Impact of cloud parameterization schemes on the simulation of cyclone *Vardah* using the WRF model

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The objective of this study is to examine the sensitivity of cumulus and microphysics schemes when simulating the track, intensity and inner core structure of the very severe cyclonic storm (VSCS) *Vardah* using the Weather Research and Forecasting (WRF) model. Four cumulus parameterization schemes (CPS) and six microphysics schemes (MPS) were used. Both the track and intensity of cyclone *Vardah* are seen to be sensitive to the CPS and MPS. New simplified Arakawa–Schubert scheme (NSAS) as CPS and Kessler scheme (KS) as MPS combination has better predicted the track and intensity of the cyclone with respect to the Indian Meteorological Department (IMD) data when compared to other schemes. To verify the robustness of the best set of schemes for cyclone *Vardah*, two random sets of schemes as well as the best set of schemes were run for cyclones *Hudhud* and *Thane.*

Keywords: Cyclone *Vardah*, cumulus parameterization, microphysics parameterization, WRF model.

TROPICAL cyclones cause torrential rains, intense winds and large storm surges at the location of landfall in tropical regions all over the world. On an average, about 3–4 cyclonic storms form in the Bay of Bengal annually[1]. Although this frequency is less when compared to other regions like the Atlantic and Pacific basins, the accompanying damage during landfall is severe due to high-population density, flat and low-lying coastal terrain and shallow bathymetry[2–4]. Studies[5,6] show that there has been an increase in intensity of tropical cyclones across all the basins in the world. The intensity of tropical cyclones in the Bay of Bengal region in particular during the post-monsoon season (October–December) increased over the years[7]. In a recent study[8], it was reported that the frequency may rise further. In view of the above, there is a pressing need to predict the track and intensity of tropical cyclones in this region, to make well-informed decisions to better mitigate the effects of the disaster.

Over the years, continuous development and improvement of numerical weather prediction models and growing computational power have improved model resolution and accuracy of predictions. Cloud processes are important for track and intensity prediction as they are responsible for production and distribution of heat, mass and momentum, both horizontally and vertically, in the atmosphere with the help of precipitation, winds and turbulence[9]. When the cloud processes cannot be resolved by a numerical model, then parameterization in terms of variables at grid points becomes imperative. Cloud processes are treated in the model, implicitly by a cumulus parameterization scheme (CPS) and explicitly by a cloud microphysics scheme (MPS). CPS removes the convective instability and MPS allows treating the cloud precipitation processes on the convectively stable and nearly neutral layer[10]. Both these schemes control the spatial and temporal distribution of precipitation and consequently yield distinct vertical profiles of heating and moistening in the atmosphere. Both the parameterizations together contribute to the representation of convection in the model without double-counting its thermodynamic impacts[11].

Several studies[12–15] have addressed the effect of physics parameterizations on the cyclones in North Indian Ocean (NIO) region. A study on the sensitivity of parameterization schemes during cyclone *Jal* revealed that cumulus, microphysics and planetary boundary layer (PBL) parameterizations had greater effect on the simulation of track and intensity of the cyclone compared to other parameterizations[16]. Yonsei University (YSU) PBL Scheme and Kain–Fritsch CPS were found to simulate better track and intensity in a study that was carried out on 5 different cyclones of 2008 in the NIO region[17]. A cloud parameterization sensitivity in the MM5 model on a super cyclone suggests that explicit convection in the innermost domain with less than 5 km resolution predicts the intensity better than when a CPS scheme is used[18]. YSU as PBL, BMJ as CPS and WSM6 as MPS produced a better forecast of track and intensity in a parameterization sensitivity study done on cyclone *Laila*[19]. The WRF model produced good predictions of the tropical cyclones in the Bay of Bengal when a study was carried out for 21 cyclonic storms[20].

Cyclone *Vardah* wreaked havoc during the post-monsoon season of 2016 in the states of Tamil Nadu and Andhra Pradesh. About 26 deaths were reported and about 16,000 people were evacuated. Infrastructure

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and crops were also heavily damaged. The present study addresses the impact of CPS and MPS on the track, intensity, rainfall and inner core structure of the very severe cyclonic storm *Vardah* using the WRF model.

Synoptic history of cyclone *Vardah*

Vardah, the first severe cyclonic storm in 2016, had a recurving track with an initial northwards movement to west-northwestwards and then west-southwestwards after landfall. It developed from a low pressure area over the south Andaman Sea adjoining Sumatra on 4 December morning. It lay as a well marked low pressure area on the night of 5 December 2016 over south Andaman Sea and adjoining the southeast Bay of Bengal. Moving westwards, it concentrated into a depression over the southeast Bay of Bengal in the afternoon of 6 December. Moving northwestwards initially and northwards thereafter, it intensified into a deep depression in the midnight of 7 December, into a cyclonic storm on 8 December morning and into a severe cyclonic storm on 9 December midnight. It then moved west-northwestwards and intensified further into a very severe cyclonic storm over the west-central and the adjoining south Bay of Bengal on the evening of 10 December. The storm then moved nearly westwards and reached its peak intensity of about 36 m/s on 11 December evening and maintained the same intensity till noon on 12 December. It weakened into a severe cyclonic storm at the time of landfall and then crossed north Tamil Nadu coast near Chennai between 1500 and 1700 IST (0930–1130 UTC) on 12 December 2016 with a wind speed of 30.5 m/s gusting to 35 m/s. After landfall, the system moved west-southwestwards and weakened gradually to a depression by the evening of 13 December.

Model description, data and methodology

The model used in this study is the Advanced Research WRF (WRF-ARW) model[21] version 3.7.1, a non-hydrostatic compressible meso-scale model developed by the National Centre for Atmospheric Research (NCAR). The model domains, resolution and physics schemes used are illustrated in Table 1 and the domains are shown in Figure 1. All domains were discretized into 30 vertical terrain following sigma (σ) layers with a higher resolution in the boundary layer. A detailed description of all parameterization schemes available in WRF model can be found elsewhere[22]. Experiments related to CPS sensitivity were carried out on two domains (D1 and D2), whereas experiments related to MPS sensitivity were carried out on three domains (D1, D2 and D3). The initial and boundary conditions were provided by the Global Forecast System (GFS) model run with $0.5° \times 0.5°$ resolution. Three-hourly output data from the GFS model were used to obtain the lateral boundary conditions for the WRF model. The boundary conditions of the inner fine domains were provided by the outer coarser domains. Since a two-way nesting was used in this study, the solutions from the finer mesh were input back to update the coarser mesh after every timestep. Since the landfall of the cyclone occurred between 0930 and 1130 UTC on 12 December, the model was initiated approximately 72 h before the landfall (12 UTC on 9 December 2016) and was allowed to run for 84 h (00 UTC on 13 December). The model initiation and runtime were the same for all runs.

A sensitivity study with respect to CPS was performed initially using four schemes namely Kain–Fritsch[23] (KF), New Simplified Arakawa–Schubert[24] (NSAS), Betts–Miller–Janjic[25] (BMJ) and Grell–Devenyi Ensemble[26] (GDES) schemes. In all the four runs, Kessler scheme was used as the microphysics scheme and other schemes were as mentioned in Table 2.

In the study of CPS sensitivity, all parameters were constant in the runs except for CPS. The model output was saved every 6 h. Since the simulations were run on two domains, the values from domain 2 which was the finer domain were used for the analysis.

The best scheme that was determined from the CPS sensitivity study was the one with the lowest RMS errors of track and intensity. Upon doing this, the best cumulus scheme was employed for carrying out the MPS sensitivity study. This study was performed using six microphysics schemes namely Kessler[27] (KS), WRF single-moment 3-class[28] (WSM3), WRF single-moment 6-class[29] (WSM6), Lin *et al.*[30] (LIN), Thompson[31] (TS) and Morrison 2-moment[32] (MOR) schemes.

In the MPS sensitivity study, all other parameters were constant except for the MPS. CPS was not used in domain 3 and explicit convection was allowed, as the domain had a resolution less than 5 km (ref. 18). The model output was saved every 3 h. Since the simulations were run on three domains, the values from domain 3 that has the finest resolution were used for the analysis.

The track and intensity simulated from the model were evaluated against IMD data[33], whereas the rainfall was validated against the Tropical Rainfall Measurement Mission (TRMM 3B42-V7) data[34]. The 3B42 version 7 product is available over the regions between 60°N and 60°S, with a spatial resolution of $0.25° \times 0.25°$ and with a temporal resolution of 3 h.

After obtaining the best set of schemes for cyclone *Vardah*, there was a need to verify the robustness of best set of schemes for other cyclones. For this purpose, two cyclones namely extremely severe cyclonic storm *Hudhud* (2014) and very severe cyclonic storm *Thane* (2011) were chosen and two random sets of schemes along with the best set of schemes obtained for cyclone *Vardah* were chosen as parameterization schemes. The simulations for both cyclones were started 72 h before landfall and were run for 84 h just as in the case for cyclone *Vardah*. In the

Table 1. Overview of the model configuration used in the present study

Model configuration	Details
Initial and lateral boundary conditions data	Global forecast system (GFS) model 0.5° × 0.5° data
Model integration time	From 9 December 12 UTC to 13 December 00 UTC, 2016 (84 h)
Horizontal resolution	27 × 27 km in domain 1 (D1) 9 × 9 km in domain 2 (D2) 3 × 3 km in domain 3 (D3)
Central point for D1	13°N, 92°N
Number of horizontal grid points in *X* and *Y* directions	D1 – 450 × 350 D2 – 580 × 490 D3 – 790 × 670
Number of domains in a run	Two domains (D1 and D2 only) for CPS sensitivity runs Three domains for MPS sensitivity runs
Time step	120 sec, 40 sec, 13.33 sec for D1, D2 and D3 respectively

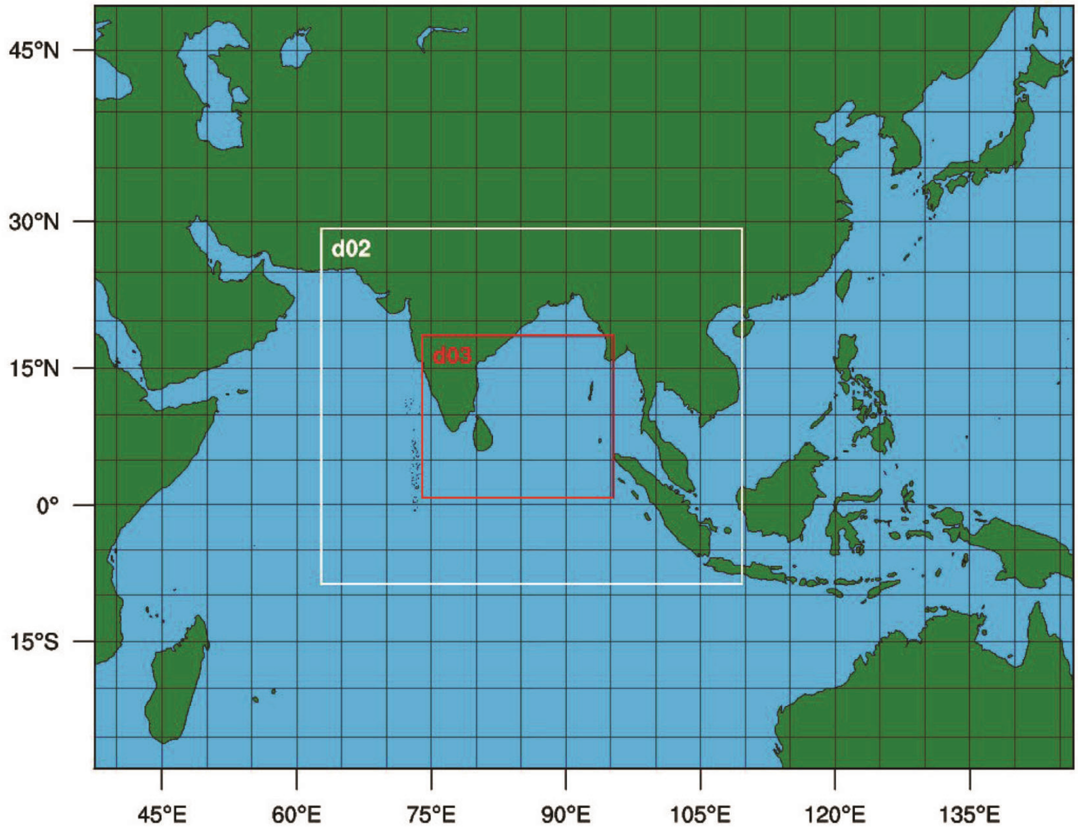

Figure 1. Configuration of model domains used in the present study.

two selected random schemes, all schemes excluding CPS and MPS were the same as in cyclone *Vardah*. In the first random set (Random 1), KF, as CPS and WSM3, was used as MPS whereas in the second random set (Random 2), BMJ was chosen as CPS and TS was chosen as MPS. The simulations were validated against IMD data.

Results and discussion

In the first set of experiments, a sensitivity study was carried out on the four CPS. Cyclone tracks, track errors, absolute errors of central sea level pressure (CSLP) and maximum surface wind (MSW) are plotted in Figure 2 *a–d.* All simulated tracks showed an initial error of 44 km with respect to IMD track data and all tracks were found to be moving in the westward direction. A marker is placed for every 12 h of forecast on the cyclone track in this figure. All tracks have a northward bias when compared to the IMD track data. Figure 2 *b* shows that the track error is least for NSAS till about 54 h of the forecast time whereas BMJ has lesser track error between 54 and 84 h of the forecast time. Overall, it was observed that the NSAS

Table 2. Overview of the parameterization schemes used in the present study

Physics option	Parameterization scheme
Cumulus parameterization	Kain–Fritsch scheme New simplified Arakawa–Schubert scheme Betts–Miller–Janjic scheme Grell–Devenyi ensemble scheme
Microphysics	Kessler scheme WRF Single–moment 3-class scheme WRF Single–moment 6-class scheme Lin *et al.* scheme Thompson scheme Morrison 2–moment scheme
Planetary boundary layer	Mellor–Yamada Nakanishi Niino (MYNN) Level 2.5 scheme
Radiation longwave	Rapid radiative transfer model (RRTM) longwave scheme
Radiation shortwave	RRTM for global circulation models (RRTMG) shortwave scheme
Land surface	Rapid update cycle (RUC) land surface model
Surface layer	Mesoscale model (MM5) similarity scheme

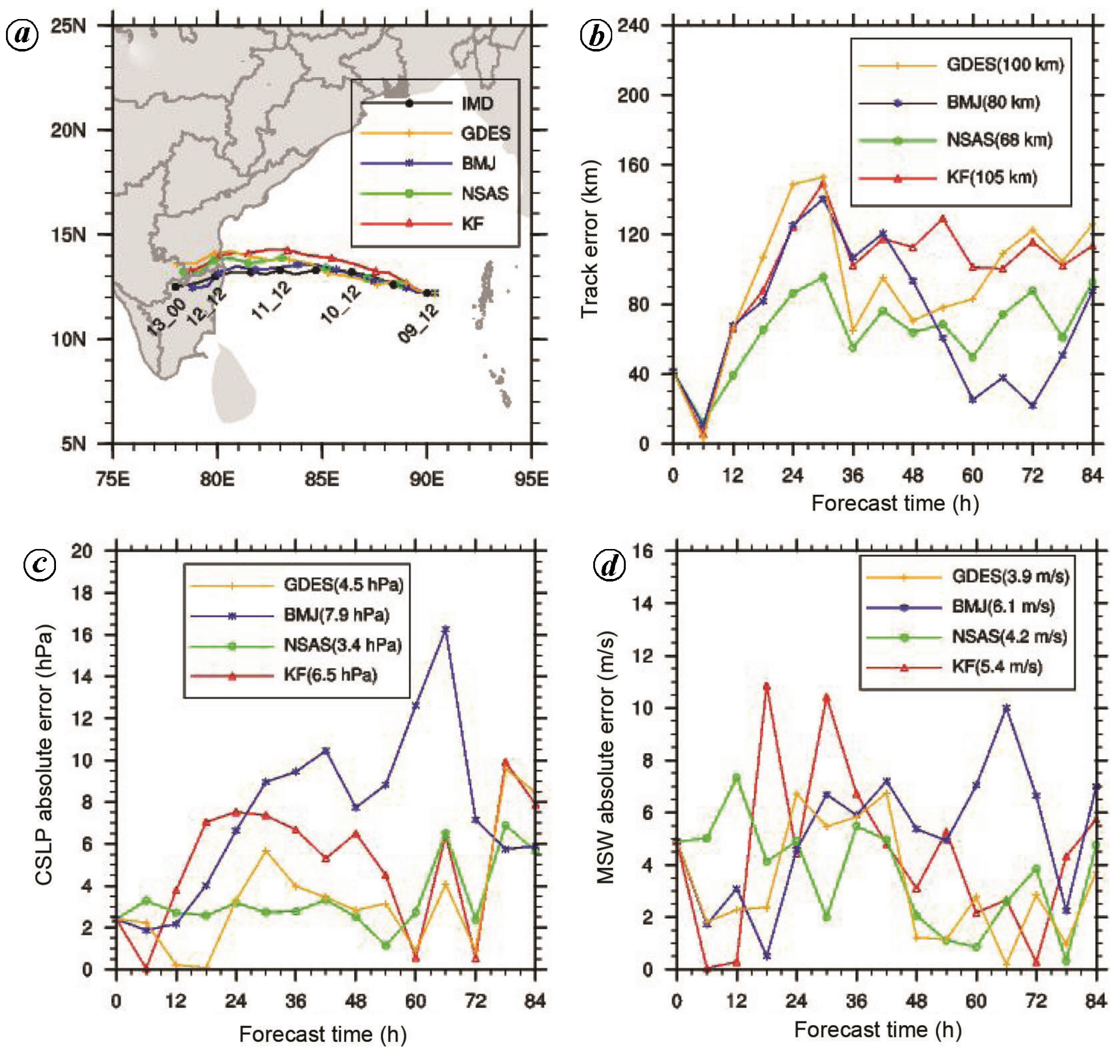

Figure 2. (***a***) Model simulated tracks along with IMD track and time series plots of (***b***) track error (in km), (***c***) central sea level pressure absolute error (in hPa) and (***d***) maximum surface wind absolute error (in m/s) for CPS sensitivity study. The values in the brackets represent RMS error.

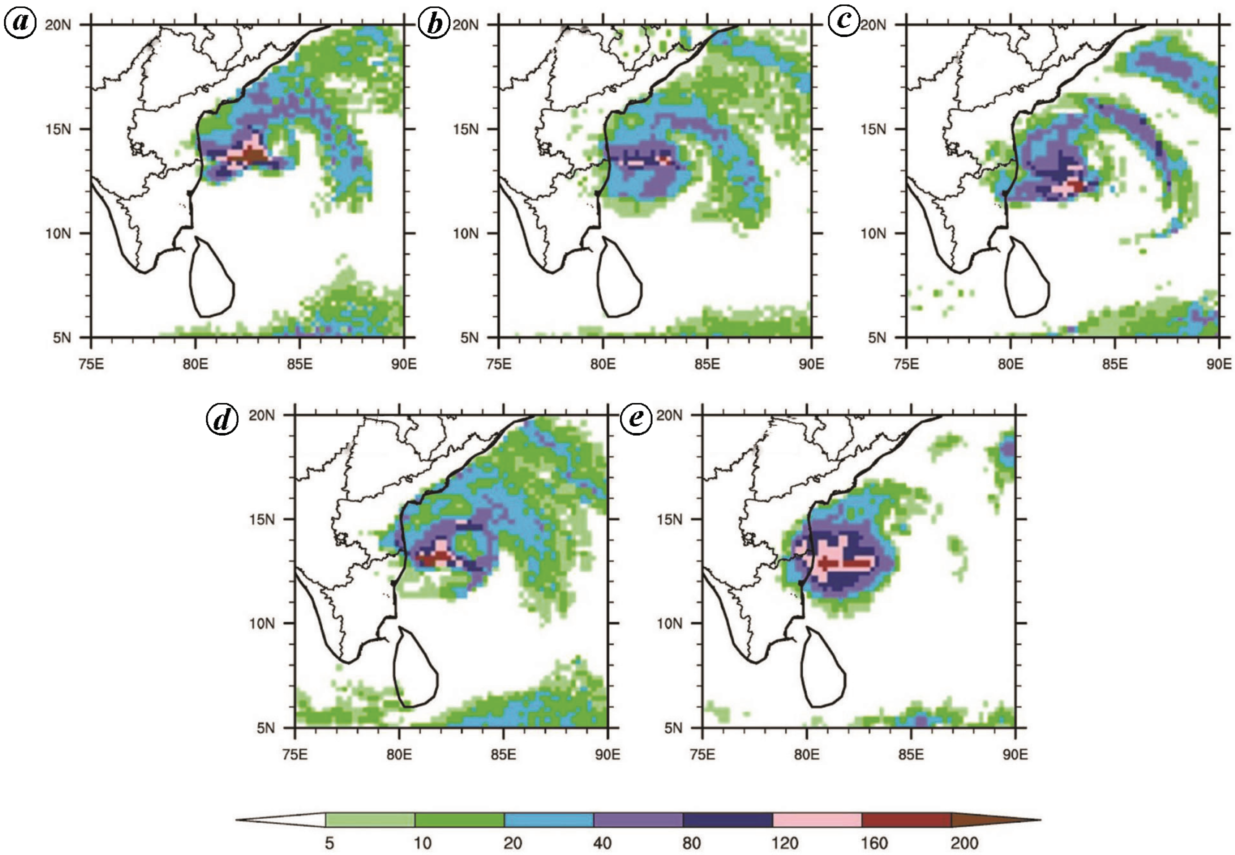

Figure 3. 24 h accumulated rainfall (in mm) before landfall for (***a***) KF, (***b***) NSAS, (***c***) BMJ, (***d***) GDES, (***e***) TRMM data for CPS sensitivity study.

(68 km) had the lowest RMS error followed by BMJ (80 km). In Figure 2 *c–d*, the absolute errors of CSLP and MSW are plotted with respect to forecast time and it is observed that NSAS and GDES schemes simulate the values of CSLP and MSW close to the IMD data. This is reflected in RMS errors in which NSAS shows values of 3.4 hPa and 4.2 m/s and GDES shows values of 4.5 hPa and 3.9 m/s respectively. KF scheme predicted a more intense storm and BMJ has predicted a storm with lesser intensity.

In Figure 3, the 24 h accumulated precipitation before the landfall of the cyclone for all the schemes is plotted and compared with TRMM data. The model simulated precipitation is re-gridded to the TRMM grid with $0.25° \times 0.25°$ spatial resolution before the comparison. Since landfall has occurred between 9 and 12 UTC on 12 December 2016, the 24 h accumulated rainfall between 06 UTC of 11 December and 6 UTC of 12 December was plotted. The KF scheme simulated the intensity of precipitation, but the system was displaced northwards. The NSAS scheme simulated the location of rainfall well but it underpredicted the intensity. Both BMJ and GDES predicted the rainfall intensity but as it was slow moving system, rainfall was predicted on the east and on the north of actual rainfall respectively. No scheme among these could predict the spatial distribution of the rainfall with reference to the TRMM data accurately.

From Figures 2 and 3, one can say that NSAS has better all round prediction of track, intensity and rainfall compared to other schemes. The NSAS was therefore used as the CPS in the study of MPS sensitivity.

In the second set of experiments, a sensitivity study was carried out on six MPS. In Figure 4 *a–d*, cyclone tracks, track errors, absolute errors of CSLP and MSW are plotted. Figure 4 *a* and *b* indicates that only the KS track follows IMD track closely and all other schemes have a northwestward bias in their tracks. Similar to CPS study, all tracks have an initial track error of 44 km. Till 48 h into the forecast, all the schemes follow the actual track closely but after that all tracks move northwestwards except for the KS track. Therefore, KS has the least RMS track error (64 km), whereas all other schemes have an RMS track error in excess of 100 km. In Figure 4 *c* and *d*, absolute errors of CSLP and MSW are plotted with respect to forecast time respectively. In Figure 4 *c*, KS and LIN have CSLP values close to IMD data as reflected in RMS errors, whereas KS has an RMS error of 5.3 hPa and the LIN scheme has an RMS error of 5.2 hPa. All other schemes have predicted a higher CSLP value compared to actual values. In Figure 4 *d*, MSW values

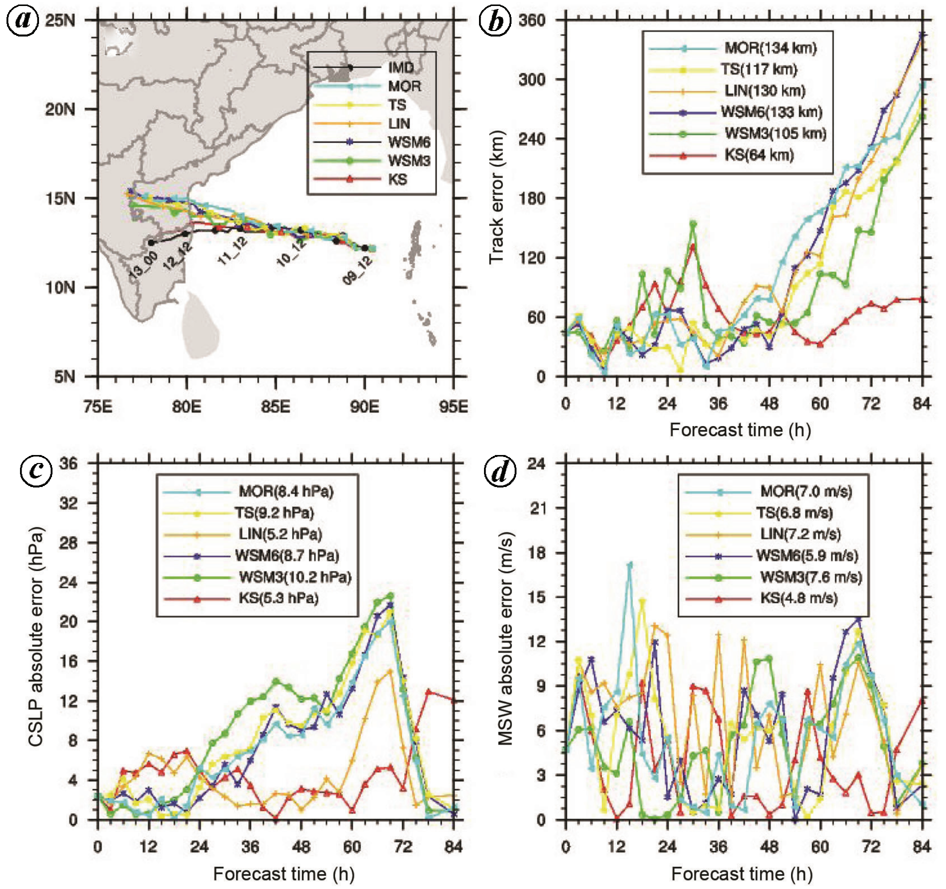

Figure 4. (***a***) Model simulated tracks along with IMD track and time series plots of (***b***) track error (in km), (***c***) central sea level pressure absolute error (in hPa) and (***d***) maximum surface wind absolute error (in m/s) for MPS sensitivity study. The values in the brackets represent RMS error.

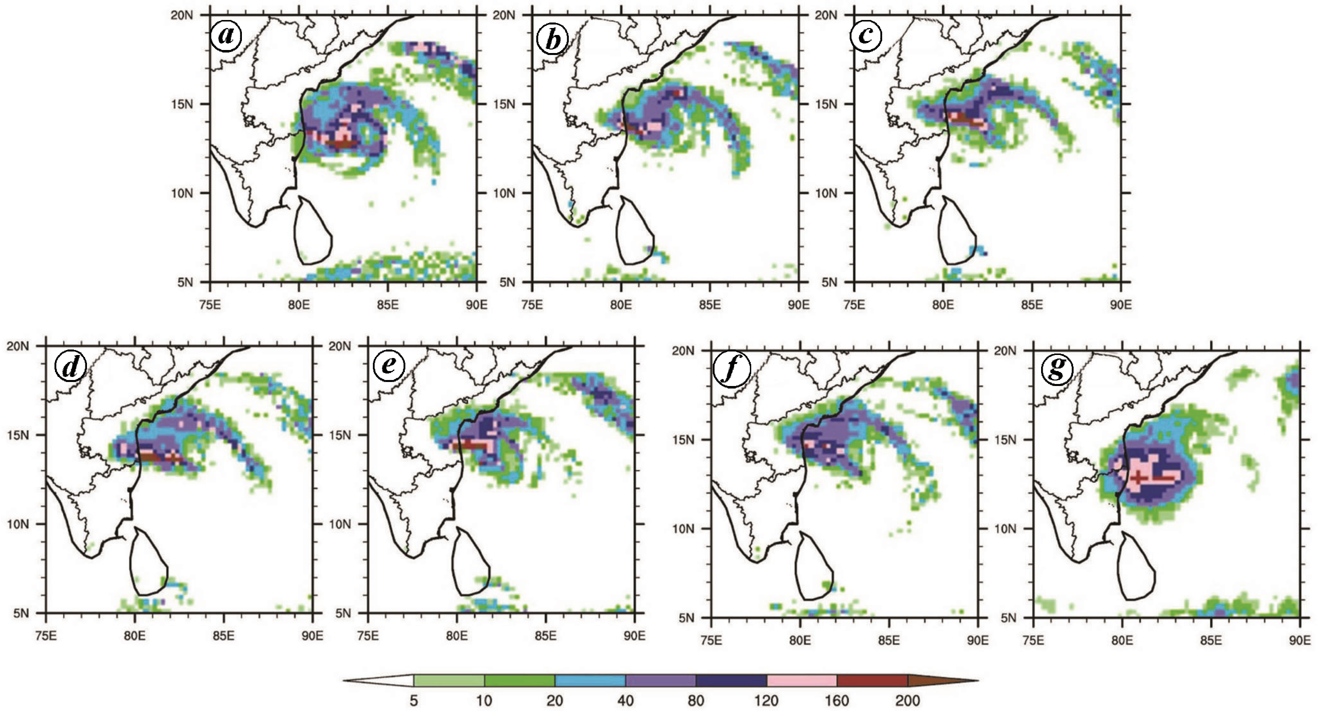

Figure 5. 24 h accumulated rainfall (in mm) before the landfall for (***a***) KS, (***b***) WSM3, (***c***) WSM6, (***d***) LIN, (***e***) TS, (***f***) MOR, (***g***) TRMM data for MPS sensitivity study.

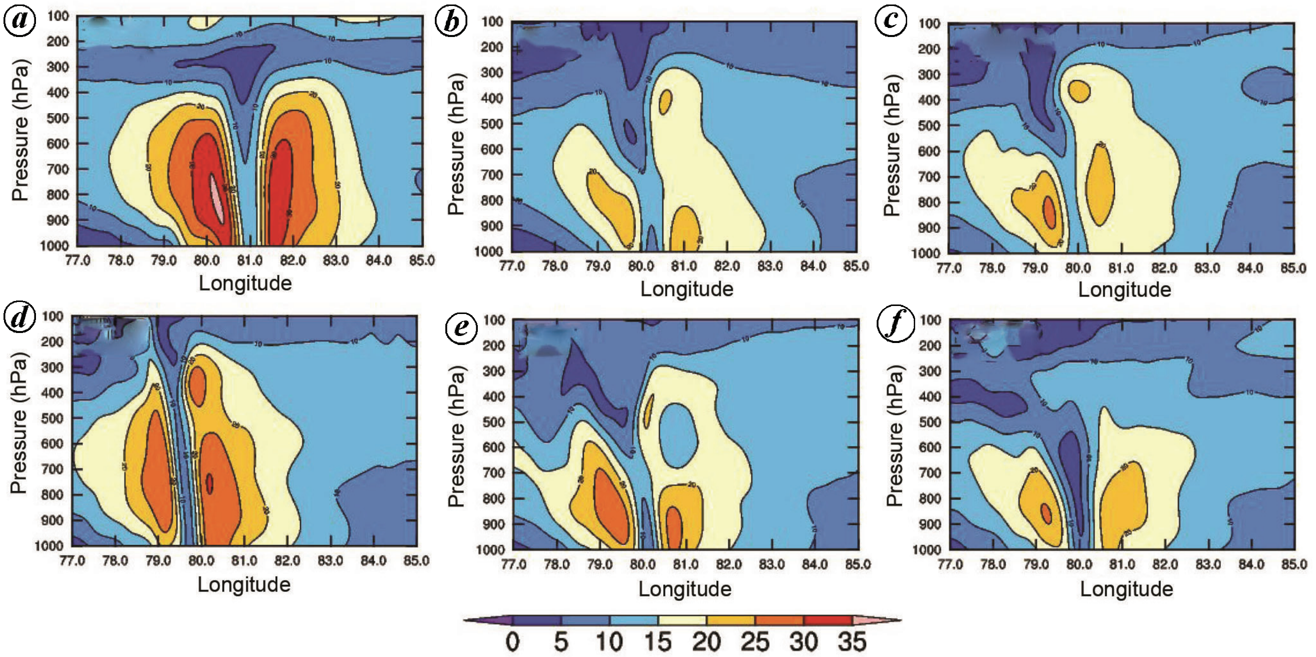

Figure 6. East-west cross section of horizontal velocity (in m/s) through the centre of the cyclone for various MPS (***a***) KS, (***b***) WSM3, (***c***) WSM6, (***d***) LIN, (***e***) TS, (***f***) MOR at 06 UTC on 12 December 2016.

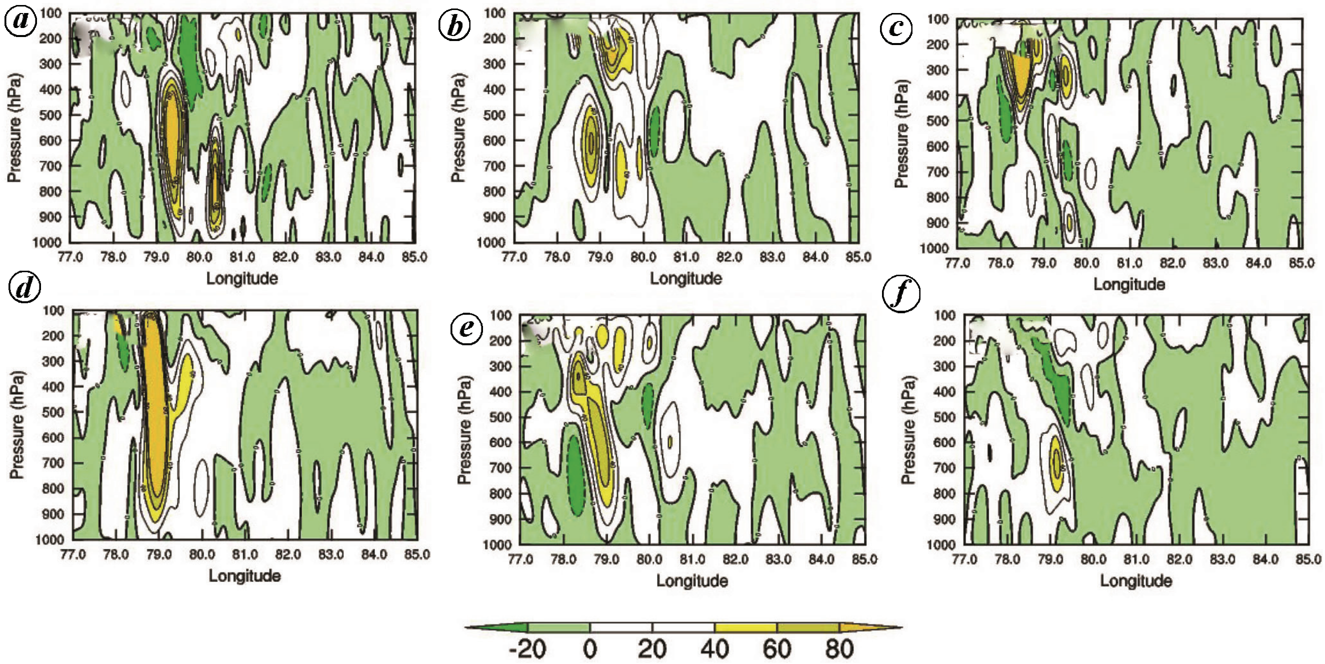

Figure 7. East-west cross section of vertical velocity (in cm/s) through the centre of the cyclone for various MPS (***a***) KS, (***b***) WSM3, (***c***) WSM6, (***d***) LIN, (***e***) TS, (***f***) MOR at 06 UTC on 12 December 2016.

from the KS scheme are seen to follow the IMD data quite closely. In the remaining schemes, some have over-predicted and some have under-predicted the MSW values. KS has the lowest RMS error value of 4.8 m/s for MSW.

In Figure 5, the 24 h accumulated precipitation before the landfall of the cyclone has been plotted for all schemes and compared with the TRMM data. Of all the schemes, only KS simulated the intensity and location of the rainfall well compared to other schemes. As was

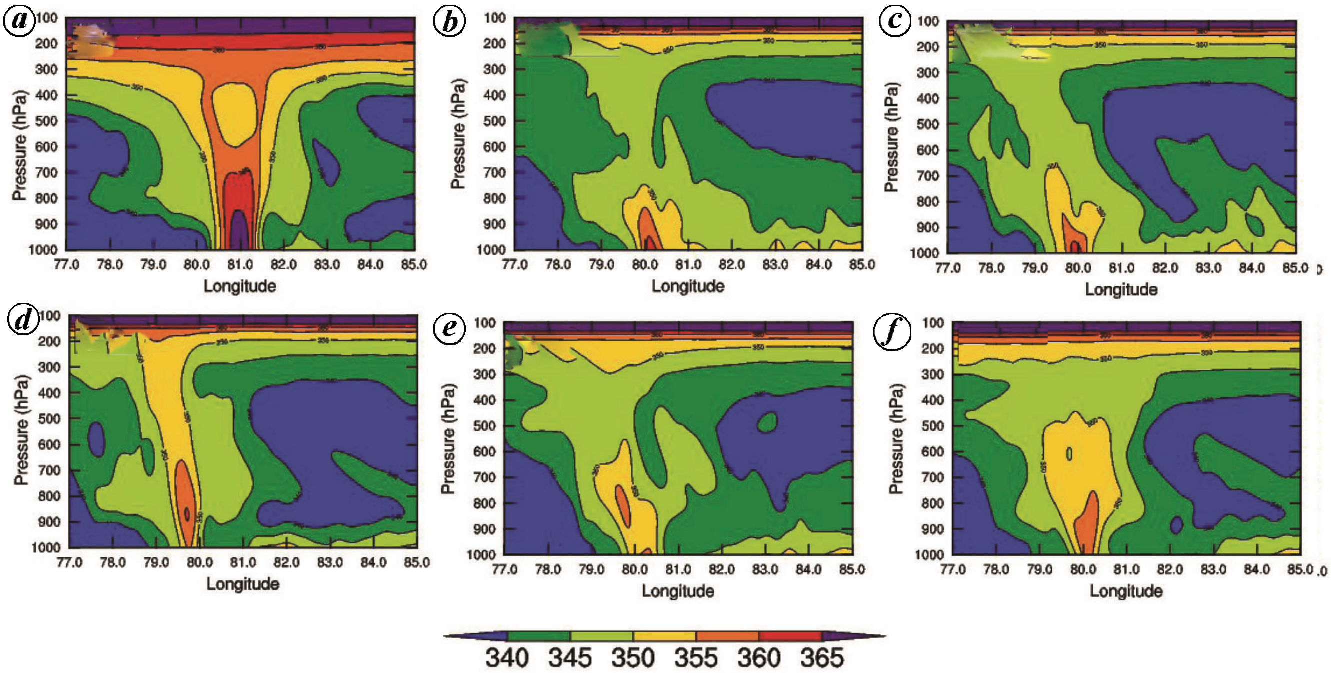

Figure 8. East-west cross section of equivalent potential temperature (in K) through the centre of the cyclone for various MPS (***a***) KS, (***b***) WSM3, (***c***) WSM6, (***d***) LIN, (***e***) TS, (***f***) MOR at 06 UTC on 12 December 2016.

observed in the case of tracks, all other schemes simulated precipitation towards north of the actual location. Even the spatial distribution of rainfall with respect to the TRMM data was simulated well in KS compared to other schemes.

After the track, intensity and rainfall, the sensitivity of MPS to the inner core structure of the cyclone was studied. The east-west cross-section of horizontal velocity, vertical velocity and equivalent potential temperature were plotted at the most intense stage of cyclone *Vardah*. From the IMD data, it was observed that a minimum CSLP of 975 hPa and a maximum of MSW of 36 m/s were recorded for the cyclone at 06 UTC on 12 December 2016. The output of the model at this time was therefore used for analysis of the inner structure of the cyclone. In Figure 6, the east-west cross sections of the six MPS have been plotted. Well-defined eye-walls with speeds exceeding 35 m/s were simulated by KS. In the KS scheme, proper delineation was present on both sides of the eye and strong horizontal winds were extended vertically till 400 hPa. The eyewall was moderately delineated in the case of LIN and TS schemes and the wind speed was under predicted. In the case of WSM3, WSM6 and MOR, eyewall was improperly delineated and the speed was also under predicted.

Vertical velocity also plays an important role in determining the kinetic structure of the cyclone. In Figure 7, the east-west cross-sections of the vertical velocity for the 6 MPS are plotted. Only KS and LIN showed strong updrafts ranging from 40 to 80 cm/s in mid-levels which is important for cyclone intensity. Both schemes produced significant updrafts on the western side of the eye with the updraft from LIN being the strongest. These updrafts near the eye allow inflow of sensible heat and latent heat from the outer regions to the inner core of the cyclone and helps in its intensification. In schemes other than KS and LIN, no significant updrafts in the mid levels were found.

Figure 8 shows the east-west cross-sections of the equivalent potential temperature for the six MPS. An intense warming ($\theta_e > 350$ K) in inner core of the storm can be found in KS and LIN schemes. This is one of the key markers of a severe cyclonic storm[35]. KS scheme produced much higher values of θ_e (more than 365 K) near the surface which is not the case in the LIN scheme. The warm inner core structures and significantly higher values of θ_e near the surface could be attributed to the large scale upward surface fluxes of sensible and latent heat from the underlying warm ocean due to strong updrafts in the eyewall region and the substantial reduction in cooler penetrative downdrafts because of the increased warming tendencies in the core region of the cyclone[36].

From the above results and the accompanying discussion, it is evident that KS scheme is superior to other schemes for simulating track, intensity, precipitation and the inner core structure of cyclone *Vardah*. KS scheme successfully captured the eye, eyewall and outer region of the storm.

Cyclone tracks, track errors, absolute errors of CSLP and MSW plotted for cyclone *Hudhud* with the best set of

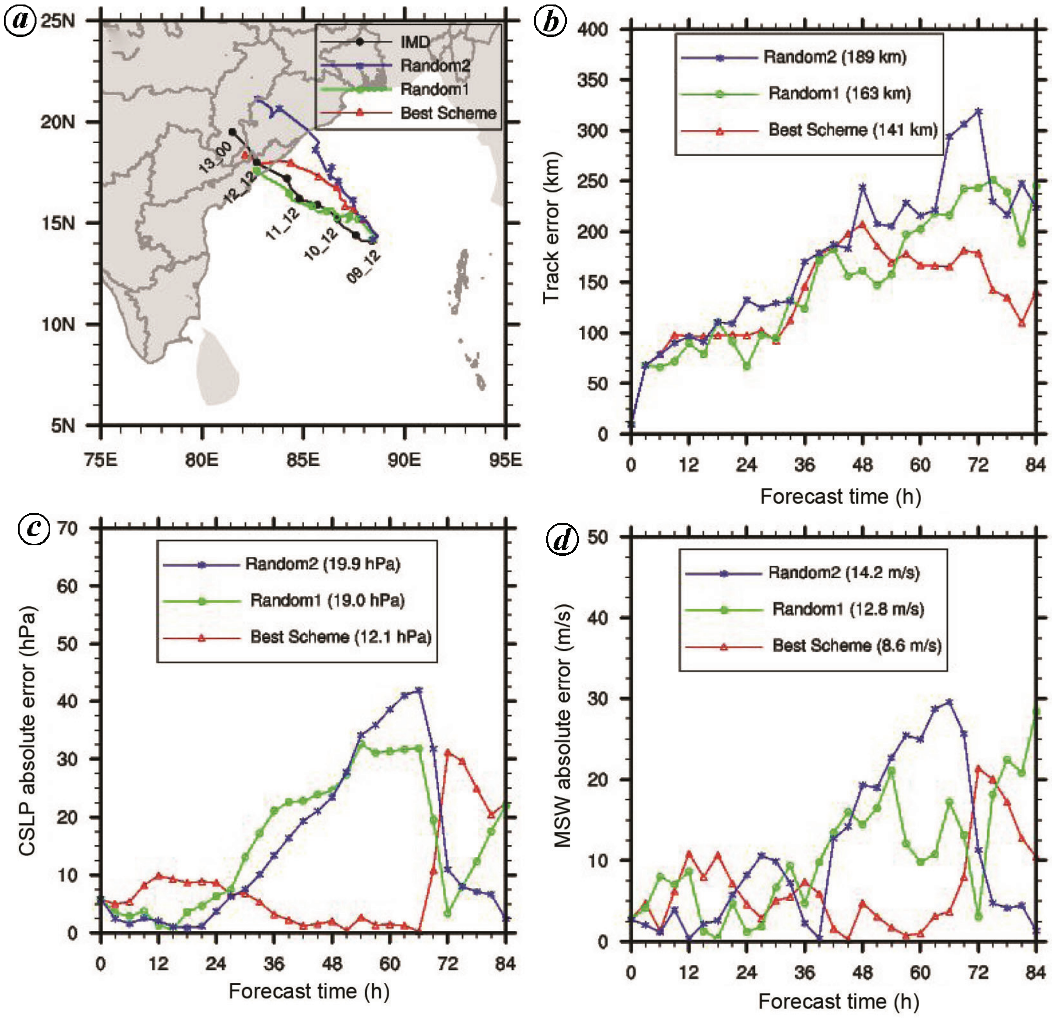

Figure 9. (***a***) Model simulated tracks along with IMD track and time series plots of (***b***) track error (in km), (***c***) central sea level pressure absolute error (in hPa) and (***d***) maximum surface wind absolute error (in m/s) for cyclone *Hudhud*. The values in the brackets represent RMS error.

schemes and 2 random sets of schemes are shown in Figure 9 *a–d*. Those plotted for cyclone *Thane* are shown in Figure 10 *a–d*. Although RMS track errors show more or less the same performance across simulations performed for cyclone *Thane*, the best set of schemes performed better than the two random sets of schemes across all parameters such as RMS errors of track, CSLP and MSW for both the cyclones. The best set of schemes shows smaller RMS errors of CSLP and MSW.

Conclusion

A sensitivity study of cumulus and microphysics parameterizations on cyclone *Vardah* was conducted using the WRF model. Simulations were started from 12 UTC on 9 December 2016 – around 72 h before the landfall. The model was integrated for 84 h till 00 UTC on 13 December. First, a CPS sensitivity study was carried out and with the best CPS, a study on MPS sensitivity study was carried out. The CPS sensitivity study was conducted on two domains with four CPS schemes KF, NSAS, BMJ, GDES. NSAS scheme was better in predicting the track, intensity and precipitation compared to other schemes.

With NSAS as CPS, a sensitivity study was performed on microphysics parameterization. In this case, all the three domains were considered but the convection was explicitly resolved without the use of cumulus scheme in the innermost domain. MPS sensitivity study was conducted using six schemes KS, WSM3, WSM6, LIN, TS and MOR. The track, intensity, precipitation and inner core structure of the cyclone were studied and KS scheme could simulate these parameters accurately. Additionally the eye, eyewalls and the outer regions were also clearly simulated by the KS scheme.

The results demonstrate that the track, intensity, precipitation and inner core structure of a cyclone are sensitive to cloud parameterizations. NSAS scheme as CPS and KS as MPS could accurately predict cyclone *Vardah*.

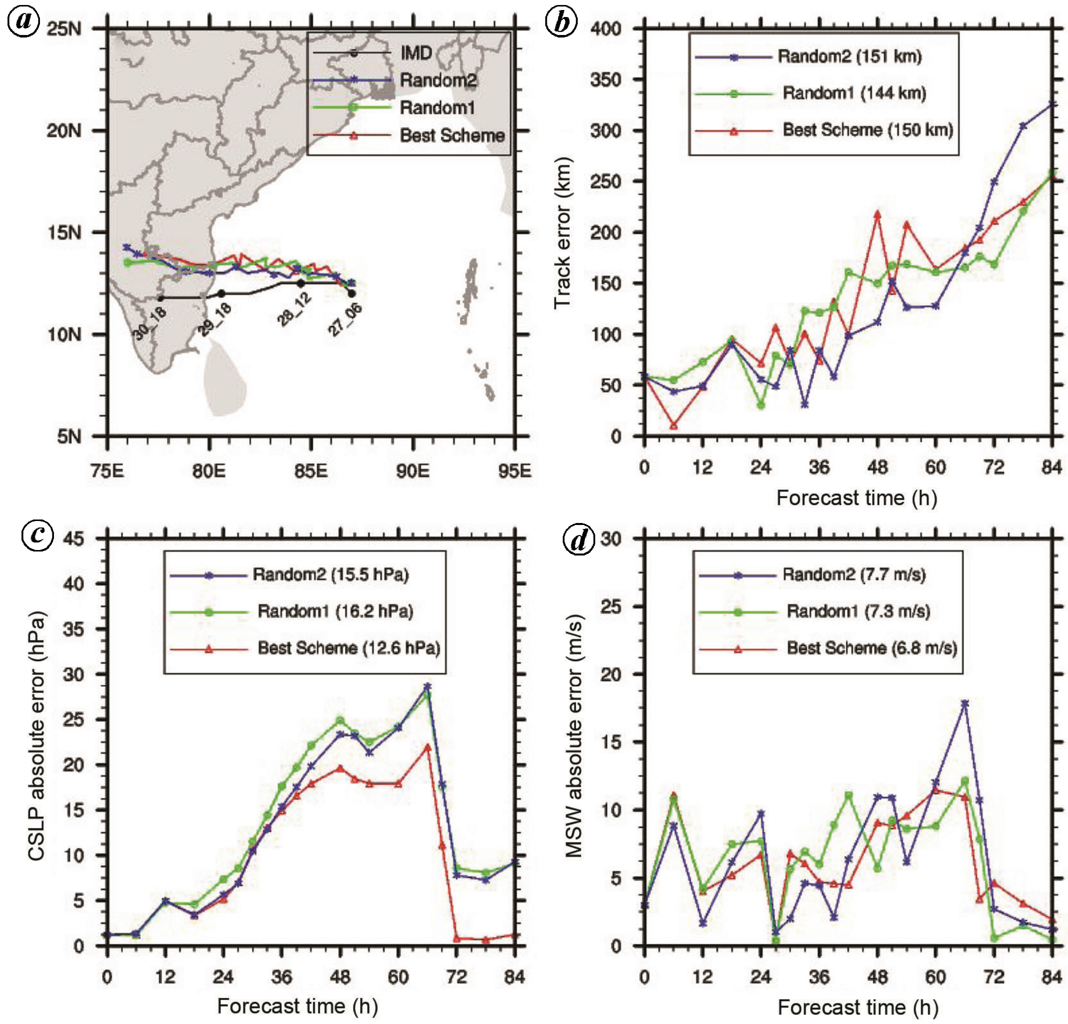

Figure 10. (***a***) Model simulated tracks along with IMD track and time series plots of (***b***) track error (in km), (***c***) central sea level pressure absolute error (in hPa) and (***d***) maximum surface wind absolute error (in m/s) for cyclone *Thane*. The values in the brackets represent RMS error.

Dynamic aspects of the cyclone were studied with the help of a numerical model. More realistic/observed features of the cyclone were simulated well with this particular set of physics options.

Based on the analysis of many cyclones, it can be concluded that the best set of schemes for cyclone *Vardah* performs better than the random sets of schemes. This corroborates the robustness of the proposed best set of schemes.

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