



Numerical Simulation of an Extremely Severe Cyclonic Storm Hudhud over the North Indian Ocean in a Medium Range Scale: Influence of Cloud Microphysical Schemes

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Abstract—One of the most challenging tasks in atmospheric modeling is accurate spatio-temporal forecasting of extremely severe cyclonic storms (ESCSs). This study critically examined the numerical simulation of ESCS Hudhud, which formed over the North Indian Ocean basin in October 2014 on a medium-range (7-day) scale using six different cloud microphysical schemes of the Weather Research and Forecasting model. NCEP PREBUFR observation was used to improve the initial condition using a three-dimensional variational data assimilation system. A 7-day simulated track, intensity, and rapid intensification of ESCS were validated against the India Meteorological Department best-fit track observations. The least track error was about 42 km, 67 km, 87 km, and 192 km from Day 4 to Day 7 by using the Goddard Microphysical Scheme (MPS). Mean track error for 7 days was about 129 km, followed by the Lin MPS (~ 136 km) and WSM6 MPS (~ 139 km). The least mean absolute error in maximum surface winds is ~ 4 m/s using the Goddard, Lin, and WSM19 MPSs with a correlation coefficient > 0.93. Probability of detection for rapid intensification/dissipation was about 70% using WSM6 and Goddard MPSs, which was relatively better compared to other MPSs. Results clearly demonstrate that latent heating between 500 and 200 hPa was very important and contributed to intensification, and the maximum magnitude of latent heating correlated well with MSW of ESCS. Simulated maximum reflectivity was compared with the Doppler Weather Radar (DWR) observation from Visakhapatnam, and results indicate that reflectivity is well represented. However, the magnitude was slightly under-predicted compared to DWR in the Goddard MPS. The vertical distribution of hydrometeors and microphysical latent heating is found to play an important role in the initiation and development of cyclonic systems.

Keywords: ESCS, hudhud, WRF, microphysics, data assimilation.

1. Introduction

Tropical cyclones (TCs) are considered one of the most hazardous mesoscale weather phenomena during landfall, especially extremely severe cyclonic storms (ESCSs; wind speed > 46 m/s). Over the past 2 decades, the skill level related to TC tracks and intensity prediction has improved because of radical developments in atmospheric numerical weather prediction models in terms of physical processes, significant advancement in data assimilation techniques, and the availability of high-resolution spatial and temporal observations (satellite and conventional). Since 2003, many TC warning centers have been involved in providing 3–5-day track forecasts (Elsberry 2007; 2014). Yamaguchi et al. (2015) summarized the storm track error of all Regional Specialized Meteorological Centers (RSMCs) for 5-day track forecasts. Hence, it is important and necessary to increase the prediction length of TCs from 5 to 7 days in atmospheric numerical modeling systems.

The forecasting capability of the atmospheric modeling system has improved because of the availability of satellite and conventional observations. This in turn has improved the initial condition through data assimilation techniques thereby improving the model forecast (Chen 2007; Zhang et al. 2007; Pu et al. 2009; Osuri et al. 2015; Singh and Bhaskaran 2018; Singh et al. 2019). Therefore, it is expected that an improved initial condition of the mesoscale model through the data assimilation technique is very important and can lead to better forecasting of the ESCS. Selection of the optimum domain size is an issue and a challenge in atmospheric models as it depends on the study region and

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regional application (Denis et al. 2002). A recent study by Albert and Bhaskaran (2020) shows the importance of an optimal grid resolution in the detection lead time of cyclogenesis in the North Indian Ocean (NIO) region. Their study conducted a series of model-based sensitivity experiments to evaluate the tropical cyclogenesis lead detection time for different cyclone cases with varying grid resolutions in the NIO region. Campbell et al. (2011) suggested that a larger model domain is advantageous in prediction, since a bigger domain allows capturing the growth of large-scale atmospheric flow patterns. Hence, it is expected that by selecting a bigger domain, the large-scale flow pattern and eventually the track forecast will improve. Numerous studies suggested that simulation will be more realistic with increasing vertical model resolution (Zhang and Wang 2003; Kimball and Dougherty 2006). A study by Aligo et al. (2009) suggested that increased vertical resolution will improve forecasting in the convective boundary layer, and the cloud microphysical processes will be better resolved in mesoscale models using higher vertical resolution. Therefore, it is expected that by using higher vertical resolutions, the forecast of intensity and structure of the ESCS will improve. Keeping this in mind, it is expected that including these parameters in the modeling system will provide important features of ESCS to better track and forecast the intensity in the medium range.

The representation of cloud microphysical parameterization schemes (MPSs) in the atmospheric numerical modeling system is one of the central issues playing a pivotal role in the forecasting of tropical cyclones, convective systems, and rainfall events. The MPSs provide the necessary atmospheric heat, moisture tendencies, and cloud-related activities (Tao et al. 2003; Morrison et al. 2005, 2009; Thompson et al. 2008; Das et al. 2015). Several studies on NIO suggested that MPSs are important in track and intensity forecasting (Singh and Mandal 2014; Kanase and Salvekar 2015; Douluri and Annapurnaiah 2016; Maw and Min 2017; Chutia et al. 2019). Relevant studies conducted for the Bay of Bengal region also indicated that physical processes including MPSs play an important role in improving forecast models (Deshpande et al. 2010;

Srinivas et al. 2013; Choudhury and Das 2017a, b; Saikumar and Ramashri 2017; Sandeep et al. 2018). Therefore, it is also expected that MPSs will have a crucial role in the 7-day forecasting of ESCS over NIO, and this can lead to better accuracy in terms of tracking and intensity forecasting using improved initial conditions.

Several studies also suggested the difficulties involved in a 5-day forecast of TC intensity especially during rapid intensification and dissipation (Rappaport et al. 2009; Zhang et al. 2011). The forecast of rapid intensification (RI) just before landfall of an ESCS in a mesoscale model is crucial for warning bulletins and information dissemination by operational centers, considering the catastrophic effects due to increased storm surges, flooding, extreme winds and waves in coastal and nearshore regions (Bhaskaran et al. 2000; Bhaskaran et al. 2013a, b; Sahoo et al. 2018; Sahoo and Bhaskaran 2019). A study by Knutson et al. (2010) suggested that intensity along with the number of intense TCs will increase in the future. Murakami et al. (2017) pointed out that increasing frequency of ESCS is being observed over the Arabian Sea in NIO. Hence, forecasting the TC track and intensity of an ESCS about 7 days in advance is an important but difficult task. The present study is an attempt to forecast ESCS Hudhud, which formed over the Bay of Bengal region in the NIO, 7 days in advance. The main objectives addressed in this study are the following: (1) does the WRF model simulate the track and maximum intensity of ESCS Hudhud when the model is initialized at a stage when the storm was in its developing stage and extend the forecast up to 7 days? (2) Does the WRF model simulate the intensification of ESCS Hudhud by using six MPSs? The study is organized as follows: first, the introduction section, followed by a brief description of ESCS Hudhud in Sect. 2. In Sect. 3, the data used and numerical experiments are discussed in Data and Methodology. The simulated results are presented in Sect. 4 in the Results and Discussion. Finally, Sect. 5 discusses the overall conclusions of the study.

2. Details of ESCS Hudhud

A low-pressure system was reported by the India Meteorological Department (IMD) near the Andaman Sea on 6 October 2014, and this intensified into a mature cyclonic storm named ‘Hudhud’ on 8 October 2014. The system made landfall at 0630–0730 UTC on 12 October near Visakhapatnam with recorded maximum wind gusts of 210 km/h at Visakhapatnam. Figure 1 illustrates the landfall (location and time) of ESCS Hudhud with satellite images from METEO 7 showing different parameters such as the temperature at 0700 UTC, water vapor at 0730 UTC and visibility at 0800 UTC on 12 October, 2014. The observed (IMD best-fit) track details of ESCS Hudhud from 7–14 October 2014 are shown in Fig. 2a. The red color along the track in Fig. 2a represents the rapid dissipation stage (past 24 h wind changes were > 30 knots). The image from the Doppler Weather Radar (DWR) at Visakhapatnam on 11 October at 2100 UTC is shown in Fig. 2b. Figure 2c illustrates the 24-h wind changes from 0300 UTC on 8 October to 0300 UTC on 14 October. More details on ESCS Hudhud are provided in Sirisha et al. (2015) and Murty et al. (2016). This was the first post-monsoon cyclone since 1985 to cross the Visakhapatnam coast (Murty et al. 2016). The diameter of the closed eye was about 40.8 km (Fig. 2b) as reported by DWR at Visakhapatnam on 11 October at 2100 UTC. During the time of landfall, the minimum central pressure, maximum surface wind and pressure drop were about 950 hPa, 100 knots, and 54 hPa, respectively (IMD Report, 2014). The ESCS experienced rapid intensification on 11 October 2014 at 0600 UTC, followed by rapid dissipation from 12 October (1200 UTC) to 13 October (1200 UTC) with a decrease in maximum surface wind speed from 70 knots to 35 knots (Fig. 2c). The ESCS resulted in extremely heavy rainfall and damages in several districts of Andhra Pradesh such as Visakhapatnam, Vizianagaram, and Srikakulam.

3. Data and Methodology

A compressible non-hydrodynamic atmospheric Advanced Research of WRF (ARW; version 3.6.1)

was used to simulate the ESCS Hudhud. The physics, dynamics, and numeric and governing equations of the model are available in Skamarock et al. (2005). This study used a total of 73 vertical levels with higher levels prescribed for the lower and mid-tropospheric height. Table 1 provides more details on the model configuration used for the present study. The model’s initial condition was improved using the three-dimensional data assimilation system of the WRF model. The importance of the assimilation system is that it produces an improved analysis at the initialization time by minimizing the $J(x)$ of the following equation:

$$J(x) = J^b + J^o = \frac{1}{2}(x - x^b)^T B^{-1}(x - x^b) + \frac{1}{2}[y - H(x)]^T R^{-1}[y - H(x)], \quad (1)$$

where $J(x)$ refers to the total cost function as a sum of J^b (background cost function) and J^o (observation cost function). The assimilated observation was NCEP PREBUFR, and the assimilation time window was a cutoff ± 3 h. The initial condition was improved at 0000 UTC on 7 October 2014 by using the three-dimensional assimilation method of the WRF model on the NCEP PREBUFR dataset. The land surface parameters for the study region were obtained from the United States Geographical Survey (USGS). Simulated results (track, intensity, rapid intensification, and landfall) were compared with the best-fit track datasets obtained from the India Meteorological Department (IMD). The ARW model was configured with a single domain and integrated for 7 days starting from 7 October 2014 (0000 UTC) to 14 October 2014 (0000 UTC) for the entire life history until the landfall of ESCS Hudhud. The 73 vertical levels used in this study had a higher resolution between the surface to 900 hPa levels (lower boundary) and between 450 and 200 hPa levels (Fig. 3). The initial conditions used for numerical simulations were obtained from the European Centre for Medium Range Weather Forecasts (ECMWF), having a spatial resolution of approximately 80 km (T255 spectral). The model’s upper boundary was considered 1 hPa, based on the availability of ECMWF datasets. The temporal lateral boundary condition was updated from ECMWF at 6-h intervals.

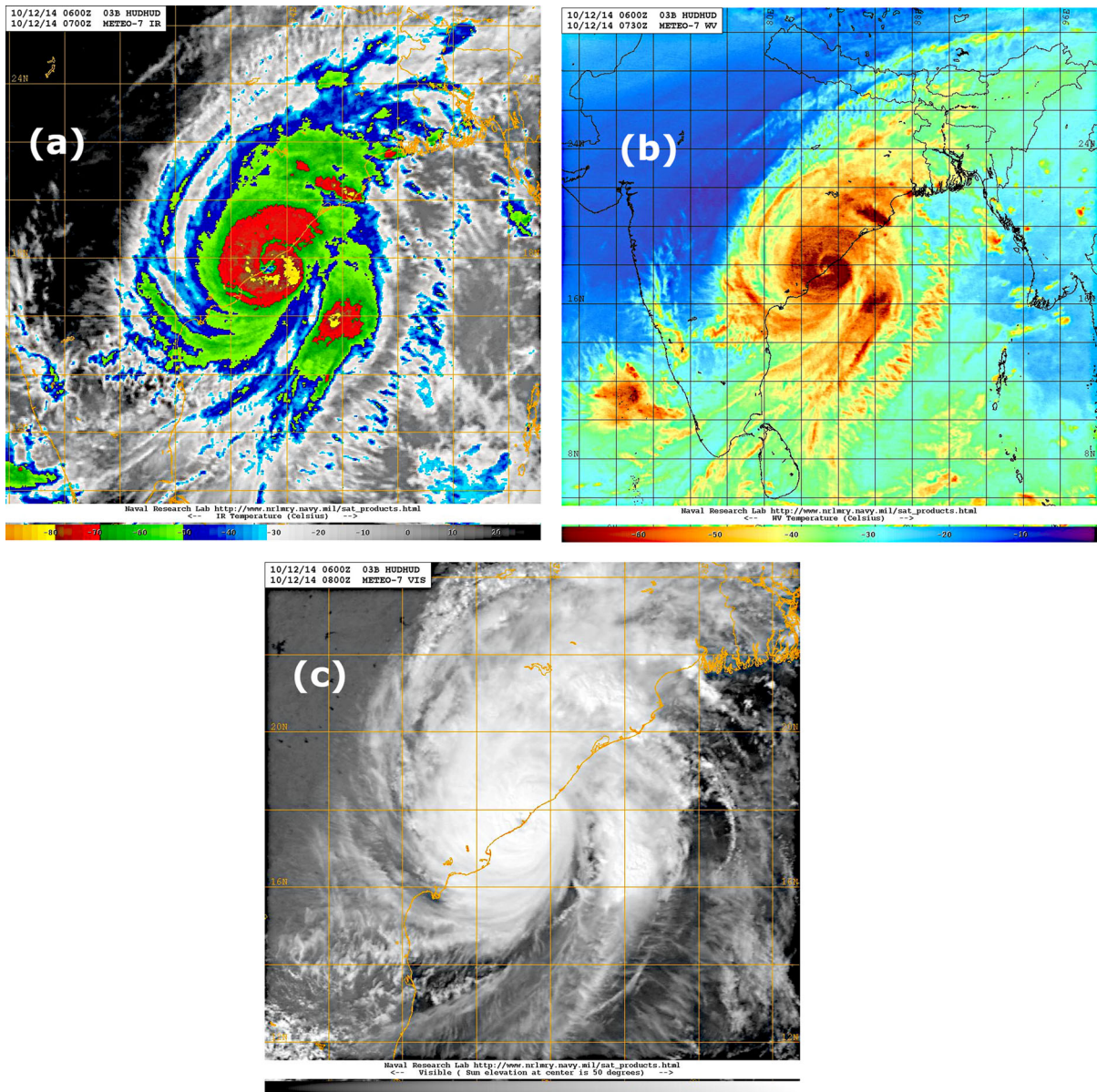


Figure 1

Satellite images from METEO 7 of the ESCS Hudhud on the day of landfall, 12 October 2014. **a** IR temperature (in Celsius) at 0700 UTC, **b** water vapor at 0730 UTC, and **c** visibility at 0800 UTC

Figure 4 presents the ARW model domain with 25 km horizontal resolution used in the present study covering the geographical area bounded by 15° S–40° N and 45° E–115° E.

In this study, the work gravity wave drag option and air-sea flux options of Donelan C_d (drag coefficient for momentum) along with the constant Z_{0q} for

alternative C_k (exchange coefficients for temperature and moisture) formulated for cyclone application were implemented. As mentioned above, the initial condition was improved by the 3D-VAR technique. In the present study, six numerical simulations were conducted using six different microphysical schemes in WRF (WSM), and each scheme in the model had a

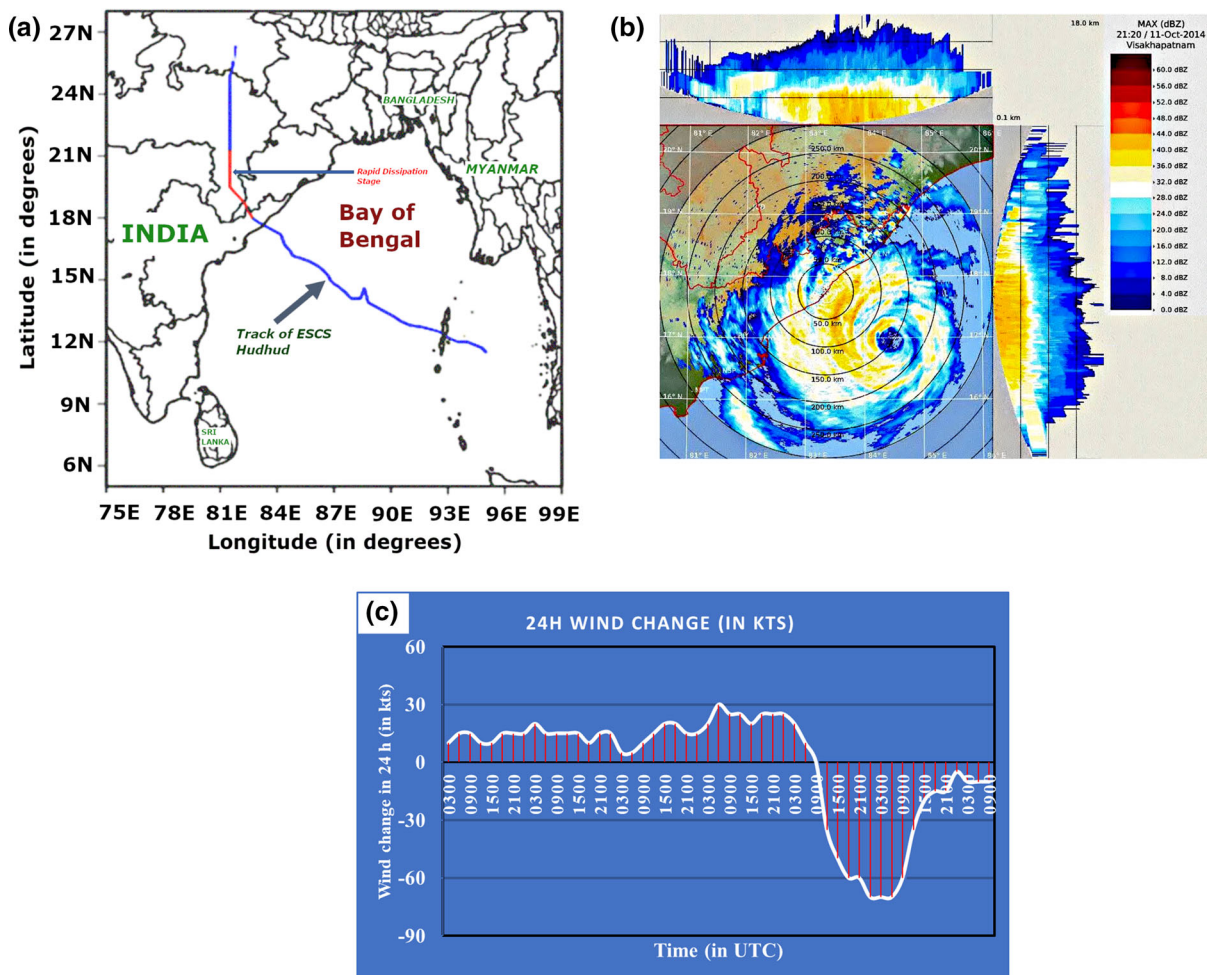


Figure 2

a Track of ESCS Hudhud, 7–14 October 2014 (red colour indicates rapid dissipation), obtained from IMD best-fit tracking, **b** Visakhapatnam Doppler Weather Radar image at 2100 UTC on 11 October, and **c** 24 h wind changes from 0300 UTC on 8 October to 0300 UTC on 14 October

unique number. These schemes included the Lin (Lin et al. 1983), WSM6 (referred to as WSM6; Hong et al. 2006), Goddard (referred to as WSM7; Tao et al. 1989), New Thompson (referred to as WSM8; Thompson et al. 2008), NSSL and NSSL-2 (referred to as WSM17 and WSM19; Mansell et al. 2010, where the National Severe Storms Laboratory is named NSSL). The numbering 6, 7, 8, 17, and 19 represents the unique number of each MP in the model WRF model, and more details on these selected MPs are presented in Table 2. The selection of MPs is based on the literature, which provided better forecasts (Tao et al. 2011; Srinivas

et al. 2013; Halder and Mukhopadhyay 2016), and not tested for the NIO domain. More details pertaining to the other physical processes and configurations of the modeling system are provided in Table 1.

4. Results and Discussion

In this section, the performance of six MPs of the ARW model, based on the initial condition improved through data assimilation, was evaluated in the forecasting of ESCS Hudhud. Results from the

Table 1

Configuration of the WRF-ARW model used in the study

Dynamical core	Non-hydrostatic, WRF-ARW (version 3.6.1)
Domain size	15° S–40° N, 45° E–115° E
Initial condition	ECMWF 80 km (T255 spectral).
Lateral boundary conditions	ECMWF 6 hourly
Vertical levels	73
Model top	1 hPa
Gravity wave drag (GWD)	Yes
Topography	USGS 10 min
Shortwave and longwave radiation	Dudhia (Dudhia 1989) and RRTM (Mlawer et al. 1997)
Cumulus parameterization	Simplified Arakawa-Schubert (SAS; Pan and Wu 1995)
PBL scheme	YSU scheme (Hong et al. 2006)
Microphysics	1. Lin (Purdue; Lin et al. 1983) 2. WSM6 (WSM6; Hong et al. 2006), 3. Goddard (WSM7; Tao et al. 1989), 4. New Thompson (WSM8; Thompson et al. 2008), 5. NSSL (WSM17; Mansell et al. 2010) and 6. NSSL-2 (WSM19; Mansell et al. 2010)
Land surface scheme	Noah land surface (Niu et al. 2011)
Coefficient enthalpy	istfcfx = 1 [Donelan Cd (drag coefficient for momentum) + constant Z_{0q} for alternative Ck (exchange coefficient for temp and moisture)] formulated for cyclone application
Forecast length and initialization	7 days forecast, 0000 UTC on 7 October 2014
Assimilated observation	NCEP PREBUFR (https://rda.ucar.edu/datasets/ds337.0/)

numerical experiments emphasize the track forecast, intensity, rapid intensification, and dissipation of the ESCS. These parameters were further validated against the IMD best-fit track observations. The simulated maximum reflectivity was also compared with the available IMD DWR observation at Visakhapatnam. The study also discusses the model performance pertaining to the intensity prediction of MSW using the derived parameters. To achieve this, some of the derived simulated parameters, such as microphysical latent heating, cloud mixing ratio, graupel mixing ratio, divergence, horizontal eddy diffusivity, and hydrometeors, were considered to evaluate the model performance, and relevant

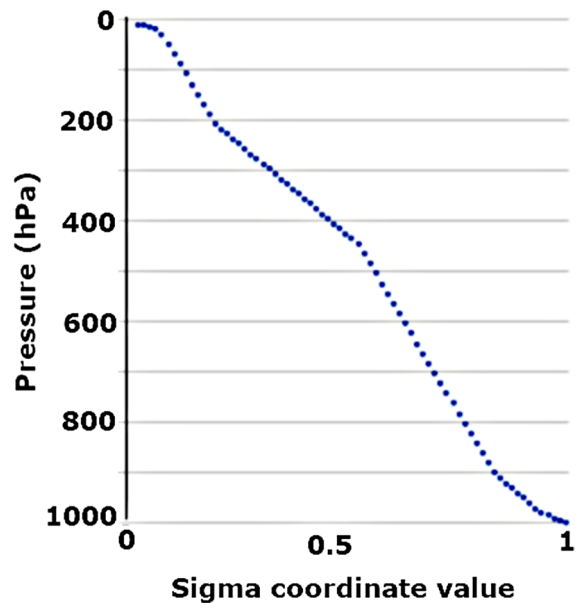


Figure 3

The 73 vertical sigma level structure used in the configuration of the WRF model

discussions on the importance of intensity forecast of the ESCS were carried out.

4.1. Track and Intensity Forecast of ESCS Hudhud

Figure 5 shows the model simulated track error (in km) for ESCS Hudhud along with the IMD best-fit track for 7 days at 3-h intervals from numerical experiments using the six MPSs. The track error is also presented on a daily basis for 7 days to better understand the performance of individual MPSs. Results clearly indicate that the simulated tracks compare reasonably well with the IMD observed track throughout the simulation period with most of the MPSs except the WSM17 experiment. The performance of Lin, WSM6, and WSM7 MPSs for a 78–138 h period (0600 UTC on 10 October to 1800 UTC on 12 October) resulted in the least track errors (< 100 km) compared with other MPSs. This corresponds to the period when ESCS Hudhud made landfall on 12 October 2014 (0700 UTC). The results clearly signify that during the time of landfall the track forecast was well simulated by the model in most of the experiments. Considering the 7-day simulation period, analysis of the mean track error

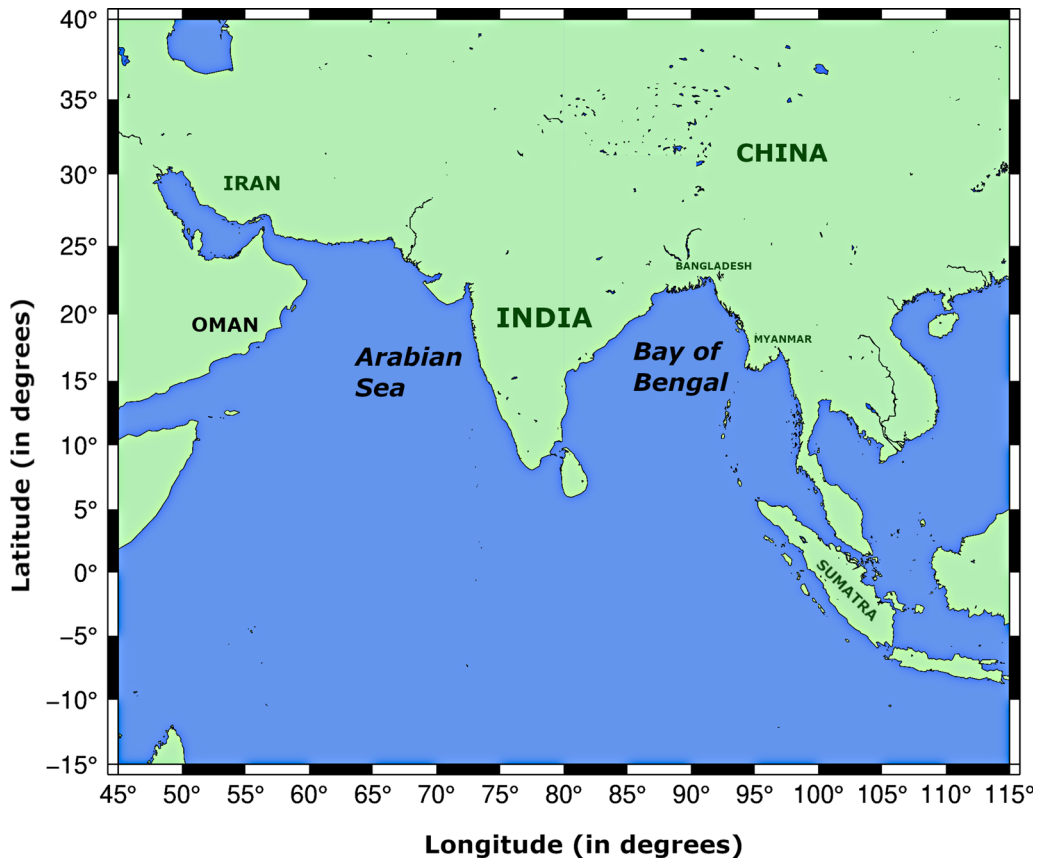


Figure 4
WRF model domain used in the study

Table 2
Details on the different cloud microphysical schemes used in the study

MPSs	Lin (LIN)	WSM6 (WSM6)	Goddard (WSM7)	Thompson (WSM8)	NSSL-2 (WSM17)	NSSL-1 (WSM19)
Moment	Single	Single	Single	Double	Double	Single
Mass variables	Q_c, Q_r, Q_i, Q_s, Q_g	Q_c, Q_r, Q_i, Q_s, Q_g	Q_c, Q_r, Q_i, Q_s, Q_g	Q_c, Q_r, Q_i, Q_s, Q_g	$Q_c, Q_r, Q_i, Q_s, Q_g, Q_h$	$Q_c, Q_r, Q_i, Q_s, Q_g, Q_h$
Number variables	–	–	–	N_i, N_r	$N_c, N_r, N_i, N_s, N_g, N_h$	V_g

Hydrometeors: c, r, i, s, g, h indicate cloud, rain, ice, snow, graupel, and hail, respectively
 V_g indicates the graupel variable

obtained at every 3-h interval revealed that the WSM7 MPS resulted in the least error of 129 km, whereas the maximum error of about 220 km was seen in the WSM17 experiment. Mean track error for the entire simulation period was about 136 km, 139 km, 149 km, and 170 km, respectively, with

Lin, WSM6, WSM8, and WSM 19 MPSs (Table 3). Figure 5b shows that on Day 4 the WSM6, Lin, and WSM7 MPS experiments exhibited the least track error and thereafter increased up to Day 7. However, in the WSM8 experiment the error was about 44 km, 95 km, and 165 km on Day 5 to Day 7, respectively.

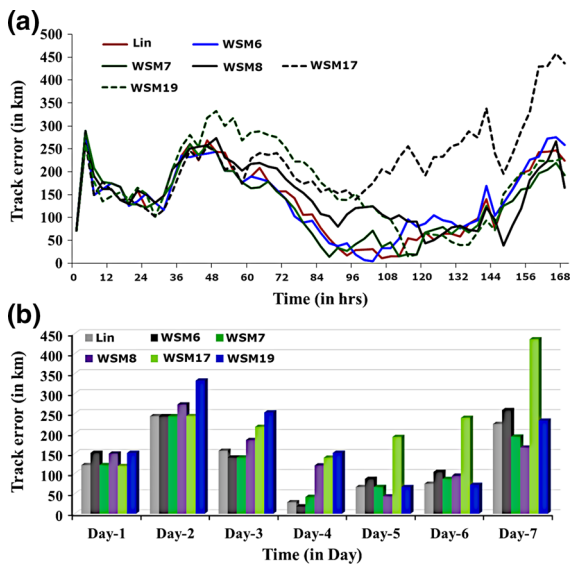


Figure 5

Model simulated track error (in km) for ESCS Hudhud along with the IMD best-fit track using six cloud microphysical parameterization schemes for the 7-day forecast **a** at every 3-h interval and **b** on a 1 day basis

Overall, considering the 7-day forecast, the movement of ESCS Hudhud was clearly better simulated by the WRF-ARW model employing the WSM6, Lin, and WSM7 MPSs. The forecasted track was also compared with the Joint Typhoon Warning Center (JTWC) and the track error on a daily basis for each MPS (Table 4). Results signify that the forecasted track errors with the Lin, WSM6, and WSM7 experiments were less compared to the WSM8, WSM17, and WSM19 experiments. During the landfall time, the track error was better forecasted in the Lin, WSM7, and WSM8 experiments. The highest track error was in the WSM19 experiment.

Overall, the forecasted results were best in the Lin and WSM7 experiments.

The time variation of the minimum central pressure (MCP) and maximum surface wind (MSW) for the 7-day forecast of ESCS Hudhud using six numerical simulations of MPSs and the IMD best-fit track are shown in Fig. 6. Simulations revealed that MCP follows a similar pattern as observed with the Lin, WSM6, WSM7, and WSM8 experiments, and the results obtained from WSM17 had greater deviation compared to observation. Also, during the first 5 days of the MCP forecast, the results were slightly better predicted with the WSM 19 experiment. In terms of the MSW forecast, the model predicted reasonably well for the first 4 days in most of the experiments. In general, the WSM 17 MPS failed to better predict the MSW, MCP, and rapid dissipation of ESCS Hudhud. Furthermore, the study also performed statistical evaluation to assess the performance and identify the best-performing MPSs. Statistical measures such as the mean absolute error (MAE) and correlation coefficient (CC) were calculated using the 3-h model forecast against the observed IMD datasets for MCP and MSW and presented in Table 3. Statistical parameters (MAE and CC) indicated that for MSW the Lin, WSM 19, and WSM 7 experiments resulted in the least MAE < 4 m/s and showed a good correlation coefficient > 0.93. In terms of intensity, the maximum MAE in MCP and MSW (9.37 hPa and 5.62 m/s) and CC (0.74 and 0.72) respectively was seen in WSM 17 MPS.

The variation corresponding to 24 h maximum surface winds (rapid intensification and dissipation

Table 3

Statistical analysis of the model simulated cyclone parameters against the IMD best-fit observations

S. no.	Parameters	Statistical analysis	Numerical experiments					
			Lin	WSM6	WSM7	WSM8	WSM17	WSM19
1.	MCP	CC	0.92	0.89	0.91	0.92	0.74	0.93
		MAE (in hPa)	8.12	8.77	8.96	8.54	9.37	7.96
2.	MSW	CC	0.93	0.91	0.94	0.93	0.72	0.94
		MAE (in m/s)	3.86	4.02	3.78	4.05	5.62	3.73
3.	RI	POD	0.6	0.7	0.7	0.6	0.4	0.6
4.	Track error	MAE (in km)	136	139	128	150	220	170

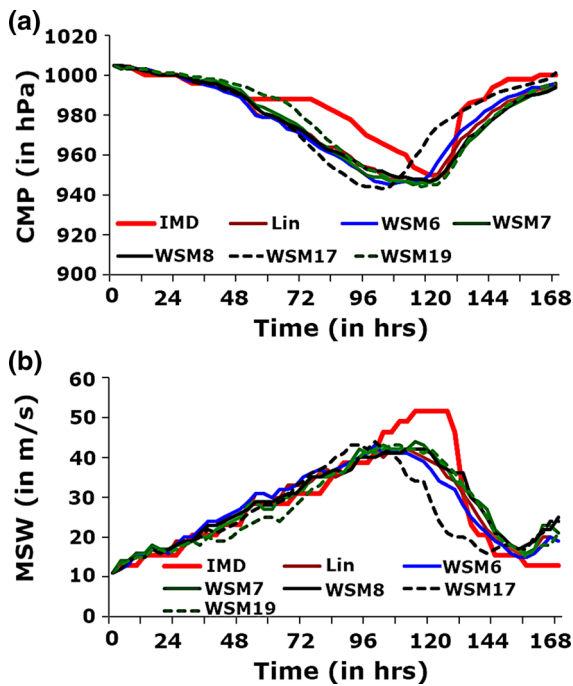


Figure 6

Variation of **a** minimum central pressure (MCP; in hPa) and **b** maximum surface wind (MSW, in m/s) for 7-day duration using numerical simulations and the IMD best-fit track

expressed in m/s) as a function of time (in h) obtained from different experiments along with the best-fit track data of IMD is shown in Fig. 7. The dissipation characteristics were well captured in most of the MPSs except the WSM19. The probability of detection (POD, or hit rate, which is the fraction of the observed event that was forecasted correctly) of rapid intensification and dissipation [for changes in wind speed > 15.46 m/s (≥ 30 knots) in the past 24 h] was also estimated during the entire simulation period for six MPSs (Table 3). The POD is calculated using the equation: $POD = \left[\frac{a}{a+c} \right]$, where a refers to the event forecast and occurrence, and c refers to the opposite of a (Jolliffe and Stephenson 2012). The result demonstrates that the POD for rapid intensification/dissipation was better simulated in the WSM6 and WSM7 experiments by about 70%.

4.2. Structure Forecast of ESCS Hudhud

Figure 8 shows the time versus height for model-simulated microphysical latent heating, the cloud

Table 4
Track forecast errors using different MPSs along with JTWC

	Lin	WSM6	WSM7	WSM8	WSM17	WSM19
Day 1	154	185	154	183	152	185
Day 2	232	232	232	260	241	318
Day 3	124	106	103	159	182	228
Day 4	26	29	30	120	151	154
Day 5	52	76	51	59	197	58
Day 6	80	110	127	49	198	105

mixing ratio, and divergence, which is averaged over the active region of the ESCS between 78° E–94° E and 8° N–20° N, obtained from different cloud MPSs for the entire 7-day simulation period. Results clearly show that the magnitude of the higher microphysical latent heating, cloud mixing ratio, and divergence correlates well with MSW of the ESCS Hudhud in each simulation. The higher microphysical latent heating between 500 and 200 hPa played an important role in the intensification and resulted in the maximum surface winds (between 72 and 132 h forecast). The forecasted higher MSW was about 44 m/s on 12 October 2014 (1800 UTC) corresponding to the 114-h forecast in WSM7, which correlated well with the maxima in the forecasted latent heating compared to other MPSs. The results clearly demonstrate that the forecasted microphysical latent heating at the upper levels played a vital role in the growth and strengthening of ESCS Hudhud. The upper level divergence exhibited a similar pattern of intensification as noticed in the case of latent heating. The results clearly indicate that the vertical distribution of microphysical latent heating, upper level divergence,

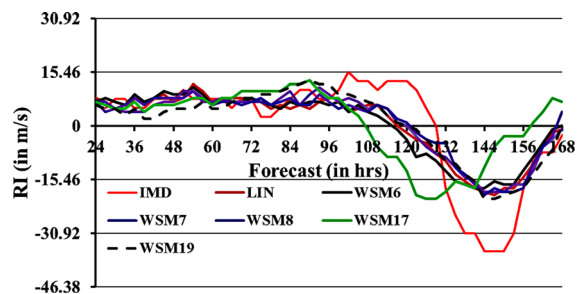


Figure 7

Variation of maximum surface wind changes in 24 h (rapid intensification and dissipation, in m/s) with time (in h) in different numerical simulations along with the IMD best-fit track data

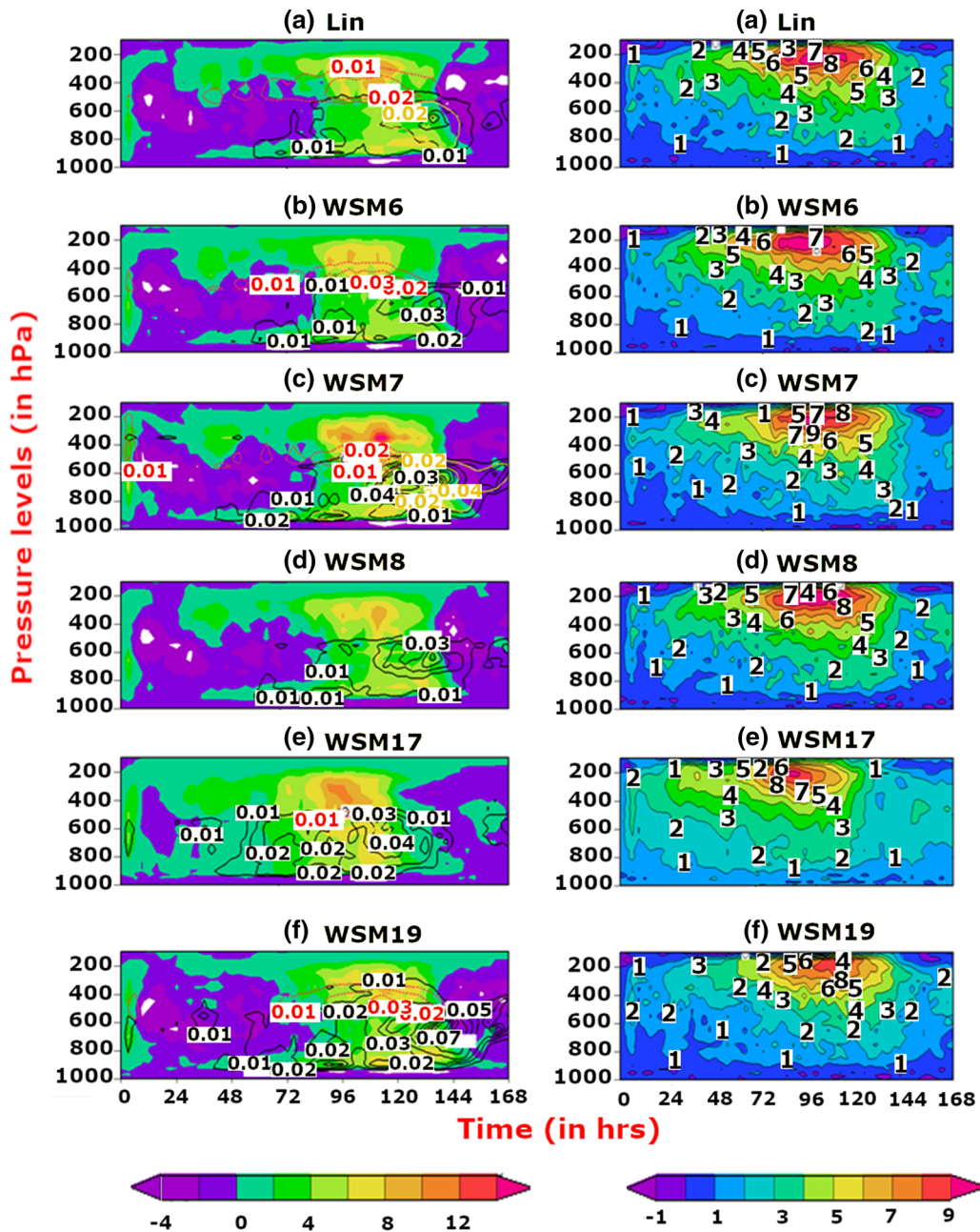


Figure 8

Model simulated time (168 h) variation with height (in hPa) for microphysics latent heating (left panel, in $10^{-5} \times \text{K s}^{-1}$) in which the solid black line represents the cloud mixing ratio (g/kg) and divergence (right panel, in $10^{-5} \times \text{s}^{-1}$), averaged over the active region of the cyclone between 78°E – 94°E and 8°N – 20°N , obtained from different cloud MPS

and hydrometeors play an important role during the intensification stage, which involves timely initiation and development of the cyclonic system.

Figure 9 presents the simulated horizontal eddy diffusivity of heat, as the case analyzed with latent heating. It is observed that the maximum horizontal eddy diffusivity of heat varied between two different

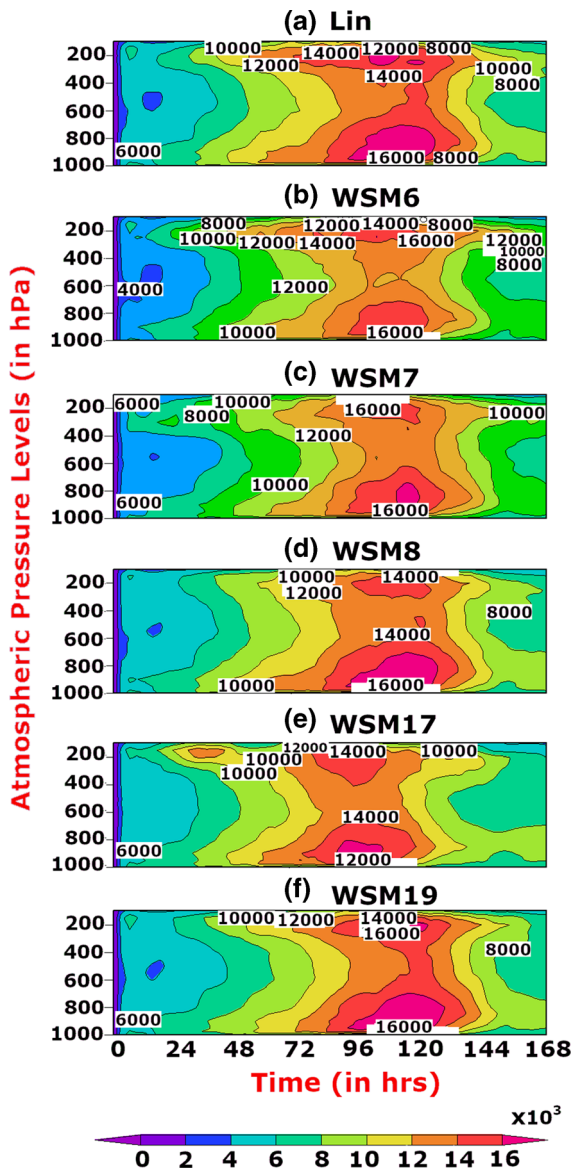


Figure 9

Model simulated time (168 h) variation with height (hPa) for horizontal eddy diffusivity of heat (in m^2s^{-1} , color bar indicates in 10^3), averaged over the active region of the cyclone between $78^\circ E-94^\circ E$ and $8^\circ N-20^\circ N$ from six different cloud MPSs

levels: first, from the surface to 700 hPa; second, at the upper level. Based on the analysis of two levels, the MSW during simulation period correlates well with the magnitude of maximum horizontal eddy diffusivity of heat in all the MPSs. Figure 10 shows that the simulated hydrometeors and graupel mixing ratio were also important in the intensification during the simulation period. Overall, the findings from the

study indicate that the intensity of the simulated storm correlated reasonably well with the vertical distribution of hydrometeors (species types: ice, snow, graupel, and cloud), microphysical latent heating, and upper level divergence, which play an important role in the initiation and development of the cyclonic storm Hudhud using different cloud microphysical parameterization schemes. Findings from the above analysis indicate the role of MPSs in governing the track and intensity prediction of the ESCS. WSM 17 and WSM19 are the latest schemes included in the model. Model results show that both schemes do not behave well for the considered cyclone case. As mentioned in Table 2, a number of variable schemes do not perform well in track and intensity forecasting. These schemes are more suitable for cloud resolving simulations (when model horizontal resolutions are < 2 km) as pointed out in previous studies. The importance of micro-physical parameterization schemes (MPSs) depends on the vertical distribution of mass (hydrometeors: ice, snow, graupel, cloud, rain, and hail) and also the vertical distribution of latent heating (Figs. 8, 9, 10). Figures 8, 9, and 10 clearly indicate that the above two parameters are very important in governing the evolution of the system. The timely initiation and development of the system are not well captured by these schemes; hence, the model performance is not good compared to the other schemes. The spatial distributions of simulated (MPSs) and observed (DWR at Visakhapatnam) maximum reflectivity for the study region corresponding to 12 UTC, 15 UTC, 18 UTC, and 21 UTC on 11 October and at 00 and 03 UTC on 12 October 2014 are shown in Fig. 11. Simulated maximum reflectivity considered only three MPSs (Lin, WSM7, and WSM19) as this resulted in relatively better track and intensity forecasts of ESCS Hudhud. The simulated reflectivity of ESCS varied in the range between 42 and 56 dBZ, whereas the maximum reflectivity in the DWR image varied up to 60 dBZ. It is also noted that the simulated reflectivity in terms of spatial distribution and magnitude was relatively better in WSM7 MPS than in other MPSs. It is also important to note that due to lower model resolution, the signatures of maximum reflectivity were not fully resolved. Finally, the result signifies that the maximum

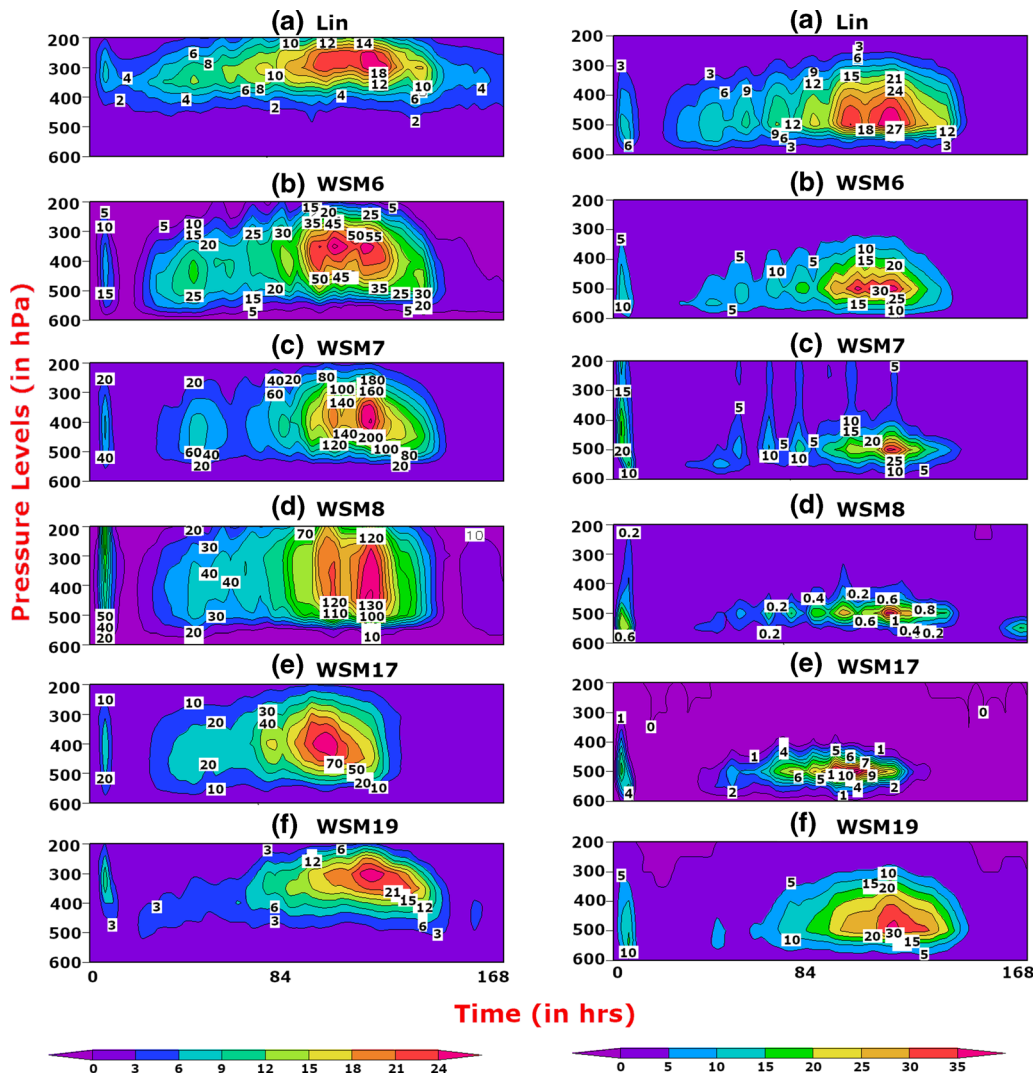


Figure 10

Model simulated time (168 h) variation with height (in hPa) for hydrometeors (first column, in g/kg) and graupel mixing ratio (second column, in g/kg), averaged over the active region of the cyclone between 78° E–94° E and 8° N–20° N from six different cloud MPSs

reflectivity and magnitude were better in the forecast scenario with the WSM7 experiment.

5. Conclusions

This study is an effort to verify the forecast accuracy and robustness of the WRF-ARW model in the track and intensity simulation of ESCS Hudhud, which developed over the North Indian Ocean basin during 2014. Model simulation was performed for a

7-day period covering the life span of ESCS. The study critically examined and evaluated the performance of six different microphysical parameterization schemes (MPSs) on the improved initial condition through data assimilation. NCEP PREBUFR observation was assimilated using the 3D-VAR at 0000 UTC on 7 October 2014. In addition, the model configuration considered the option of gravity waves, larger spatial domain, and 73 high-resolution vertical levels covering the upper atmospheric boundary to the 1 hPa level. The main

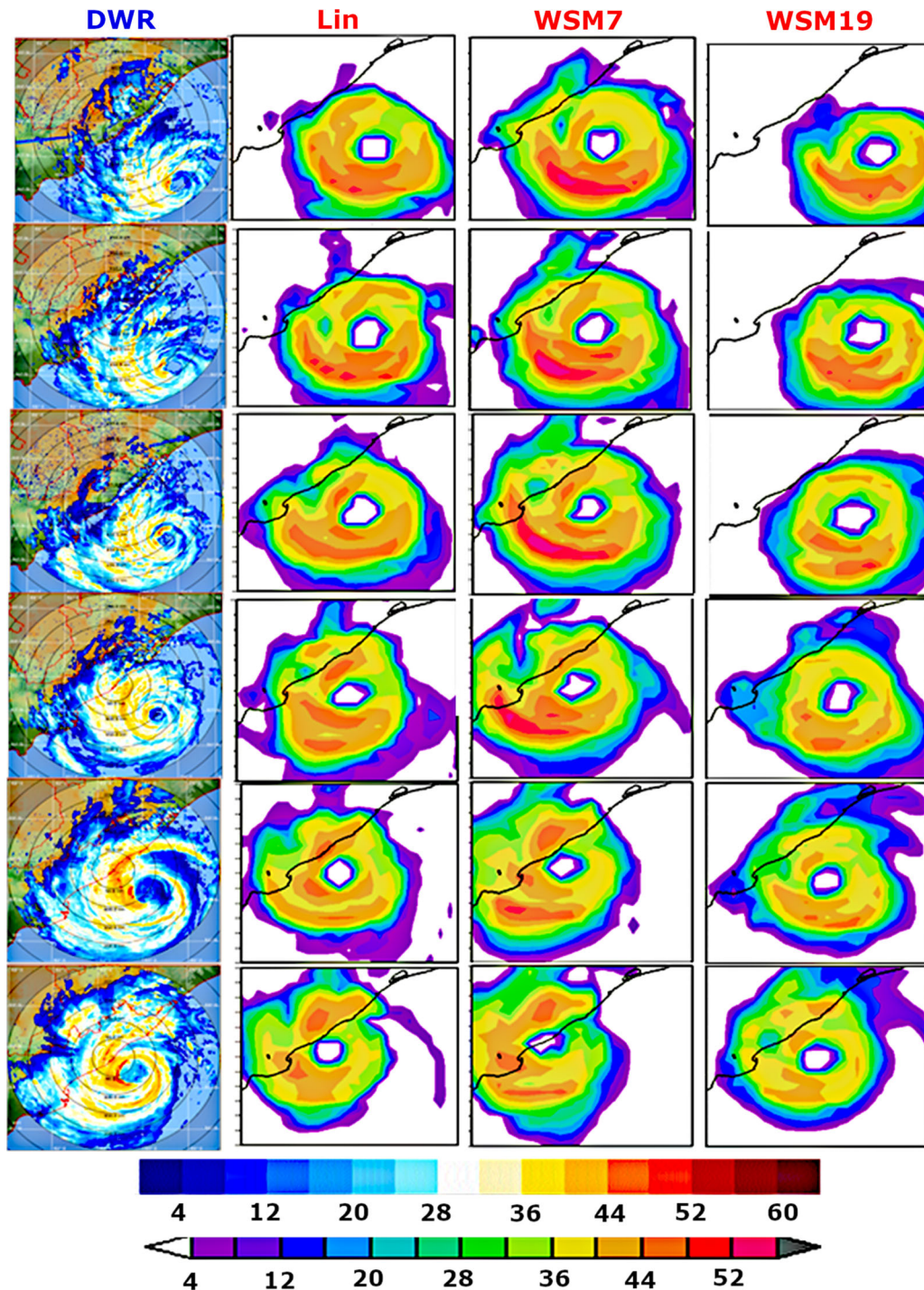


Figure 11
 Maximum reflectivity (in dbz) from Visakhapatnam DWR (column 1), Lin (column 2), WSM7 (column 3), and WSM19 (column 4) at 12 UTC, 15 UTC, 18 UTC, 21 UTC on 11 October and 00, 03 UTC on 12 October 2014 from row 1 to row 6, respectively

conclusions derived from the present study are summarized as follows:

- The WRF model predicted the track of ESCS Hudhud reasonably well, and the least track error

noticed was about 42 km, 67 km, 87 km, and 192 km on Day 4 to Day 7 with WSM7 MPS. The least mean track error for the 7-day simulation period analyzed at 3-h intervals was about 129 km.

- Results obtained from the statistical analysis clearly indicate that the MSW was better simulated with WSM7, Lin, and WSM19 MPSs, which showed the least mean absolute error of about 4 m/s with a correlation coefficient > 0.93 .
- The result for rapid intensification/dissipation reveals that the simulated dissipation was reasonably well represented in most of the MPSs with the exception of WSM19 MPS. The probability of detection (POD) indicates that rapid intensification/dissipation was better in WSM6 and WSM7 experiments with a score level of about 70%.
- The simulation error by employing WSM17 MPS was relatively higher for the track and intensity compared to other MPSs. This may be attributed to the faster translation speed of the storm. The performance is expected to be better in the cloud resolving simulation.
- The study postulates that the observed higher magnitude of microphysical latent heating between 500 and 200 hPa and divergence between 500 and 200 hPa has an important role in the intensification process and correlates well with the MSW of the storm.
- The maximum reflectivity and its magnitude were better simulated with the WSM7 (Goddard) microphysical parameterization scheme in the WRF model in forecasting ESCS Hudhud over the North Indian Ocean.

Based on the results obtained and overall discussion, it can be concluded that for the 7-day (168-h) simulation period, the track (movement) and intensity (MCP and MSW) forecast was better simulated using the Goddard MPS on the improved initial condition. However, the present findings and conclusion are based on simulation of a single ESCS event over the North Indian Ocean basin. It is warranted to meticulously examine a number of cases that have developed over the NIO basin, which will be dealt in a separate future study.

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