Prediction of landfalling Bay of Bengal cyclones during 2013 using the high resolution Weather Research and Forecasting model

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Abstract
The present study investigated the capability of the Weather Research and Forecasting (WRF) model in the forecast/simulation of five landfalling Bay of Bengal (BoB) cyclones during 2013. A 3D variational (3DVar) method of data assimilation of the WRF model was used to assimilate the Global Telecommunication System and satellite radiances to improve the initial conditions. The results demonstrated that the model has the ability to simulate the cyclone track, intensity and structure. The study also indicates that predicted storm track, landfall and intensity improved with the 3DVar technique compared to without it. This was due to better initial conditions in the 3DVar experiment. The predicted track errors of the five storms were compared to available global and regional forecasting systems and the results show that the model has the capability for prediction of cyclones over the BoB region. The forecasted mean track errors were about 70, 114, 182 and 184 km; minimum centre pressure was about 8, 10, 13, 13 hPa and maximum surface wind was about 6, 10, 9, 8 m s\(^{-1}\) on day 1 to day 4 forecast respectively. The study also presents some of the important predicted diagnostic parameters such as temperature anomaly, divergence, heating rate, frozen hydrometeors, vorticity field, equivalent potential temperature, maximum reflectivity, accumulated rainfall and horizontal wind fields compared to available observations for the extremely severe cyclonic storm Phailin. The warm core structure of the Phailin cyclone was resolved in the model between 9 and 15 km compared to satellite observations. The statistical analysis, distribution and magnitude of forecasted accumulated rainfall are also compared to the rainfall of 174 automatic weather stations.

KEYWORDS
3DVar, BoB, landfalling, Phailin, track, WRF

1 INTRODUCTION

Tropical cyclones (TCs) during landfall result in massive loss to life and cause damage to property and communications. The increased intensity of TCs together with high population density near coastal belts have posed an increased risk over coastal regions in terms of coastal vulnerability at a faster rate associated with landfalling TCs (Sahoo and Bhaskaran, 2015). In a global perspective, the Indian sub-continent is highly vulnerable to the impact from TCs.
compared to other regions. Interestingly, at present in a changing climate it is seen that TCs that form over the North Indian Ocean (NIO) have experienced increased size and intensity (Murty et al., 2016) and the frequency of intense cyclonic storms in the NIO shows an increasing trend (Singh et al., 2000; 2001; Srivastav et al., 2000). The TC forecast errors in the Bay of Bengal (BoB) region are still significantly higher compared to the prediction skills for hurricanes and typhoons in the North Atlantic and Pacific Ocean respectively (Mohapatra et al., 2013a; 2013b). Being a tropical region there are inherent difficulties involved in the prediction skills of TCs in the Indian Ocean compared to the Atlantic and Pacific Ocean basins. The forecast accuracy in terms of track and intensity of the storms over the Atlantic and Pacific Oceans was investigated by Goerss (2007) and Chen et al. (2012); more details are presented in the annual National Hurricane Centre verification reports available from the URL link: https://www.nhc.noaa.gov/verification/verify3.shtml. However, quite recently there have been tremendous improvements in the predictive capability, especially the location of landfall, for TCs that originate in the Indian Ocean basin. For example, the ensemble prediction system by the India Meteorological Department (IMD) using an ocean–atmospheric coupled model providing the prospective track and cyclone intensification was quite successful in the accurate prediction of tropical cyclones such as Phailin (2013), Hudhud (2014), Nilofar (2014), Chapala (2015), Ockhi (2017), Titli (2018) and Fani (2019). Very recently the United Nations have applauded India for the accurate prediction of the Fani (2019) cyclone and rapid evacuation for more than a million people, drastically minimizing the loss of life on the Odisha coast. For the Atlantic and Pacific Ocean basins, the operational hurricane forecast models by the National Hurricane Center are more skillful measured relative to the persistence technique and standard climatology for track forecast compared to intensity (DeMaria et al., 2002; 2005). The study by DeMaria et al. (2005) indicates that for the Atlantic the official intensity forecasts have improved by 5, 10 and 15% at 24, 48 and 72 hr respectively. The improvements seen in the skill level of track forecasts are primarily attributed to the dynamic tropical cyclone track forecast guidance and also to the application of consensus forecasting techniques (Elsberry and Carr III, 2000; Aberson, 2001; Carr III et al., 2001). For emergency preparedness and planning operations it is an essential prerequisite to have an accurate forecast of TCs over the BoB to reduce substantial losses.

Several studies have investigated the prediction of BoB TCs by using mesoscale models such as MM5, Weather Research and Forecasting (WRF) and Hurricane WRF (HWRF) (Pattanayak and Mohanty, 2008; 2010; Mandal and Mohanty, 2010; Mohanty et al., 2010; 2015; Pattanayak et al., 2012; Singh and Mandal, 2015). In the last one and a half decades, a number of studies attempted to evaluate better physical processes in the mesoscale model for prediction of BoB cyclones (Patra et al., 2000; Mandal et al., 2004; Bhaskar Rao and Prasad, 2006, 2007; Srinivas et al., 2007, 2012; Deshpande et al., 2010; Raju et al., 2012; Singh and Mandal, 2014; Singh and Bhaskaran, 2017). Some studies also reported that the predicted storm track, landfall (position and time) and intensity improved when satellite and conventional observations were assimilated (Sandeep et al., 2006; Abhilash et al., 2007; Srinivas et al., 2010; 2013; Rakesh and Goswami, 2011; Greeshma et al., 2015; Osuri et al., 2015; Routray et al., 2016; Singh and Bhaskaran, 2018). The study by Osuri et al. (2013) suggested that prediction of NIO TCs at 9 km resolution was more accurate than 27 and 18 km resolutions based on 100 simulations for 17 cyclone cases during 2007–2011. Yesubabu et al. (2014) evaluated the performance of the WRF model using the 3D variational (3DVar) assimilation method and reported that track errors were reduced by 25, 21 and 38% and storm intensity was reduced by 57, 36 and 39% on days 1 to 3. Singh et al. (2019) reported that the initial conditions (ICs) and forecast of cyclonic storm Sidr were improved through the 3DVar assimilation technique of the WRF model; the assimilated observations were satellite radiances in combination with the Global Telecommunication System (GTS). It was observed that the track errors improved by about 46, 62, 90 and 86%, respectively, for a 24–96 hr forecast compared to without data assimilation. Mandal et al. (2016) reported that mean track errors (MTEs) for different ICs on days 1–4 were less than 100 km for the prediction of extremely severe cyclonic storm (ESCS) Phailin over the BoB region. A recent study by Singh and Tyagi (2019) suggested that the predicted storm track error and intensity were reduced using the 3DVar technique and with parameterization of the air–sea flux scheme in the WRF model. A study by Singh and Bhaskaran (2018) suggested that high resolution and more frequent lateral boundary conditions with assimilation of conventional and satellite radiances provide a better forecast of BoB TCs. These improvements in track predictions were achieved using proper representation of physical processes, improved ICs through the 3DVar method, increased model resolution and regional background error statistics. Hence, there is a need and necessity to test the performance of the model on near real-time forecasts of TCs in the BoB region under different environmental conditions with assimilation of available observations.

The aim of the study was to evaluate the model efficiency in simulating storm track, landfall and intensity under different environmental conditions for five landfalling TCs during 2013 over the BoB region. To accomplish the objective two aspects were covered: first the impact of data assimilation on
ESCS Phailin and second the WRF model performance in the forecast of other cyclonic storms during 2013. The paper is organized as follows. The first section covers the introduction and relevant literature review and a brief description of cyclonic cases is presented in Section 2; the model description and its configuration are discussed in Section 3. The results and discussion are presented in Section 4, and lastly Section 5 gives a summary and conclusion.

2 | BRIEF DESCRIPTION OF 2013 CYCLONES OVER THE BoB REGION

Five storms developed in the BoB region during 2013. The post-monsoon season was quite active and resulted in one that intensified into an ESCS (where the maximum sustained surface wind [MSSW] varies between 90 and 119 kn) named the Phailin cyclone, two that intensified into very severe cyclonic storms (VSCSs) (where the MSSW varies between 64 and 89 kn) named Lehar and Madi and one that intensified into a severe cyclonic storm (SCS) (where the MSSW varies between 48 and 63 kn) named the Helen cyclone. In the pre-monsoon season (April–May) only one cyclonic storm named Viyaru (where the MSSW varies between 34 and 47 kn) developed over the BoB region. Only the Phailin storm crossed the coast as a VSCS; the Viyaru and Helen cyclones made landfall as cyclonic storms, whereas Lehar and Madi crossed the coast as a depression (where the MSSW varies between 17 and 27 kn). These stages are usually classified based on the MSSW speed as per the definition of the IMD. The Lehar cyclone crossed the Andaman and Nicobar Islands as an SCS, and it was the first SCS that crossed the Andaman and Nicobar Islands since November 1989. The Lehar cyclone had a straight track, whereas the tracks for the remaining four cyclones were recurving in nature. Whilst ESCS Phailin recurved after landfall, Helen recurved just before landfall and Madi and Viyaru recurved over the sea. Of these five cyclones, the movement of the Madi cyclone was unique. The movement of these storms over the BoB is shown in Figure 1 and their salient features, period, landfall, category and maximum intensity are presented in Table S1.

3 | METHODOLOGY AND DATA

The non-hydrostatic mesoscale modelling system of Advanced Research WRF (WRF-ARW), version 3.4.1, was used for forecasting. The atmospheric model physics, dynamics, primitive equations and grid staggering are available in Skamarock et al. (2008). A horizontal resolution of the nested domains of the model of about 27 km for the outer domain (151 × 151 grid points) and 9 km for the finer domain (316 × 286 grid points) was considered in the study. The model domains with topography (in metres) are presented in Figure 2. A total of 35 unequal vertical levels with model top about 10 hPa was used. The physical parameterization schemes including planetary boundary layer, cumulus, microphysics, radiation and land surface were taken from the study by Singh and Bhaskaran (2018). Table S2 provides the selected model configuration, and the

![Figure 1](image1.png)

**Figure 1** India Meteorological Department best-fit tracks of Bay of Bengal cyclones during 2013. The intensity of the storms is shown as follows: green, depression; blue, deep depression; black, cyclonic storm; cyan, severe cyclonic storm; red, very severe cyclonic storm

![Figure 2](image2.png)

**Figure 2** Model domains used in the study with topography (in m)
 initialization time and predicted mean intensity during landfall for each case are presented in Table S3. It is important to note that the forecast length of each experiment was considered to be 96 hr and the predicted results were validated with available IMD observations. The lateral boundary conditions for prediction were derived from available 3 hr forecasted 0.5° × 0.5° resolution datasets from the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS). The model ICs for all cases were taken from 0.5° × 0.5° resolution analysis GFS datasets.

To improve the ICs the 3DVar assimilation system of the WRF model was used. Assimilated observations are radiiances from the Advanced Microwave Sounding Unit (AMSU), the High Resolution Infrared Radiation Sounder (HIRS) and the Microwave Humidity Sounder (MHS); surface observations from SYNOP, METAR, SHIPS, BUOY, SONDE_SUF; upper air observations from SOUND, PILOT, GEOAMV; and surface wind from QSCAT. The spatial resolutions of the AMSU-A, AMSU-B, HIRS3, HIRS4 and MHS satellites are about 48, 16, 20, 10 and 16 km respectively and are available on a real-time basis at 6 hr intervals on the NCEP website. The details pertaining to data thinning, selection of channel, observational error, quality control and bias correction of the simulated channel were adapted based on the studies by Singh et al. (2019). The IMD observations were used to validate the predicted results including storm track, landfall and intensity. The predicted MTE was also compared to several operational global as well as regional models documented by Kotal et al. (2013). The capability of the atmospheric modelling system in the prediction of TCs was also discussed in terms of the time series of warm core structure, diabatic heating rate, divergence and frozen hydrometeors for ESCS Phailin. The 3 hr analysis datasets of the 3B42 Tropical Rainfall Measuring Mission (TRMM) were used to validate the rainfall pattern and distribution. The 24 hr accumulated rainfall from 174 automatic weather stations was used to validate the forecasted rainfall. The model forecasted warm core structure and reflectivity were also compared to the AMSU satellite derived analysis (Demuth et al., 2004) and the Visakhapatnam Doppler weather radar (DWR) reflectivity respectively.

4 | RESULTS AND DISCUSSION

Section 4.1 describes the impact of the 3DVar assimilation on the ICs and forecast of track and intensity for ESCS Phailin. Some important basic features pertaining to the prediction of ESCS Phailin are discussed in Section 4.2 to understand the capability of the WRF model in simulating the storm structure and intensity. Section 4.3 shows the forecasted MTEs and intensity of the five cyclonic storms that formed over the BoB region in 2013.

4.1 | Impact of data assimilation on IC and prediction of ESCS Phailin

The impact of 3DVar assimilation of the GTS observations with satellite radiances on the ICs was investigated for ESCS Phailin for three different ICs: 0000 UTC October 9 (Exp. 1), 1200 UTC October 9 (Exp. 2) and 0000 UTC October 10 (Exp. 3). In the assimilation experiment (named the DA experiment) a significant reduction of about 11% was observed in mean initial position error compared to without assimilation (CNTL experiment). This mean initial positional error was about 57 km in the CNTL experiment. The improvement in model ICs through assimilation was mainly due to the quality of the high resolution satellite observations and regional background error statistics. The impact of different types of observations assimilated in the study are presented in Table 1. The initial intensity both in terms of minimum central pressure (MCP) and maximum surface wind (MSW) of ESCS Phailin was also marginally improved in the DA experiment compared to the CNTL experiment. The amount of improvement with assimilation of different observations is calculated and presented in Table 1. A statistical analysis in terms of average root mean square error (RMSE) for two components of wind (U, V), the temperature (K) and the specific humidity (g·kg⁻¹) of departures of the analysis from observations (O-A) and departures of the first guess from observations (O-B) is shown in Table 1. The results clearly indicate that the RMSE for O-A is less than for O-B for all parameters at three different ICs in most of the observations. The decrease in RMSE between observation and analysis is mainly due to assimilation of observations and shows that the analysis moves toward the real state (observation) and hence provides better ICs. Overall, the results suggest that the ICs are improved through 3DVar data assimilation.

The predicted tracks from the DA and CNTL experiments along with the IMD best-fit track suggested that storm movement in both experiments was close to observation during the entire forecast period, while track errors were somewhat improved in the assimilation experiment compared to the CNTL experiment. The track errors in the CNTL experiment were about 69, 41, 38 and 65 km, whereas in the DA experiment the MTE was about 65, 41, 35 and 57 km respectively at 24, 48, 72 and 96 hr forecast respectively. The mean landfall of ESCS Phailin was also improved in the DA experiments. The mean landfall errors in the CNTL experiment were 2 hr and 38 km, whereas these errors in the DA experiment were about 1 hr and 33 km. The result in terms of statistical analysis suggested that track and landfall of the storm were better predicted in the DA experiment.

The time evolution of the observed (IMD) and predicted (DA and CNTL) intensity (MCP and MSW) for ESCS Phailin for Exp. 2 is presented in Figure 3. The results show...
that storm intensification and dissipation are well captured in terms of MCP but are slightly better predicted in the DA experiment. In terms of MSW, the sharp intensification during the initial time period (first 24 hr forecast) was well captured, but the intensification over 24–39 hr was not captured and hence the maximum intensity during the intense stage was significantly under-predicted. The results show that the sharp dissipation of the storm was also well predicted in both experiments. The average RMSE for MSW at 24, 48, 72 and 96 hr forecast for ESCS Phailin was 7, 13, 13 and 6 m s\(^{-1}\) respectively, whereas for MCP these errors were about 9, 5, 7 and 8 hPa on days 1–4 respectively in the DA experiments.

### 4.2 Forecast of the structure of ESCS Phailin

Some important basic parameters were evaluated to test the capability of the WRF-ARW modelling system to predict

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**TABLE 1** Mean root mean square error (RMSE) between assimilated observations with model first guess (O-B) and with 3D variational analysis (O-A) at three different initial conditions

| Parameter          | U wind (m s\(^{-1}\)) | V wind (m s\(^{-1}\)) | Temperature (K) | Specific humidity (g kg\(^{-1}\)) |
|--------------------|------------------------|------------------------|-----------------|-----------------------------------|
|                    | O-B        | O-A        | O-B        | O-A    | O-B        | O-A    | O-B        | O-A    |
| SOUND              |            |            |            |        |            |        |            |        |
| Exp. 1             | 2.85      | 2.51      | 2.63      | 2.46   | 1.44      | 1.22   | –          | –      |
| Exp. 2             | 2.67      | 2.40      | 2.29      | 2.17   | 1.33      | 1.15   | –          | –      |
| Exp. 3             | 2.78      | 2.54      | 2.79      | 2.57   | 1.39      | 1.20   | –          | –      |
| SONDE_SFC          |            |            |            |        |            |        |            |        |
| Exp. 1             | 1.64      | 1.18      | 1.93      | 1.57   | 1.22      | 0.75   | 2.06       | 1.71   |
| Exp. 2             | 1.76      | 1.41      | 1.29      | 1.16   | 1.72      | 1.06   | 2.58       | 2.08   |
| Exp. 3             | 2.16      | 1.58      | 2.06      | 1.63   | 1.19      | 0.74   | 1.88       | 1.54   |
| SYNOP              |            |            |            |        |            |        |            |        |
| Exp. 1             | 2.72      | 1.70      | 1.84      | 1.43   | 1.91      | 1.53   | 2.78       | 2.44   |
| Exp. 2             | 2.52      | 1.64      | 1.73      | 1.58   | 2.04      | 1.73   | 4.39       | 4.03   |
| Exp. 3             | 2.50      | 1.54      | 1.73      | 1.40   | 2.09      | 1.60   | 2.77       | 2.38   |
| GEOAMV             |            |            |            |        |            |        |            |        |
| Exp. 1             | 4.12      | 4.06      | 3.13      | 2.97   | –         | –      | –          | –      |
| Exp. 2             | 3.72      | 3.62      | 2.88      | 2.89   | –         | –      | –          | –      |
| Exp. 3             | 3.97      | 3.92      | 3.25      | 3.20   | –         | –      | –          | –      |
| PILOT              |            |            |            |        |            |        |            |        |
| Exp. 1             | 1.73      | 1.64      | 1.51      | 1.44   | –         | –      | –          | –      |
| Exp. 2             | 1.83      | 1.76      | 1.61      | 1.52   | –         | –      | –          | –      |
| Exp. 3             | 2.00      | 1.90      | 1.98      | 1.92   | –         | –      | –          | –      |
| METAR              |            |            |            |        |            |        |            |        |
| Exp. 1             | 1.81      | 1.35      | 1.41      | 1.17   | 1.38      | 1.12   | 2.27       | 1.84   |
| Exp. 2             | 1.86      | 1.42      | 1.72      | 1.60   | 1.83      | 1.55   | 2.73       | 2.30   |
| Exp. 3             | 1.77      | 1.51      | 1.61      | 1.50   | 1.58      | 1.27   | 2.76       | 2.27   |
| SHIPS              |            |            |            |        |            |        |            |        |
| Exp. 1             | 2.08      | 1.99      | 3.42      | 3.38   | 1.33      | 1.14   | 1.59       | 1.48   |
| Exp. 2             | 1.74      | 2.01      | 1.99      | 1.95   | 2.05      | 1.75   | 2.98       | 2.90   |
| Exp. 3             | 1.82      | 1.81      | 2.14      | 2.07   | 1.51      | 1.45   | 1.55       | 1.46   |
| QSCAT              |            |            |            |        |            |        |            |        |
| Exp. 1             | 1.78      | 1.66      | 2.59      | 2.21   | –         | –      | –          | –      |
| Exp. 2             | 1.75      | 1.66      | 2.20      | 1.74   | –         | –      | –          | –      |
| Exp. 3             | 0.40      | 0.45      | 1.24      | 1.32   | –         | –      | –          | –      |
| BUOY               |            |            |            |        |            |        |            |        |
| Exp. 1             | 1.71      | 1.52      | 1.04      | 0.94   | 1.05      | 1.19   | –          | –      |
| Exp. 2             | 2.14      | 1.93      | 3.27      | 3.01   | 1.05      | 0.98   | –          | –      |
| Exp. 3             | 2.51      | 2.11      | 2.95      | 2.56   | 0.97      | 0.89   | –          | –      |
| AMSU-A             |            |            |            |        |            |        |            |        |
| Radiances (Tb)     |            |            |            |        |            |        |            |        |
| Exp. 1             | 0.37      | 0.30      | –         | –      | 2.40      | 1.26   | 0.91       | 0.43   |
| Exp. 2             | 0.31      | 0.23      | –         | –      | 1.95      | 1.24   | –          | –      |
| Exp. 3             | 0.29      | 0.21      | –         | –      | 1.91      | 1.04   | 0.71       | 0.41   |

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the structure of ESCS Phailin; the analysis was taken from the results of the improved model IC forecast at 1200 UTC on October 9, 2013. The qualitative description and quantitative estimation of the parameters, namely the time–height series of the warm core structure, diabatic heating, divergence, frozen hydrometers and east–west cross-section of vorticity and equivalent potential temperature, are presented.

The spatial distribution of maximum reflectivity, rainfall and wind speed are also shown in this section.

Figure 4 shows the time–height series of the warm core structure, diabatic heating, divergence and frozen hydrometers from 1500 UTC October 9 to 0300 UTC October 13. These parameters were estimated at hourly time steps using an area average of 200 km radius from the storm centre. A negative anomaly indicates that the forecasted temperature was cooler and a positive anomaly indicates that the forecasted temperature was warmer than the normal temperature (reference value). The forecasted temperature anomaly is derived by using temperature at a specific time minus the environmental temperature at each level (Kidder et al., 2000). The results suggest that the forecasted intensity (MCP and MSW in Figure 3) was well correlated with temperature anomaly. A higher warm core pattern occurs between 8 and 16 km height during 1200 UTC October 11 up to 1500 UTC October 12 and suddenly decreases after landfall. A negative warm core is noticed at the lower levels in the model forecast and satellite, and this could be attributed to heavy rainfall contamination. The overall results suggest that the warm core structure was well resolved in the model. A similar pattern was noticed in the forecasted diabatic heating (K h\(^{-1}\)). There was higher diabatic heating at different levels, with strong maxima around 12 and 16 km

**FIGURE 3** Time evolution of intensity in terms of minimum central pressure (MCP) (hPa) and maximum surface wind (MSW) (m s\(^{-1}\)) from the India Meteorological Department (IMD) best-fit track and forecast (DA and CNTL) for extremely severe cyclonic storm Phailin at 1200 UTC October 9, 2013

**FIGURE 4** Model simulated time variation with height: (a) temperature anomaly (K), (b) divergence (10\(^{-6}\) s\(^{-1}\)), (c) diabatic heating (K h\(^{-1}\)), (d) frozen hydrometeors (g kg\(^{-1}\)), averaged over a 200 km radius from the centre of the storm
height. During 2100 UTC October 11 to 1200 UTC October 12 higher diabatic heating was observed between 2 and 17 km height. The results demonstrate that storm development and intensification depend on heating rate. A similar pattern was observed in the divergence and frozen hydrometers for intensification of the storm.

Figure 5a–c represents the predicted vorticity field of the storm through the centre as obtained from model forecasts. The relative vorticity increases continuously from day 1 \((200 \times 10^{-5} \text{ s}^{-1})\) to day 3 \((250 \times 10^{-5} \text{ s}^{-1})\) and extends up to 100 hPa with relative vorticity more than \(100 \times 10^{-5} \text{ s}^{-1}\) at the intense stage. In the horizontal direction, the vorticity zone extends up to 100–150 km on both sides of the storm centre, which is typical in a strong storm that has a maximum positive vorticity of about 850 hPa. Figure 5d–f represents the east–west cross-section of equivalent potential temperature \((\theta_e\text{ in kelvins})\) obtained from model predictions valid at days 1–3. It is found that \(\theta_e\) has a good correlation with the predicted storm intensity, since a high value of \(\theta_e\) from the ocean surface is an important mechanism for the maintenance and growth of TC eye-wall convection (Chen and Yau, 2003). From day 1 to day 3, \(\theta_e\) increases from 354 to 363 K near the storm centre. The above results indicate more intense eye-wall convection with a strong low-level convergence, and stronger vorticity that led to a rapid intensification rate for ESCS Phailin from day 1 to day 3.

Figure 6 shows the reflectivity predicted from the model and observed for 1500 UTC (before landfall), 1700 UTC (during landfall) and 1800 UTC (after landfall) on October 12, 2013. The results indicate that the predicted landfall time matches well with observation including the location of landfall. The model results indicate that dense convective bands aligned in the southwest and south quadrants in a radius of 50 km agree well with the DWR observation.
relatively higher convective activity along the Odisha coast and the adjoining coast of Andhra Pradesh. The eye is visible in both model prediction and observation.

Figure 7 shows the 3 hr accumulated rainfall (in cm) from the model forecast and the TRMM estimates valid at 0600 UTC on October 12, 2013, superimposed with the Kalpana-1 satellite image from the very high resolution radiometer (VHRR) sensor. The study shows that the distribution of rainfall associated with the storm is reasonably well captured over the ocean, although the magnitude of maximum rainfall is over-predicted in the eye-wall region. The model was unable to capture the pattern and magnitude of the storm over land. The distribution of the outer rain band on the northeast side of the storm was captured. The forecasted and observed (174 AWSs) 24 hr accumulated rainfall valid at 0300 UTC on October 13 was also calculated. The magnitude and distribution of the 24 hr accumulated rainfall was in good agreement with observation but predicted rainfall was over-predicted in most of the locations of the AWSs (Figure 8). The forecasted maximum rainfall was about 40 cm, whereas the observed rainfall was 38 cm. A statistical analysis, i.e. the RMSE, mean absolute error (MAE), correlation co-efficient (CC) and probability of detection (POD), of 24 hr accumulated rainfall at 174 AWSs on 0300 UTC October 13 was also made. The POD or hit rate, i.e. the fraction of the observed event that was forecast

FIGURE 6  Simulated and observed maximum reflectivity (in dBZ) valid at 1500 UTC (before landfall), 1700 UTC (during landfall) and 1800 UTC (after landfall) on October 12, 2013: left, model forecast; right, from Doppler weather radar (Visakhapatnam) observation
correctly for a threshold value, was estimated at 174 AWS locations. The results from the statistical parameters RMSE (about 8.6 cm), MAE (about 5.8 cm) and CC (about 0.43) indicated that the forecasted rainfall with WRF-ARW was in good agreement with observation. The POD of heavy rainfall showed that the model predicted approximately 90, 76 and 53% of the observed rain at 174 locations with threshold values of 2.5, 5.0 and 10 cm respectively.

Figure 9 represents the spatial distribution of surface wind speed (m/s) and wind vector valid at the intense stage obtained from the model forecast and GFS analysis: Viyaru valid at 1200 UTC May 14, Phailin at 0000 UTC October 12, Helen at 1200 UTC November 21, Lehar at 0000 UTC November 27 and Madi at 0000 UTC December 10, 2013. It is observed that the inner core cyclonic structure in all cases is reasonably well captured. For ESCS Phailin the model predicted that the wind pattern is symmetric and the MSW of the storm varied along the eastern side. For cyclonic storm Viyaru, the movement of the storm is slightly faster in the northeast direction; the inner core structure and magnitude of the wind speed are well represented in the model. For the cyclones Helen and Madi, the inner core structure, magnitude of wind speed and location of the storm are also well captured.

4.3 | Track and intensity forecast during 2013 cyclones

The forecasted MTEs of the individual cyclones and the mean of the five storm track errors on a daily basis are presented in Figure 10 and were prepared by using the IMD best-fit track. From the results it was observed that the movements of the storms are well captured in the WRF model compared with the observed track during the prediction period except for the cyclonic storm Viyaru. The forecasted MTE in the case of Viyaru is 88, 180, 302 and 296 km on days 1–4 respectively. The forecasted track of ESCS Phailin closely followed the observed track during the prediction period; the MTEs are about 68, 45, 36, and 57 km at 24–96 hr. A similar pattern is observed in the case of the Helen cyclone. The forecasted mean track of VSCS Lehar is reasonably well predicted by the model and a similar pattern is observed in the case of VSCS Madi. The forecasted MTE in the case of Lehar is 72, 126, 172 and 182 km on days 1–4 respectively, while the results suggest that the forecasted MTE of all cases on days 1–4 is about 70, 114, 182 and 184 km. The results show that the forecasted track error is less in high intensity storms (Phailin, Madi, Helen and Lehar) compared to the less intense cyclone Viyaru (Ryerson et al., 2007).

The forecasted MTE of the five storms using the WRF model along with the forecasted MTE by global and regional
numerical weather prediction models are shown in Table 2. The results show that movement of the storm is slightly better predicted with the WRF model compared to other models on days 1 and 2. The IMD multi-model ensemble (IMD-MME) forecast and the European Centre for Medium-Range Weather Forecast (ECMWF) model forecast on day 3 and the NCEP-GFS and ECMWF model forecast on day 4 are slightly better than the WRF model. The forecasted MTE is higher in the forecasts of the IMD quasi-Lagrangian model (QLM) on day 1 (230 km), of the IMD-WRF on days 2 and 3 (288, 340 km) and of the IMD-HWRF on day 4 (401 km). The MTE in the IMD-MME and NCEP-GFS forecasts is about the same order representing 90 km at 24 hr to 189 km at 72 hr respectively. At 24 hr the forecast track errors are
about the same order in the IMD-HWRF, UK Meteorological Office (UKMO) and ECMWF models, whereas in IMD-OFFICIAL these errors varied by about 109 km on day 1 to 251 km on day 4 forecasts. In the WRF model, the MTEs are about 70, 114, 182 and 184 km, whereas these errors are 66, 98, 143 and 147 km for the mean of SCSs (except for the Viyaru case, low intensity cyclone) at 24–96 hr forecasts.

| Model        | Day 1  | Day 2  | Day 3  | Day 4  |
|--------------|--------|--------|--------|--------|
| WRF-ARW      | 70     | 114    | 182    | 184    |
| IMD-GFS      | 119    | 200    | 213    | 254    |
| NCEP-GFS     | 79     | 131    | 189    | 159    |
| UKMO         | 144    | 209    | 306    | 337    |
| ECMWF        | 149    | 153    | 173    | 104    |
| IMD-HWRF     | 139    | 227    | 316    | 401    |
| IMD-MME      | 90     | 132    | 175    | 210    |
| IMD-OFFICIAL | 109    | 157    | 195    | 251    |
| JMA          | 184    | 217    | 210    |        |
| IMD-WRF      | 153    | 288    | 340    |        |
| IMD-QLM      | 230    | 252    | 238    |        |

Note: The bold values signify the notable ones among the different models corresponding for Days 1, 2, 3, and 4.

Figure 11 presents the time evolution of the forecasted MAE in the intensity of the individual storms (histogram plot) and the MAE in intensity for all predictions (line plot) in terms of MCP and MSW. The predicted intensity for cyclonic storm Viyaru is over-predicted during the entire forecast period, having higher intensity errors compared to the other cases. The absolute error on days 1–4 for the predicted MCP is about 12, 19, 19, 22 hPa and for MSW is about 12, 18, 10 and 15 m s⁻¹. The trend of storm intensification and dissipation is well captured in terms of the MCP but not the forecasted MSW for ESCS Phailin. The predicted MSW at the intense stage is significantly under-predicted. The absolute errors for the MCP at 24, 48, 72 and 96 hr are about 9, 5, 7 and 8 hPa and for MSW are about 8, 10, 9 and 6 m s⁻¹ for ESCS Phailin. The intensification trend exhibited a similar pattern in both MCP and MSW for SCS Helen. The intensity of cyclone Lehar is over-predicted during the prediction period. In the case of VSCS Madi, the intensity is again well predicted and closely matches with observation. The MAEs in intensity for all cases are about 8, 10, 13 and 13 hPa for MCP and about 6, 10, 9 and 8 m s⁻¹ for MSW. The intensity error during landfall time is presented in Table S3. The MAEs in landfall location and time are about 48 km and 2 hr respectively; these errors were highest for the Viyaru cyclone and least for the Helen, Lehar, Madi and Phailin cyclones. More details about these errors are presented in Table 3.

A comparison of MCP and wind speed distribution frequency (in a histogram plot) and the Weibull probability distribution functions (PDFs) (in a line plot) between the model forecast and observation (IMD) for all cases is presented in Figure 12. It is evident that the Weibull PDFs for MCP are well correlated and show a similar pattern but this feature was not well captured for MSW. It is seen that the frequency of lower MCP up to 990 hPa and MSW up to 20 m s⁻¹ is under-predicted. A similar pattern is also observed in the frequency of higher MSW (more than 50 m s⁻¹). The wind frequency predicted by the WRF-ARW model tends to show more change in magnitude compared to the IMD wind speed at a threshold wind speed between 25 and 37 m s⁻¹. Overall, the MCP frequency distribution matches well with observations, however, the wind frequency distribution does not match well with the observations that is analogous with wind speed distribution frequency and Weibull PDFs.

5 | SUMMARY AND CONCLUSIONS

The study evaluates the performance of the Weather Research and Forecasting (WRF) model with assimilation of the Global Telecommunication System and satellite datasets toward mesoscale prediction of Bay of Bengal cyclones during 2013. First the impact of data assimilation was
investigated on extremely severe cyclonic storm (ESCS) Phailin with (DA) and without (CNTL) data assimilation experiments and the results show that the initial conditions improved due to 3D variational assimilation of the available observations. The prediction with improved initial conditions suggested that the forecasted track, intensity and landfall of the storm were improved in the DA experiment compared to the CNTL experiment.

The forecasted structure of ESCS Phailin was also evaluated. The results suggest that the warm core structure in ESCS Phailin was well resolved in the model. The storm intensification and higher intensity have a dependence on a higher temperature anomaly and higher diabatic heating rate. The statistical analysis shows that the forecasted rainfall for ESCS Phailin also matches well with observation, and a higher magnitude of rainfall was observed in the predicted storm inner core. The wind field pattern and magnitude of wind speed during the time of maximum intensity were also captured in the model.

The results obtained from this study show that the forecasted track performs reasonably well including the looping storm Madi. The result signifies that the predicted track was also well predicted in the WRF model compared to global and regional models. The mean track errors in the WRF model on days 1–4 were about 70, 114, 182 and 184 km respectively. The storm intensity (minimum central pressure MCP and maximum surface wind MSW) was well predicted in most of the storms during 2013. The mean absolute error in terms of MCP and MSW on days 1–4 are 8, 10, 13, 13 hPa and 6, 10, 9, 8 m s$^{-1}$ respectively.

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REFERENCES

Aberson, S.D. (2001) The ensemble of tropical cyclone track forecasting models in the North Atlantic basin. Bulletin of the American Meteorological Society, 82, 1895–1904.

Abhilash, S., Das, S., Kalsi, S.R., Gupta, M.D., Mohan, K., George, J.P., Banerjee, S.K., Thampi, S.B. and Pradhan, D. (2007) Impact of Doppler radar wind in simulating the intensity and propagation of rain bands associated with mesoscale convective complexes using MM5 3D-VAR system. Pure and Applied Geophysics, 164, 1491–1509.

Bhaskar Rao, D.V. and Prasad, D.H. (2006) Numerical prediction of the Orissa super cyclone (1999): sensitivity to the parameterization of convection, boundary layer and explicit moisture processes. Mawsam, 57(1), 61–78.

Carr, L.E., III, Elsberry, R.L. and Peak, J.E. (2001) Beta test of the systematic approach expert system prototype as a tropical cyclone track forecasting aid. Weather Forecasting, 16, 355–368.

Chen, C., Li, Q., Yu, J. and Chen, L. (2012) Evaluating the performance of western North Pacific tropical cyclone intensity guidance. Part I: Basic characteristics. Tropical Cyclone Research and Review, 1(3), 340–352.

Chen, Y. and Yau, M.K. (2003) Asymmetric structures in a simulated landfalling hurricane. Journal of the Atmospheric Sciences, 60, 2294–2312.

DeMaria, M., R. M. Zehr, J. P. Kossin, and J. A. Knaff, 2002: The use of GOES imagery in statistical hurricane intensity prediction. Preprints, 25th Conference on Hurricanes and Tropical Meteorology, San Diego, CA, USA. Meteorological Society, 120–121.

DeMaria, M.R., Mainelli, M., Shay, L.K., Knaff, J.A. and Kaplan, J. (2005) Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). Weather Forecasting, 20, 531–543.

Demuth, J.L., Demaria, M., Knaff, J.A. and Vonderhaar, T.H. (2004) Evaluation of Advanced Microwave Sounder Unit tropical cyclone intensity and size estimation algorithms. Journal of Applied Meteorology, 43, 282–296.

Deshpande, M.S., Pattnaik, S. and Salvekar, P.S. (2010) Impact of parameterization schemes on numerical simulation of super cyclone Gonu. Natural Hazards, 55, 211–231.

Elsberry, R.L. and Carr, L.E., III. (2000) Consensus of dynamical tropical cyclone track forecasts. Monthly Weather Review, 128, 4131–4148.

Goess, J.S. (2007) Prediction of consensus tropical cyclone track forecast error. Monthly Weather Review, 135(5), 1985–1993.

Greeeshma, M.M., Srinivas, C.V., Yesubabu, V., Naidu, C.V., Baskaran, R. and Venkatraman, B. (2015) Impact of local data assimilation on tropical cyclone predictions over the Bay of Bengal using the ARW model. Annales de Geophysique, 33, 805–828.

Kidder, S.Q., Goldbrig, M.D., Zehr, R.M., DeMaria, M., Purdom, J.F. W., Veldon, C.S., Grod, N.C. and Kuselsson, S.J. (2000) Satellite analysis of tropical cyclones using Advanced Microwave Sounding Unit (AMSU). Bulletin of the American Meteorological Society, 1, 1241–1259.

Kotal, S.D., Bhattacharya, S.K., Roy Bhowmik, Rama Rao, Y.V., and Sharma, A., 2013. Report on Very Severe Cyclonic Storm Phailin over the Bay of Bengal. New Delhi: IMD (NWP Division) ESSO Ministry of Earth Sciences.

Mandal, M. and Mohanty, U.C. (2010) Simulation of severe landfalling Bay of Bengal cyclones during 1995–1999 using mesoscale model MM5. Marine Geodesy, 33, 315–337.

Mandal, M., Mohanty, U.C. and Raman, S. (2004) A study on the impact of parameterization of physical processes on prediction of tropical cyclones over the Bay of Bengal with NCAR/PSU mesoscale model. Natural Hazards, 31(2), 391–414.

Mandal, M., Singh, K.S., Balaji, M. and Mahapatra, M. (2016) Performance of WRF-ARW model in real-time prediction of Bay of Bengal cyclone ‘Phailin’. Pure and Applied Geophysics, 172, 1–19.

Mohanty, U.C., Osuri, K.K., Routray, A., Mohapatra, M. and Pattanayak, S. (2010) Simulation of Bay of Bengal tropical cyclones with WRF model: impact of initial and boundary conditions. Marine Geodesy, 33, 294–314.

Mohapatra, M., Bandyopadhyay, B.K. and Nayak, D.P. (2013a) Evaluation of operational tropical cyclone intensity forecasts over north Indian Ocean issued by India Meteorological Department. Journal of Applied Meteorology and Climatology, 52, 427–442.

Mohapatra, M., Nayak, D.P., Sharma, R.P. and Bandyopadhyay, B.K. (2013b) Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department. Journal of Earth System Science, 122(3), 589–601.

Murty, P.L.N., Bhaskaran, P.K., Gayathri, R., Sahoo, B., Srinivasa Kumar, T. and SubbaReddy, B. (2016) Numerical study of coastal hydrodynamics using a coupled model for Hudhud cyclone in the Bay of Bengal. Estuarine, Coastal and Shelf Science, 183, 13–27.

Osuri, K.K., Mohanty, U.C., Routray, A., Mohapatra, M. and Niyogi, D. (2013) Real-time track prediction of tropical cyclones over the North Indian Ocean using the ARW model. Journal of Applied Meteorology and Climatology, 52, 2476–2492. https://doi.org/10.1175/JAMC-D-12-0313.1

Osuri, K.K., Mohanty, U.C., Routray, A. and Niyogi, D. (2015) Improved prediction of Bay of Bengal tropical cyclones through assimilation of Doppler weather radar observations. Monthly Weather Review, 143, 4533–4560. https://doi.org/10.1175/MWR-D-13-00381.1

Pattanayak, S., Santhanam, M.S., Potty, K.V.J., Tiwari, M. and Rao, P.L.S. (2000) Simulation of tropical cyclones using regional weather prediction models. Current Science., 79, 70–78.

Pattanayak, S., Mohanty, U.C. and Gopalakrishnan, S.G. (2012) Simulation of very severe cyclone Mala over Bay of Bengal with HWRF modeling system. Natural Hazards., 63, 1413–1437.

Pattanayak, S. and Mohanty, U.C. (2008) A comparative study on performance of MM5 and WRF models in simulation of tropical cyclones over Indian seas. Current Science., 95, 923–936.

Raju, P.V.S., Potty, J. and Mohanty, U.C. (2012) Prediction of severe tropical cyclones over the Bay of Bengal during 2007–2010 using high-resolution mesoscale model. Natural Hazards, 63, 1361–1374. https://doi.org/10.1007/s11069-011-9918-1

Rakesh, V. and Goswami, P. (2011) Impact of background error statistics on forecasting of tropical cyclones over the north Indian Ocean. Journal of Geophysical Research, 116, D20130. https://doi.org/10.1029/2011JD015751

Routray, A., Mohanty, U.C., Osuri, K.K., Kar, S.C. and Niyogi, D. (2016) Impact of satellite radiance data on simulations of Bay of Bengal tropical cyclones using the WRF-3DVAR modeling system.
IEEE Transactions on Geoscience and Remote Sensing, 54(4), 2285–2303.

Ryerson, W.R., Rugg, S., Elsberry, R.L. and Wegiel, J., 2007. Evaluations of the AFWA weather research forecast model Western North Pacific tropical cyclone predictions. Available at: http://ams.confex.com/ams/pdfpapers/108856.pdf [Accessed 15th June 2006].

Sahoo, B. and Bhaskaran, P.K. (2015) Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. International Journal of Climatology, 36, 95–109. https://doi.org/10.1002/joc.4331

Sandeep, S., Chandrasekar, A. and Singh, D. (2006) The impact of assimilation of AMSU data for the prediction of a tropical cyclone over India using a mesoscale model. International Journal of Remote Sensing, 27, 4621–4653.

Singh, K.S. and Bhaskaran, P.K. (2017) Impact of PBL and convection parameterization schemes for prediction of severe land-falling Bay of Bengal cyclones using WRF-ARW model. Journal of Atmospheric and Solar-Terrestrial Physics, 165, 10–24.

Singh, K.S. and Bhaskaran, P.K. (2018) Impact of lateral boundary and initial conditions in prediction of Bay of Bengal cyclones using WRF model and its 3D-Var data assimilation system. Journal of Atmospheric and Solar-Terrestrial Physics, 175, 64–75.

Singh, K.S. and Mandal, M. (2014) Sensitivity of mesoscale simulation of Aila cyclone to the parameterization of physical processes using WRF model. In: Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change. In: Springer, pp. 300–308.

Singh, K.S. and Mandal, M. (2015) Impact of initial and boundary conditions on mesoscale simulation of Bay of Bengal cyclones using WRF-ARW model. In: High-Impact Weather Events over the SAARC Region. Cham: Springer International Publishing, pp. 179–189.

Singh, K.S., Mandal, M. and Bhaskaran, P.K. (2019) Impact of radiance data assimilation on the prediction performance of cyclonic storm SIDR using WRF-3DVAR modelling system. Meteorology and Atmospheric Physics, 131(1), 11–28.

Singh, K.S. and Tyagi, B. (2019) Impact of data assimilation and air-sea flux parameterization schemes on prediction of cyclone Phailin over Bay of Bengal using WRF-ARW model. Meteorological Applications, 26(1), 36–48.

Singh, O.P., Khan, T.M.A. and Rahman, S. (2000) Changes in the frequency of tropical cyclones over the North Indian Ocean. Meteorology and Atmospheric Physics, 75, 11–20.

Skamarock, W.C., Joseph B. Klemp, Jimy Dudhia, David O. Gill, Dale M. Barker, Wei Wang, Jordan G. Powers, 2008. A description of the advanced research WRF version 3. NCAR Technical Note. NCAR/TN-475+ STR. Boulder, CO: University Corporation for Atmospheric.

Srinivas, C.V., Bhaskar Rao, D.V., Yesubabu, V., Baskaran, R. and Venkatraman, B. (2013) Tropical cyclone predictions over the Bay of Bengal using the high-resolution Advanced Research Weather Research and Forecasting (ARW) model. Quarterly Journal of the Royal Meteorological Society, 139(676), 1810–1825.

Srinivas, C.V., Venkatesan, R., Bhaskar Rao, D.V. and Prasad, D.H. (2007) Numerical simulation of Andhra severe cyclone (2003): model sensitivity to the boundary layer and convective parameterization. Pure and Applied Geophysics, 164, 1465–1487.

Srinivas, C.V., Yesubabu, V., Hariprasad, R.B.R.R., Ramarkrishna, S.S.V. and Venkatraman, B. (2012) Real time prediction of a severe cyclone Jal over Bay of Bengal using a high-resolution mesoscale model WRF-ARW. Natural Hazards, 65, 331–357. https://doi.org/10.1007/s11069-012-0364-5

Srinivas, C.V., Yesubabu, V., Venkatesan, R. and Ramarkrishna, S.S.V. (2010) Impact of assimilation of conventional and satellite meteorological observations on the numerical simulation of a Bay of Bengal tropical cyclone of November 2008 near Tamilnadu using WRF model. Meteorology and Atmospheric Physics, 110, 19–44.

Srivastav, A.K., Sinha Ray, K.C. and De, U.S. (2000) Trends in the frequency of cyclonic disturbances and their intensification over Indian Seas. Mausam, 51, 113–118.

Yesubabu, V., Srinivas, C.V., Hariprasad, K.B.R.R. and Baskaran, R. (2014) A study on the impact of observation assimilation on the numerical simulation of tropical cyclones JAL and THANE using 3DVAR. Pure and Applied Geophysics, 171(8), 2023–2042.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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