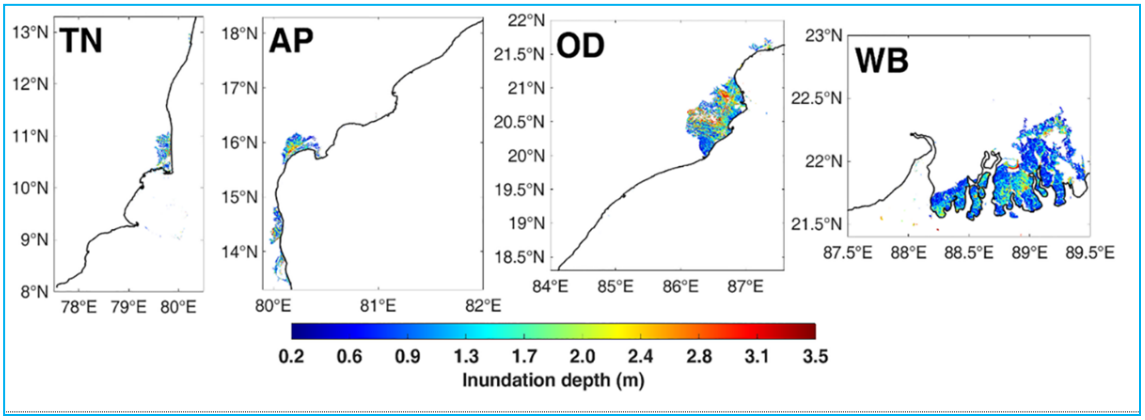


Fig. 5. (a) Standard operating procedure of the storm surge warning system (Source: Murty *et al*. 2017). (b)State-wise inland inundation due to storm surge using historic and 100-year projected cyclone tracks (Source: Murty *and Kolukula*., 2023).

Gujarat in India, as well as for Bangladesh, Myanmar, Pakistan, Sri Lanka, and Oman. These models follow a similar approach to that of Dube *et al*., (1994). The modeling studies mentioned earlier did not incorporate the assessment of coastal inundation resulting from storm surges. In the 2000s, a series of researchers (Murty *et al*., 2014; Murty *et al*., 2017; Murty *et al*., 2020; Murty *and Kolukula*., 2023) introduced the Advanced Circulation

(ADCIRC) model, a finite element-based approach, to compute storm surges and the associated inland inundation. These studies underscored the significance of integrating a coastal inundation algorithm into storm surge models.An in-depth examination of coastal inundation caused by storm surges along the east coast of India was conducted by Murty & Siva in 2020 using the ADCIRC model. The Indian National Centre for Ocean Information Services (INCOIS) team of scientists in collaboration with India meteorological Department (IMD) team developed an end-to-end operational storm surge warning system utilizing ADCIRC. The flow chart explaining the standard operating procedure of the said warning system is given in Fig. 5(a). For a comprehensive understanding of this warning system, refer to the detailed description provided by Murty *et al.* in (2017).

3.1. *Coupled models*

Tropical cyclones (TCs), also known as hurricanes or typhoons in different parts of the world, are driven by a combination of atmospheric and oceanic processes at different spatio-temporal time scales. Since the 1960s and 70s numerical models of the atmosphere have been used for understanding the behavior of TCs (e.g., Ooyama, 1969). Nevertheless, ocean atmosphere coupled models are essential for tropical cyclone forecasting because it allows accurate simulation and prediction of the behavior of these complex and highly dynamic ocean and atmosphere interactions during TC’s. Tropical cyclones derive their energy from the warm ocean waters. As the cyclone moves over the ocean, it draws heat and moisture from the sea surface. This interaction between the atmosphere and ocean is critical in determining the cyclone's intensity and track. Coupled models allow for the simultaneous simulation of the atmosphere and ocean, capturing these complex interactions (Emanuel, K., 1986). Further, feedback during TC’s can modify the ocean's surface temperature through churning and upwelling, affecting the cyclone's intensity. Coupled models can account for these feedback mechanisms and provide more accurate predictions of how a cyclone will evolve (Shay, L. K., & Brewster, J. K. (2010).

Besides the above, TC's often bring heavy rainfall, leading to flooding. Accurate forecasts of rains and locations are crucial for disaster preparedness and response (Houze Jr, R. A. (2014)). Coupled models can better simulate the complex processes governing rainfall associated with cyclones. A tropical cyclone's track depends on the atmosphere's steering winds and the cyclone's response to these winds. Coupled models provide a more realistic representation of sea surface temperatures, which is critical in fueling tropical cyclones. Accurate SSTs are essential for predicting the intensity and track of storms (Bender, M. A., and Ginis, I. (2000)). Coupled models consider air-sea heat, moisture, and momentum fluxes, allowing for a more accurate representation of the atmospheric response to oceanic conditions and vice versa. This is crucial for cyclone prediction.

The Hurricane Weather Research Forecasting (HWRF) system was developed jointly by the NCEP's Environmental Modelling Center (EMC) and other NOAA labs with the University of Rhode Island. HWRF can address the intensity, structure, and rainfall forecast problems. The NCEP has used HWRF for its operational forecasts since 2007. Under the MoES NOAA collaboration program, the HWRF modeling system with a double nesting option has been functional at IMD since 2011 to guide tropical cyclone track and intensity forecasts(Das *et al.*, 2021). Later, IMD implemented the triple nested version of the model with its improved physics schemes in 2014. In 2018, IMD started using the HWRF model coupled with the Princeton Ocean Model (POM), which provided climatological SST feedback to HWRF (Srivastava *et al.*, 2021). After collaborative efforts and experiments by the joint team of IMD and INCOIS (Indian National Centre for Ocean Information Services), the HWRF model coupled with HYCOM was made operational at IMD in 2019 with the first successful simulation of TC Fani (Joseph *et al.*, 2021). Mohanty *et al.*, 2022 have reported the positive impact of ocean coupling in predicting the rapid intensification of Ockhi well in advance. Intensity forecasts, both in terms of MSLP and maximum sustained wind at 10 m with respect to the forecast hours are provided in Fig. 6 (a & b). The observed intensity is provided along with the coupled and uncoupled simulations. There is a significant improvement in the intensity forecast in the case of coupled as compared to uncoupled. Further diagnostic analysis (Fig. 6c) also confirmed the positive role of ocean coupling could produce the realistic flux exchanges for the better prediction and understanding of TC intensity.

HWRF-HYCOM*:* With all these above-mentioned TC prediction accomplishments, the accurate intensity (pressure drop at the storm center and maximum sustained wind speed) prediction, however, could not be achieved over this basin (Srivasatv*et al.*, 2021, Mohanty *et al.*, 2022). Accurate intensity prediction is a vital aspect of the advanced forecast as the disaster mitigation strategies and precautionary action plans are highly dependent on it. The lag in intensity prediction might be due to not including ocean impact while predicting the TCs. To investigate the ocean impact on TC track and intensity prediction, real-time sea surface temperature (SST) is updated daily in the stand-alone atmospheric model (Mohanty *et al.*, 2019;

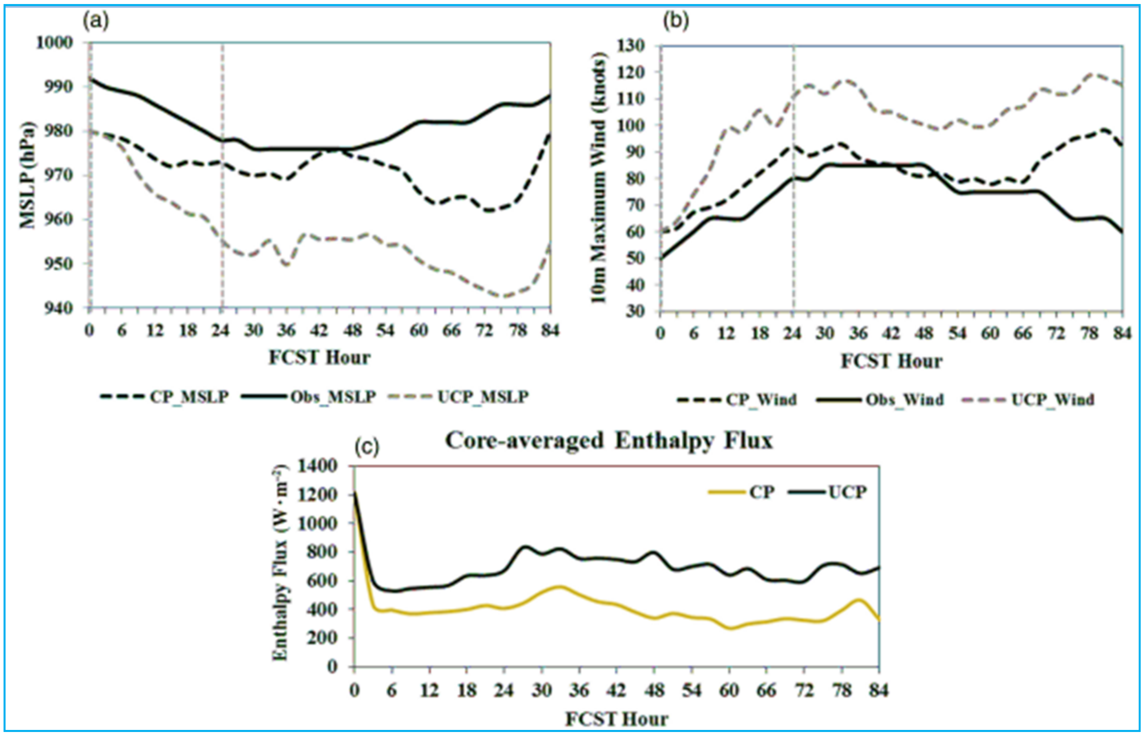


Fig. 6. Intensity evolution in terms of (a) mean sea level pressure (MSLP) and (b) maximum wind speed at 10 m. The vertical dashed lines show the period of rapid intensification (RI). (c) Time evolution of core averaged (averaged over the radius of maximum wind) enthalpy flux for coupled (CP) and uncoupled (UCP). FCST, forecast time (Source: Mohanty *et al*. 2022)

Nadimpalli *et al.*, 2023). This shows there is a significant improvement in the intensity prediction considering the ocean impact on the TCs, which demanded TC prediction with high-resolution coupled ocean-atmosphere modeling systems. TCs; Okchi, Pethei, and Fani were predicted with the ocean-atmosphere coupled modeling system and hence developed and produced remarkably improved intensity forecasts. More statistical analysis with a greater sample size is required to develop confidence in the coupled ocean-atmosphere modeling system.

Though these advanced regional models can predict storms, there is still a question about the model credibility in terms of accuracy, especially in capturing the sudden genesis, movement, and intensification rates. Hence, various data assimilation techniques/methodologies have been developed to improve the initial state of the atmosphere in numerical models.

4. Conventional and non-conventional atmospheric data assimilation

The history of data assimilation is a remarkable journey along with the development of science and technology. It covers more than a century and is characterized by important turning points in both our knowledge of the atmosphere and our capacity to use observational data to enhance weather forecasting. The practice of subjective analysis first emerged in the 19th century. The subjective analysis was a time-consuming operation where the initial values for the grids were established by arbitrarily drawing meteorological charts and interpolating between isolines. However, the method was subjective, in which the local observations and experience of the meteorologist were integrated to generate a weather map (Blayo *et al.*, 2011).

Lewis F. Richardson made the first attempt to predict the weather numerically in 1922 (Richardson, 1922), since there were no digital computers during the period, he created it by hand. Unfortunately, his weather prediction failed dramatically due to the rise of atmospheric pressure to about 145 hPa within a 6-hour period. His trial was unsuccessful because the in-situ pressure observations had not been effectively assimilated, resulting in an unbalanced initial state for the NWP model (Blayo *et al.*, 2011). Nevertheless, Lynch and Huang (1992) demonstrated that Richardson's prediction might have come true if the initial condition had been properly smoothed. Thus, his failure may be attributed to a weakness in data assimilation, and still his broad outlook on weather forecasting is employed today.

4.1. *Assimilation of conventional observations*

Conventional observation data assimilation (DA) is a fundamental part of NWP models that involves incorporating the traditional ground-based meteorological observations into the models to enhance the forecast skill of numerical models. These conventional observations measured different atmospheric parameters from surface weather stations, weather balloons (RS/RW), ships, buoys, and aircraft. The quality control procedure is necessary to identify and correct errors in the conventional observations before assimilation. This step is necessary to ensure the accuracy of the data. In general, the observational data are transformed into a format compatible with the DA system for assimilation. This step regularly involves spatial and temporal interpolation to fit the grid and time intervals of the NWP model. In the past, numerous studies reported that the assimilation of the conventional observations collected from Global Telecommunication System (GTS) or special field experiments through various data assimilation techniques on simulation of extreme weather events over Indian monsoon regime have considerably improved the analyses and enhanced the forecast skill of the NWP models (Das *et al.*, 2003; Das Gupta *et al.*, 2003; Vaidya *et al.*, 2003; Mukhopadhyay *et al.*, 2004; Hatwar *et al.*, 2005; Routray *et al.*, 2005 & 2010a; Xavier *et al.*, 2006; Mohanty *et al.*, 2012; etc.).

4.2. *Assimilation of non-conventional observations*

Conventional observations are very limited over the region and assimilation of such a limited amount of observations is ill-posed into the DA algorithm. Satellites provide an affluence of information regarding the earth's atmosphere, land surface, and oceans, and utilizing these observations in the NWP model through DA considerably helps to generate more accurate initial conditions for weather forecasts. Satellite observations are not only assimilated into the NWP models but also extend our capability to monitor and understand complex atmospheric weather phenomena, including severe weather events, tropical storms, climate patterns, and many more. Therefore, satellite-based DA is crucial for global and regional weather prediction, environmental monitoring, and climate research. In recent years, the assimilation of satellite data into the NWP models through various assimilation techniques has been adopted and it has continued to progress in many directions with the substantial increase in the availability of various satellite instruments. The R&D community active in this field is much higher in size than it was in the early years. Eyre *et al.*, (2019 and 2022) nicely reviewed the advancement of relevant satellite remote sensing technologies as well as methods for assimilation of satellite observations obtained from different instruments into the NWP models. The cited studies also provide the impact of these observations on the forecast skill of the model. In recent years, the assimilation of satellite observations in the operational centers of India considerably increased and has a positive impact on the model's forecast (Bohra *et al.*, 1998; Prasad et. 1999, 2021; Das Gupta and Rani, 2013; Kumar *et al*., 2018; *etc*). Also, recently several Observing System Experiments (OSEs) or called Data Denial Experiments (DDEs) experiments were conducted for the assimilation of satellite observations into NWP models. The OSEs results clearly suggested that the assimilation of satellite observations is showing the natural or favorable impact on forecast quality on simulation of weather phenomena over the Indian region (Rajan *et al.*, 2002; Singh and Pal 2003; Sandeep *et al.*, 2006; Xavier *et al.*, 2008; Osuri *et al.*, 2012; Routray *et al.*, 2016; Johny *et al.*, 2019; etc). Similarly, continues assimilation with a 3-hr update of Doppler radar radial velocity in three-dimensional variational data assimilation (3DVAR) models show the improvement of the prediction of the rainband movement and intensity change; thus increasing the skill for the short-range heavy rainfall forecast (Xiao *et al.*, 2004). Assimilation of global and regional background error statistics (BES) in the WRF model for the simulation of heavy rainfall events over Karnataka shows that the regional BES performed better compared to the global BES (Rakesh and Kantharao, 2017). Assimilation of cloud signal and cloud-precipitation distribution from satellite-based microwave remotes sensing in Coupled Atmosphere and Land data assimilation system with WRF model (CALDAS-WRF) over Japan improves prediction of rainfall intensity and also the precipitation duration (Seto *et al.*, 2016). Doppler weather radar (DWR) observation is now-a-days an important data source for mesoscale and microscale weather analysis and forecasting. DWR has the capability of observing, at high spatial and temporal resolution, the internal structure of storm systems from remote locations. Early work on DWR analysis mainly focused on two aspects i.e. rainfall analysis using radar reflectivity via Z-R relation (Fujiyoshi *et al.*, 1990) and the synthesis of two independent Doppler velocities (Ray *et al.*, 1980). There are several technical and scientific challenges in DWR data assimilation such as highly dense temporal and spatial data as compared to the analysis resolution; quality control of DWR data and assigned error variance of the DWR data. Although there are challenges, radar data assimilation in the NWP models could be very promising for the Indian region. The inclusion of DWR data assimilation has the potential to increase the accuracy of mesoscale analysis and numerical weather prediction. Earlier studies (Das *et al.*, 2006; Abhilash *et al.*, 2007; Srivastava *et al.*, 2010) assimilated the derived wind fields from DWR radial wind in the regional models for simulation of convective rainfall events over India. Routray *et al.*, 2010b first time assimilated direct observations obtained from Indian

DWR radial velocity and reflectivity in a mesoscale model on simulation of monsoon depressions through the WRF-3DVAR assimilation system. A similar study was extended by Osuri *et al.*, 2015 by utilizing the DWR observations on the prediction of land-falling tropical cyclones. One of the first-of-its-kind studies was to assimilate the DWR-derived rain rates into the high-resolution regional NCUM-R forecast model through latent heat nudging and has a positive impact on simulations of convective rainfall events over India (Routray *et al.*, 2021). Currently, the Indian multi-DWR radial velocity and reflectivity observations have been operationalized at National Centre for Medium-Range Weather Forecasting (NCMRWF) in the high-resolution UK Met office (NCUM-R)-4DVAR analysis system, since 2019 (Dutta *et al.*, 2019 & 2022). Further many researchers showed the importance of various satellite basedDA in regional models to predict the extreme convection. Another recent study by Nadimpalli *et al.*, (2020b) has shown the credibility of INSAT 3D/3DR sounder radiance assimilation through the GSI system of HWRF in predicting the Track, intensity, and structure of the VSCS Titli (2018) over the Bay of Bengal. The study demonstrates that the INSAT 3D/3DR experiments show the increased capability of the HWRF to reproduce the enhanced initial vortex, the evolution of TC vertical structures, and torrential rainfall associated with the storm. The mean intensity error (in terms of mean sea level pressure and 10 m wind speed) is presented in Fig. 7 and the error is minimal for longer forecast hours from INSAT3D/3DR experiment (adopted from Nadimpalli et al. 2020b). The INSAT3D/3DR run is efficacious in providing intensity forecast guidance well in advance (3-4 days ahead). The mean intensity error was reduced by 30%–47% (14%- 25%) in the INSAT 3D/3DR (GTS) runs over the CNTL runs. The results indicate that the assimilation of observation has a positive impact on the prediction of the storm track, intensity, thermodynamic structures, and rainfall. In Particular, INSAT 3D/3DR sounder radiance data assimilation along with GTS data exhibited better performance.

Recently, IMD has operationalized two mesoscale severe forecasting models High Resolution Rapid Refresh and Electric-WRF to provide guidance for severe weather forecasting in nowcast to short-range forecasting. The IMD High-Resolution Rapid Refresh (IMD-HRRR) Modeling system was implemented in 2021, in collaboration with Satellite Application Satellite ISRO. The IMD-HRRR system (based on WRF-ARW) is a real-time 2-km spatial resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model (Srivastava *et al.*, 2022). The model is updated every hour by assimilating the radar wind (radial), radar reflectivity, and surface observations (prepper) data. The forecast for 12 hours of lead time is made available to the forecasters at every 2-hour interval.Electric WRF (E-WRF) is a 3 km mesoscale modeling system having a dedicated Bulk Lightning module to calculate the parameters like the electric field of the cloud based on which the lightning flash density product has been generated. The interaction among the hydrometeors in the presence of water vapor and the various processes like rimming accretion rate etc incorporated in this model. This model assimilates lightning data through nudging and provides the next 24 to 36-hour forecasts. However, non-realistic representation of the complex and heterogeneous terrain characteristics such as soil moisture & soil temperature over the sub-continent also contributes to error growth in the numerical prediction models. Therefore, land surface data assimilation techniques have also been introduced in recent years in the regional models of IMD.

4.3. *Land surface assimilation*

The Indian region is characterized by diverse land surface conditions due to its complex topography, soil and vegetation, and rainfall distribution. The heterogeneity in surface conditions favors the initiation of convective storms and influences various weather events such as thunderstorms, monsoons, heavy rain events, and tropical cyclones. Soil moisture is one of the key parameters that control the surface energy and water balance. Land surface evaporation allows the transport of surface water from the land surface to the atmosphere and part of which converts into clouds and returns to the surface by rainfall. For such coupling, the Indian region has been identified as one of the soil moisture and rainfall coupling hotspots in the world (Koster *et al.*, 2004). There have been a number of studies demonstrating the importance of land surface processes on weather and climate systems in India (Osuri *et al.*, 2017b, 2020; Unnikrishnan *et al.*, 2017; Nayak *et al.*, 2018; Ankur *et al.*, 2021). Unnikrishnan *et al.*, 2017 examined the role of land-atmosphere coupling strength in the South Asian monsoon region and found that soil moisture makes a significant contribution to monsoon rainfall variability and is strongly coupled to the sensible heat flux over the Indian monsoon region. Baisya*et al.*, (2017) found positive S-P feedback processes associated with Indian monsoon depression through control of evapotranspiration and moisture flux convergence. Paul *et al.*, (2016) demonstrated that the weakening of Indian summer monsoon rainfall due to land use land cover changes through a decrease in evapotranspiration and subsequent decrease in the recycled component of precipitation. The LULC changes and feedback should be an integral component of short, medium, and long-range predictions over the IMR (Niyogi *et al.*, 2018). Singh *et al.*, (2016) found that the significant non-stationarity in ISMR extremes in urbanizing/developing urban areas

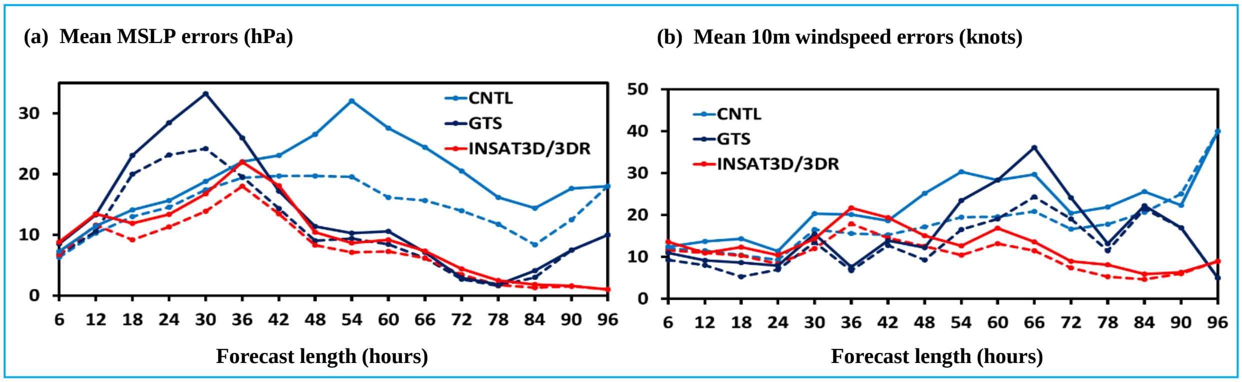


Fig. 7. (a) Mean Absolute Error (solid line) and RMSE (dashed line) of MSLP from all the 7 cases of CNTL, GTS and INSAT3D/3DR experiments calculated against IMD best estimations. (b) same as (c) but for 10m wind speed. (Source: Nadimpalli *et al*. 2020b)

(transitioning from rural to urban), compared to completely urbanized or rural areas. Devanand *et al.*, (2018) demonstrated that improved representation of land characteristics in a regional coupled atmosphericland model improves not only the land-atmosphere interactions but also the moisture contributions from distant oceanic sources. Studies suggest that the realistic representation of unmanaged irrigation and paddy cultivation over north-northwest India leads to an increase in the late-season terrestrial monsoon precipitation and intensification of widespread extreme events over Central India (Devanand *et al.*, 2018). Osuri *et al.*, (2017b) demonstrated that the realistic soil moisture (SM)/soil temperature (ST) initialization improves mass flux, convective updrafts and diabatic heating in the boundary layer that contributes to low level positive potential vorticity and thereby improves initiation, movement and timing of severe thunderstorms (Fig. 8). The high-resolution SM and ST initialization has improved the simulation of Uttarakhand heavy rainfall event (Rajesh *et al.*, 2016). Land surface observations, however, are generally available at very few locations. This constrains the representation of spatiotemporal surface variability and the associated predictability of weather and climate models. Prior efforts have therefore created analysis fields but they are inadequate for representing small scale and local changes that are important for various convective driven storms. This reinforces the need to create high-resolution surface conditions over India. Osuri *et al.*, (2017b) have developed high-resolution (4 km and 3 hourly) soil moisture and soil temperature (SM/ST) dataset surface (0-10 cm) and subsurface (10-40 cm, 40-100cm, 100-200 cm) soil layers for the Indian monsoon region using a Land Data Assimilation System (LDAS) for 14 years (2001-2014). Later, Nayak *et al.*, (2018) have expanded the dataset for 38 years (1981- 2018). Kumar et al (2021) have extensively validated the LDAS products over India and highlighted the credibility of the modeled land surface conditions over global analysis and satellite products. Long-term LDAS products replicated the diurnal variation, and the seasonal and the inter-annual variability of SM/ST. The utilization of SM/ST in initializing the WRF model improved the simulation of heavy rainfall associated with monsoon depressions and convective events (Osuri *et al.*, 2017b, 2020; Nayak *et al.*, 2018; Rajesh *et al.*, 2016). Therefore, the developed dataset has been used as land initial conditions in the weather prediction model and a significant improvement in predictingweather systems such as thunderstorms, monsoon depression and heavy rainfall events could be found, paving the way for its use in operational weather forecasting. Further, due to the lack of sufficient in-situ SM observations, there have been significant efforts to incorporate near-surface SM observations from passive and active sensor satellites into the LDAS systems, which further improve land surface processes and, as a result, improve the NWP. The Optimal Interpolation (OI) or nudging strategy for SM analysis has been replaced with the more efficient simplified Extended Kalman Filter (sEKF) in many top operational centers in recent years (Masson *et al.*, 2013; De Rosnay *et al.*, 2013; G´omez *et al.*, 2020; Lodh *et al.*, 2020). In recent years, Routray *et al.*, 2023 and Lodh *et al.*, 2022 assimilated satellite derived soil wetness data from Advanced Scatterometer (ASCAT) through sEKF LDAS on simulation of inland moving monsoon depressions (MDs) and land-falling storms over Indian region using high resolution regional NCUM-R forecasting system. The findings of this study demonstrate the positive effects of assimilating remotely observed SM on the simulation of movement, structure, and precipitation associated with the MD and cyclones.

5. International/National collaborative efforts

In October 2010, the National Oceanic and Atmospheric Administration (NOAA), USA signed an Implementing Arrangement (IA) and Memorandum of Understanding (MoU) with the Ministry of Earth Sciences (MoES), Govt. of India to improve tropical cyclone forecasting over

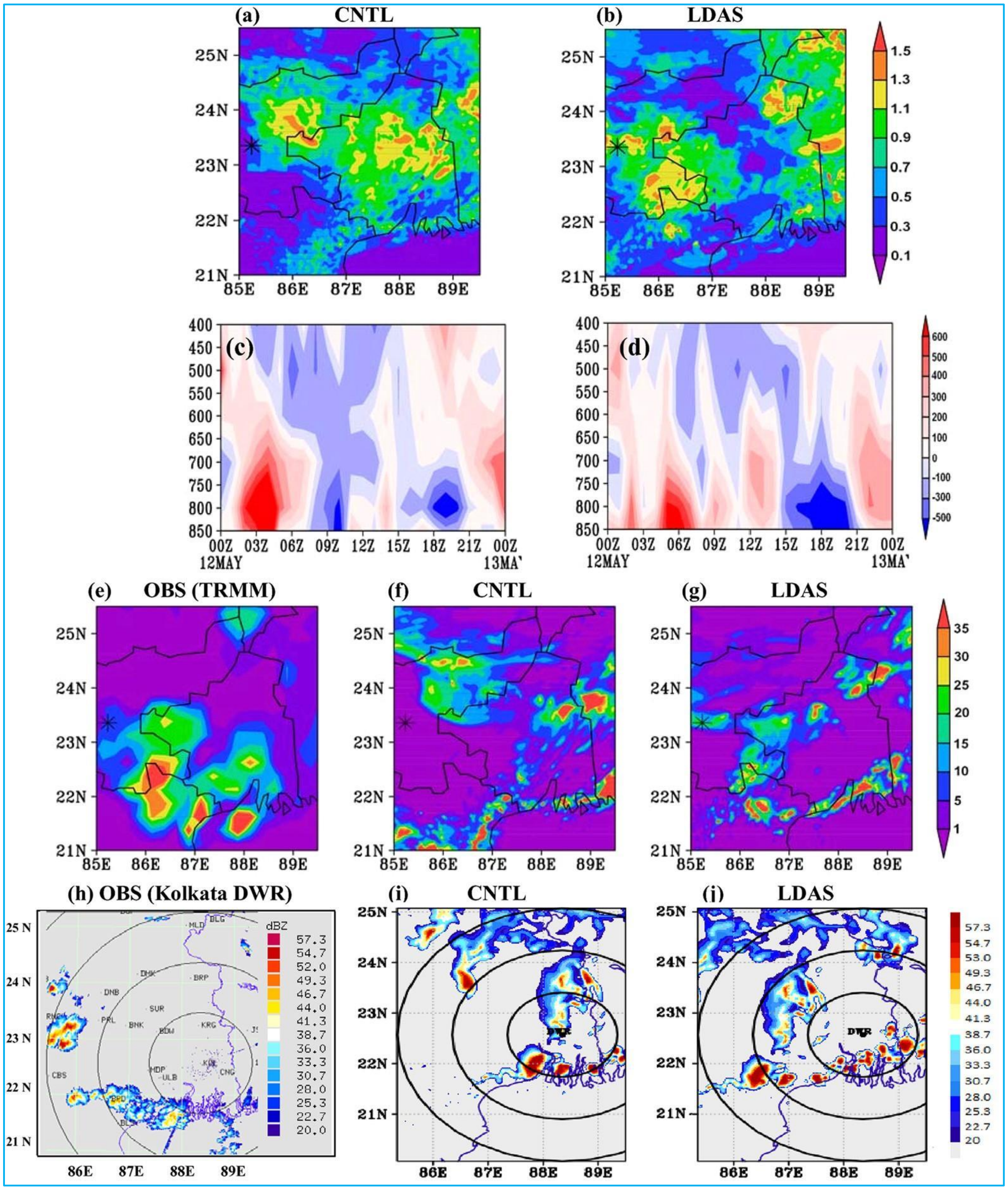


Fig. 8. Model simulated surface moisture flux (kg m−2 s−1) from (a) CNTL and (b) LDAS averaged for 9–12 UTC 12 May 2009 (case-2). (c,d) Are same (a,b) but time-vertical cross section of diabatic heating (K/h) averaged over the region 86°–88.5°E and 21.5°–24°N. 3 hr (9–12 UTC) accumulated rainfall in 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)

the Indian seas. In 2012, for the first time, the HWRF modeling system that is capable of tracking hurricanes as well as providing realistic information on the core structure of the hurricane has been implemented for the Indian seas. The HWRF was developed jointly by the Environmental Modeling Center (EMC) and the Hurricane Research Division (HRD) of NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) and implemented at the National Centers for Environmental Prediction (NCEP) and became a key model in advancing intensity forecasting. The HWRF model is now paving the way for removing the roadblocks to improvements in the operational TC intensity forecasts, which have had a virtually stagnant skill for the last two decades (Atlas, Tallapragada, and Gopalakrishnan, 2015). The HWRF system has been upgraded continuously at regular intervals for high resolution, data assimilation, and ocean coupling *etc* at IMD (Mohanty *et al.*, 2015; Osuri *et al.*, 2017a; Das *et al.*, 2013; Srivastava *et al.*, 2021; Nadimpalli *et al.*, 2016; 2020; 2021; 2022; 2023).

At the same time the Indo-US Science and Technology Forum (IUSSTF), established under an agreement between the Governments of India and the United States of America, is an autonomous, not-for-profit society that promotes and catalyzes Indo-US bilateral collaborations in science, technology, engineering, and biomedical research through substantive interaction among government, academia, and industry started supporting exciting and enabling Atmospheric science and technology program portfolio that paves way for sustainable interactions and potential collaborations through networking. Since 2012, the forum has (i) promoted and strengthened strategic partnerships in Tropical Cyclone science and technology under various intergovernmental initiatives and declarations, (ii) created awareness through the exchange and dissemination of information and opportunities toward promoting bilateral scientific and technological cooperation in Tropical Cyclone forecasting, (iii) encouraged partnership between Tropical Cyclone researchers in US, Forecasters at the India meteorological department and Academia in India to foster elements of innovation and enterprise through knowledge networking between academia and operations, (iv) Promoted the exploration of new frontiers by nurturing contacts between young and mid-career scientists to develop mutual trust, leadership and fraternity in research and development and (v) Capitalized on the scientific and technological synergy on issues of common concern in Tropical Cyclone forecasting leading to long-term partnership based on shared values.

Further, MoES research (IITM, NCMRWF) and Operational (IMD) centers collaborated with the Hurricane Research Division of AOML, NOAA, and academic partners at the University of Texas, Austin, USA, and NIT-Rourkela to accelerate the development of a Multi-scale High-Resolution Assimilation and Prediction System for Extreme Weather Events over India. The earlier collaborative effort between MoES-NOAA and the academic partners (Purdue University and IIT Delhi/Bhubaneswar) resulted in the development of high resolution SM/ST products and operationalization of the high-resolution HWRF that is starting to provide exceptional skills in track and intensity forecast over the Indian region. The same modeling system is also used for research, hence making the potential R2O efforts seamless. The strategy to advance HWRF for severe weather predictions is also consistent with IMD's need to consolidate the number of operational mesoscale modeling systems into one severe weather prediction model. Driven by the need to unify the model suite for high-impact weather and TC, the HWRF is being advanced for severe weather predictions including thunderstorm activity and mesoscale convection over land.

6. Limitations and future scope for improvements:

Prediction of severe weather with fidelity demands an atmospheric model at high definition, i.e., horizontal grid spacing less than 3 km, in order to resolve sharp gradients of momentum and moisture, which are vital in severe convection. The severe weather often spans multiple spatial scales of atmospheric motions, including the synoptic scale, mesoscale, and microscale and are often influenced by underlying land or oceanic surfaces. High definition nests focusing the region of atmospheric convection are computationally efficient and could be a practical approach to resolve clouds and convection in a forecasting system (Alaka *et al.*, 2022). High- definition nests receive synoptic scale information from the lower-resolution parent domain at the nest boundaries, and nests are allowed to communicate with the parent domain, creating a seamless flow of information between various scales of motion. In addition, local weather along coastal areas may be potentially influenced by the nearby ocean. It is important to note that severe weather warnings may not only be important for saving life and property damages in coastal areas over land but also for marine operations over coastal oceans. Subsequently prediction of the ocean as well as the land-state cannot be ignored. Therefore, the future research to operational transitions should focus on the ocean-atmosphere-land coupled models. For this proposal, the Indian HWRF modeling framework with architectural capabilities in place for moving and multiple (not just telescoping) model domain nests, will be advanced. This lays the possibility of having a high-definition (resolution) grid over the Indian region for instance that is moving with a cyclone central pressure, and there is also a static multiple high-resolution domains over different parts of the coast and inland, where there is a forecast for a high impact event such as mesoscale convection that can lead to scale interactions and cause heavy rains. An example of this scale

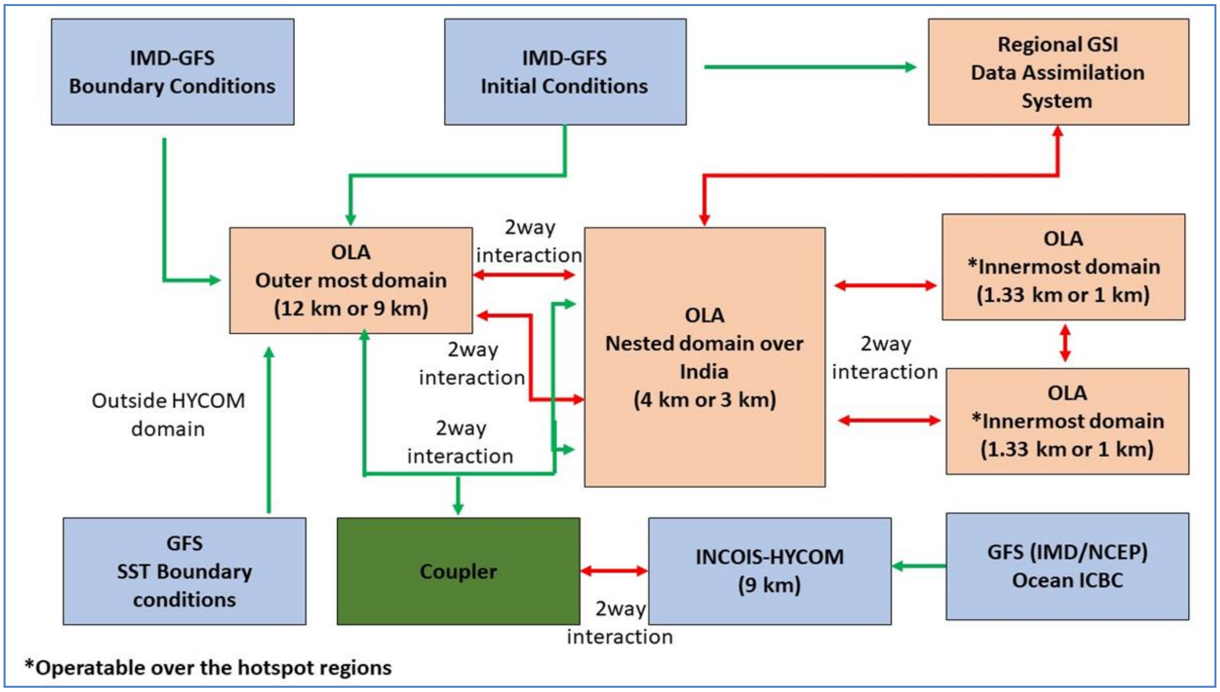


Fig. 9. Workflow of the proposes Indian Ocean-Land-Atmosphere (OLA) coupled modelling system

interaction from TCs converging with a mesoscale system and causing localized extreme rains was noted in the Chennai floods in recent years. Therefore, under the flagship programmes of the Ministry of Earth Sciences (MoES), IMD along with their national and international partners is exploring new horizons to develop an Indigenous regional Ocean-Land-Atmosphere (OLA) coupled system for forecasting severe weather conditions across different scales. The complex workflow of the OLA system for severe weather monitoring and prediction is shown in Fig. 9.

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