Tropical cyclone Hudhud Track Simulation and Sensitivity Analysis to microphysics parameterization schemes using Numerical Weather Prediction model

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Abstract— A Very Severe Cyclonic Storm (VSCS) Hudhud developed from a low pressure system that formed under the influence of an upper-air cyclonic circulation in the Andaman Sea and intensified into a very severe cyclonic storm during October 2014, caused an extensive damage and loss of life in eastern part of India and Nepal. The cyclone reached its peak intensity with a minimum central sea level pressure of 950 mbar and attains the maximum sustained wind speed of 180 km/h. The Hudhud tropical cyclone crossed the Andhra Pradesh coast near Visakhapatnam on October 12. In the present study the tropical cyclone Hudhud track simulated for different microphysics (mp) and cumulus (cu) physics parameterization schemes to find out the best combination of schemes and the sensitivity analysis of the numerical simulations of the Hudhud tropical cyclone to different microphysics parameterization schemes is carried out to predict the tropical cyclones originating in the Bay of Bengal region. The WRF–ARW simulations have performed well in predicting the propagation of the cyclone track. All the simulations have underestimated the strength of the cyclone to a larger extent. TC simulations with 08/10/2014 and 10/10/2014 initial and boundary conditions WSM3-G3D schemes and THOM2-G3D schemes gives out the best track results which closely matches with the IMD track respectively.

Keywords—Tropical Cyclone, Numerical Weather Prediction, Track Error, Parameterization Schemes

I. INTRODUCTION

The Very Severe Cyclonic Storm Hudhud (07-14 Oct. 2014) developed from a low pressure area over North Andaman Sea in the morning of 6th October 2014 and turned into a depression in the morning of the 7th October over the north Andaman Sea. It intensified into a Cyclone Strom in the morning of 8th October and further intensified into a Very Severe Cyclonic Storm (VSCS) in the afternoon of 10th October [4]. Three domains are used for the WRF simulation with a horizontal resolution of 45 km for domain1, 15 km for domain2, and 5 km for domain3. The results from the domain3 considered for analyzing and comparing with observation data from Indian Meteorological Department (IMD). Multiple simulations are carried out using initial conditions (NCEP FNL) at an interval of 6 hours, different microphysics and cumulus parameterization schemes with fixed PBL Yonsei University Scheme (YSU) throughout the simulation and time integration schemes.

II. DATA AND METHODOLOGY

The Advanced Research WRF (ARW) mesoscale model developed by NCAR is used to simulate the Hudhud Tropical cyclone track. NWP is a method of weather forecasting that uses governing equations, different numerical methods, parameterization schemes, different domains and Initial and boundary conditions. The MODIS based terrain topographical data have been used for domain1, domain2 and domain3 in the WRF Preprocessing system (WPS). The WRF model is acknowledged as one of the best performing models for cyclone prediction [6][8][9] & [11].

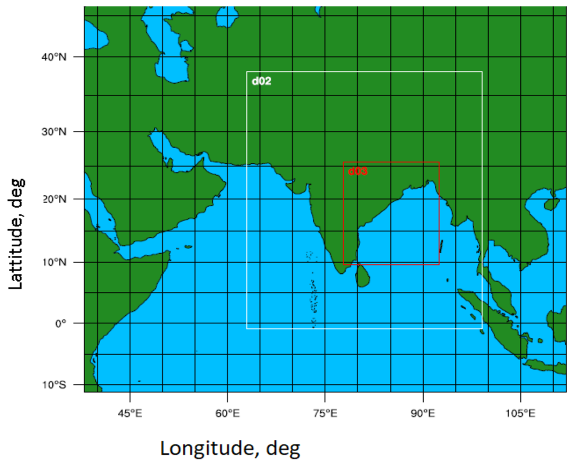


Figure. 1 The model domains used for the prediction of Hudhud cyclone with horizontal resolution of 45 km, 15km (d02) and 5 km (d03)

The WPS domain configuration shown in the Figure 1 is generated using NCL (NCAR Command Language). The WRF Model dynamics and domain details are listed in Table.1

and the micro physics and cumulus physics parameterization schemes used in the present simulation to investigate the track of the tropical cyclones were listed in Table-2.

TABLE 1 WRF Model dynamics and domain details

Model Dynamics	
Equation	Non-hydrostatic
Time integration scheme	Runge-Kutta scheme (Third order)
Horizontal grid type	Arakawa-C grid
Domain Details	
Map projection	Mercator projection
Central point of the domain	75°E, 20°N
No. of domains	3
No. of vertical layers	27
Horizontal grid distance	45 km , 15 km & 5 km for domain 1, 2 & 3 respectively
Time step	180 sec, 30 sec & 10 sec for domain 1, 2 &3 respectively
No. of grid points	173 (EW), 148 (SN) in domain-1
	253 (EW), 295 (SN) in domain-2
	310 (EW), 355 (SN) in domain-3
Data	NCEP Final Analysis (FNL) data

TABLE 2 List of MP, CP, and PBL used in WRF simulations

Model Microphysics schemes	
Kessler scheme	KS
Lin *et al.* scheme	*LIN*
WRF Single Moment 3-class simple ice scheme	WSM3
WRF Single Moment 5-class scheme	WSM5
Thompson graupel scheme 2 moment	THOM2
Model Cumulus physics schemes	
Kain-Fritsch(new Eta) scheme	KF
Betts-Miller-Janjic scheme	BMJ
Grell-Devenyi ensemble scheme	GD
Grell-3D ensemble scheme	GRE
Planetary Boundary Layer (PBL)scheme	
Yonsei University Scheme	YSU

III. RESULTS AND DISCUSSIONS

The Simulations for the Phailin cyclone were carried out in order to determine the best track of phailin cyclone. Results from the inner most domains have been used for the analysis. The Yonsei-University (YSU) planetary boundary layer (PBL) scheme is kept fixed for all the simulations [2][3][5]. The simulated track of Hudhud cyclone with different microphysics and cumulus physics parameterization schemes plotted. Grid Analysis and Display System (GrADS) used for the visualization of the wrf output. The wrf model output and the IMD observed track were compared concurrently. Track error is calculated using Haver Sine formula shown in equation (1). The track error for Hudhud TC for different CP and MP are also plotted.

$$a = sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi * \cos\varphi * sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (1)$$

$$c = 2 * \tan^{-1}\left(\frac{\sqrt{a}}{\sqrt{(1-a)}}\right) \quad (2)$$

$$D = R * c \quad (3)$$

$$\Delta\varphi = \varphi_{JTWC} - \varphi_{wrf} \quad (4)$$

$$\Delta\lambda = \lambda_{JTWC} - \lambda_{wrf} \quad (5)$$

Where D is Track error, φ is latitude, λ is longitude, R is earth's radius (mean radius = 6,371km) and the angles are in radians.

IV. HUDHUD CYCLONE TRACK SIMULATION

Hudhud TC Simulations were initiated on 08th October 2014, 0000 UTC with lateral boundary condition and were carried up to 13 October 2014, 1200 UTC. The model was run up to 144 hr. Hudhud cyclone simulations with different micro physics and cumulus schemes plotted in Figure.2.

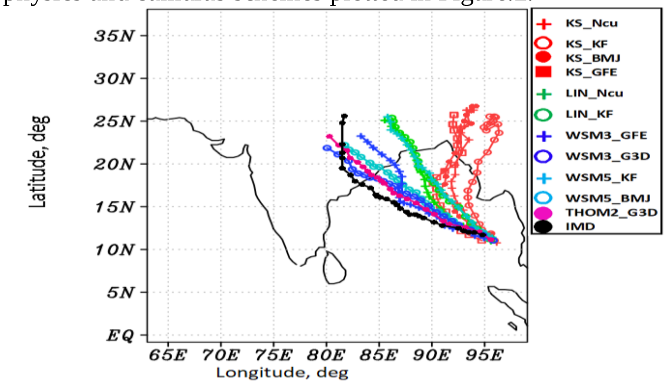


Figure 2. Hudhud cyclone with 144 hr simulations with different micro physics and cumulus schemes and 2014/10/08: 00 hr UST initial conditions

The track error and Root Mean Square Error (RMSE) of Hudhud TC simulations for different mp and cu parameterization schemes are plotted in the Figure 3.

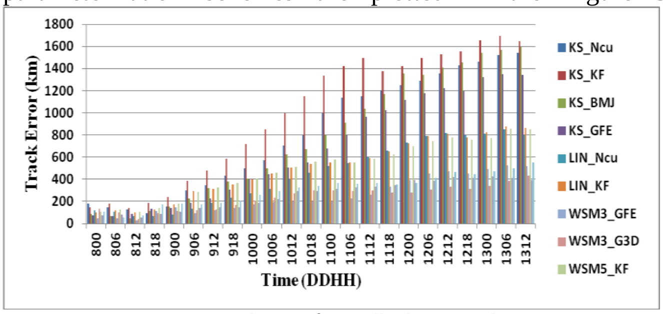


Figure 3. Track error for Hudhud TC simulations

The Root Mean Square Error (RMSE) of Hudhud TC simulations for different mp and cu parameterization schemes are plotted in Figure 4. The RMSE is minimum for WSM3_G3D scheme 259.10 km and maximum for KS_KF scheme 1136.34 km.

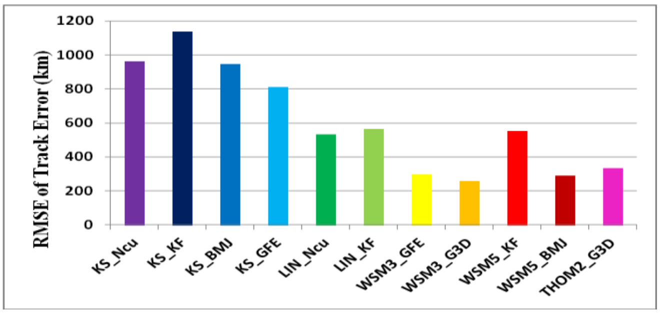


Figure 4. RMSE of Track error for Hudhud TC simulations

Time variation of model simulated central sea level pressure (CSLP) with JTWC observations for Hudhud TC in hPa is plotted in Figure 5.

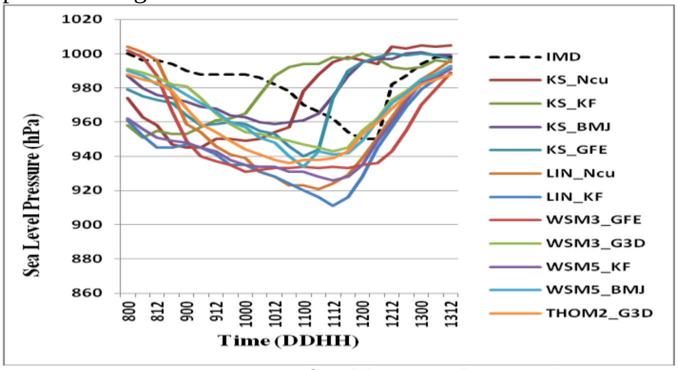


Figure 5. Time variation of model CSLP with IMD in (hPa)

The 10-m Maximum Sustained Wind speed along with IMD observation is plotted in the Figure 6.

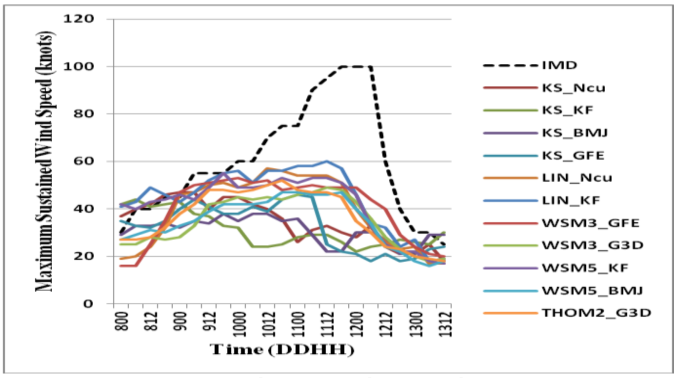


Figure 6. The MSW with IMD in (knots)

The scatter plot of Sea Level Pressure versus Maximum Sustained Wind Speed is plotted in Figure 7. The WRF-ARW model performs poorly in simulating the intensity of the Hudhud cyclone, in terms of central Pressure and maximum wind speed prediction.

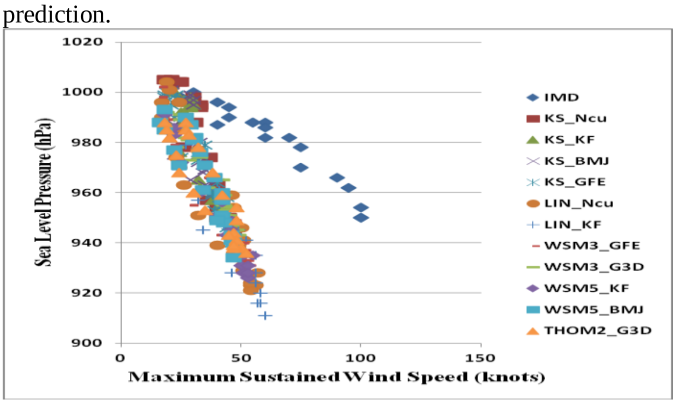


Figure 7. The scatter plot SLP vs. MSW

The simulated 24 hr accumulated rainfall on 12/10/2014 with different mp and cu physics schemes along with the TRMM is shown in Figure 8. The THOM2-G3D well simulated the 24 hr accumulated rainfall on 12/10/2014.

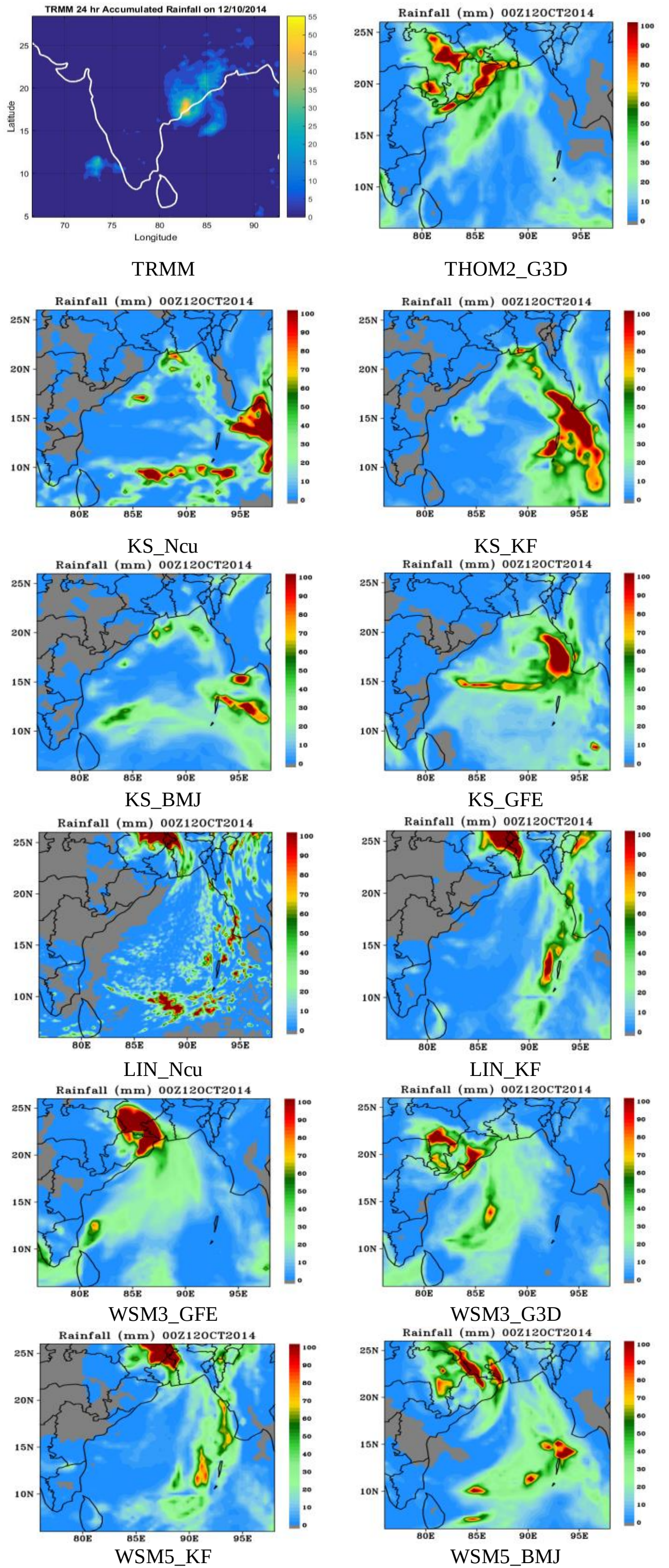


Figure 8. TRMM and different mp and cu schemes 24 hr Accumulated rainfall in (mm)

V. SENSITIVITY ANALYSIS OF HUDHUD SIMULATIONS TO MICROPHYSICS PARAMETERIZATION SCHEMES

The Numerical Weather Prediction model used is Advanced Research WRF (ARW) v 3.9.1 mesoscale model developed by NCAR. The MODIS based terrain topographical data have been used for domain-1, and domain-2 in the WRF Preprocessing system (WPS) shown in Figure 9.

The Initial and boundary conditions are obtained from the UCAR & NCAR Research Data Archive https://rda.ucar.edu/datasets/ds083.2/

The NCEP FNL data is used as the initial conditions to WRF simulations at an interval of 6 hours, Grell-3 cumulus parameterization, Yonsei University Scheme (YUS) PBL scheme and time integration schemes but with different microphysics schemes are carried out. Microphysics parameterization schemes are important in numerical weather prediction models for providing atmospheric heat and moisture tendencies [14]. Microphysics parameterization schemes include vertical flux of cloud, precipitation and sedimentation processes of hydrometeors. In this work, eight different combinations of microphysics schemes are tested for the sensitivity analysis. The investigated microphysics schemes include— Kessler scheme, Lin et al. scheme, WRF single moment 3-class (WSM3), WRF single moment 6-class (WSM6), new Thompson (THOM), Milbrandt-Yau double moment (MY2) 7-class, P13 and P13MD schemes. The WSM3 scheme is from [15]. This is a microphysics scheme with ice, in which ice crystal number concentration is assumed as a function of ice amount. The WSM6 scheme is from [16]. In this scheme, graupel is introduced as another variable, but ice number concentration follows the concept of WSM3 and WSM5. The THOM scheme [20] a generalized gamma distribution shape for each hydrometeor species is introduced with new snow parameterization depending on both ice water content and temperature. In MY2 scheme [21] & [22], hail and graupel as separate categories are added in the scheme with double-moment cloud, snow, rain, ice, graupel, and hail.

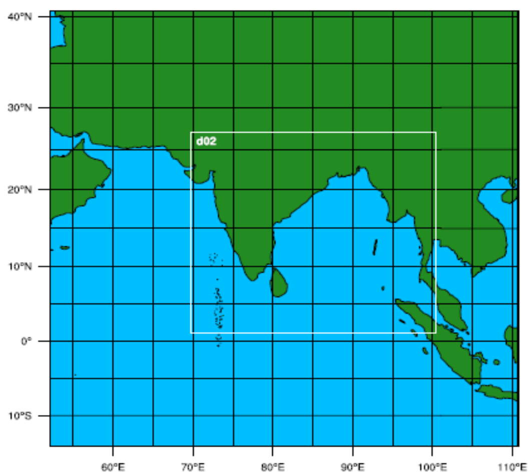


Figure 9. WPS Domain Configuration

The mp, cu and pbl schemes used in the present simulation to investigate the track of the Hudhud tropical cyclone listed in Table 1 and Table 2. WRF Model dynamics and domain details are listed in Table 3.

TABLE 3. Model microphysics parameterization schemes

Name of the microphysics scheme	Acronyms
Kessler scheme	KS
Lin et al. scheme	LIN
WRF Single Moment 3-class simple ice scheme	WSM3
WRF single moment 6-class scheme (mp=6)	WSM6
Thompson graupel scheme 2 moment (mp=8)	THOM2
Milbrandt-Yau 2-moment scheme (mp=9)	MY2
P3 1-category (mp=50)	P31
P3 1-category plus double-moment cloud water (mp=51)	P31DM

TABLE 4. Model cumulus (cu) and Planetery Boundary layer (pbl) parameterization schemes.

Name of the scheme	Acronyms
Yonsei University Scheme (pbl=1)	YSU
Grell-3D ensemble scheme (cu=5)	G3D

TABLE 5. WRF Model dynamics and domain details

Model dynamics details	
Equation	Non-hydrostatic
Time integration scheme	Third-order Runge-Kutta scheme
Horizontal grid type	Arakawa-C grid
Model Domain details	
Map projection	Mercator projection
Central point of the domain	81.4°E, 15°N
No. of domains	2
No. of vertical layers	51 eta_levels
Horizontal grid distance	27 km(domain1) and 9 km(domain2)
Time step	90 sec(domain1) and 30 sec(domain2)
Number of grid points	210 (WE), 210 (SN) in domain1
	328 (WE), 292 (SN) in domain2

Hudhud TC Simulations were initiated on 10th October 2014, 0000 UTC with lateral boundary condition and were carried up to 14th October 2014, 0000 UTC. The USGS (United States Geological Survey) 2m resolution terrain topographical data have been used for both domain1 and domain2 in the WRF pre-processing system (WPS). The model run up to 98hr and the simulated track of Hudhud cyclone with different microphysics parameterization schemes were plotted in Figure. 10. All the schemes well simulated the initial position of the storm. The track error and the RMSE of Tracks in Figure.11 & Figure.12 respectively, indicates that the WRF Single Moment 3-class simple ice scheme (WSM3) with Grell-3D ensemble scheme (G3D) produces the relatively small track error compared to other schemes.

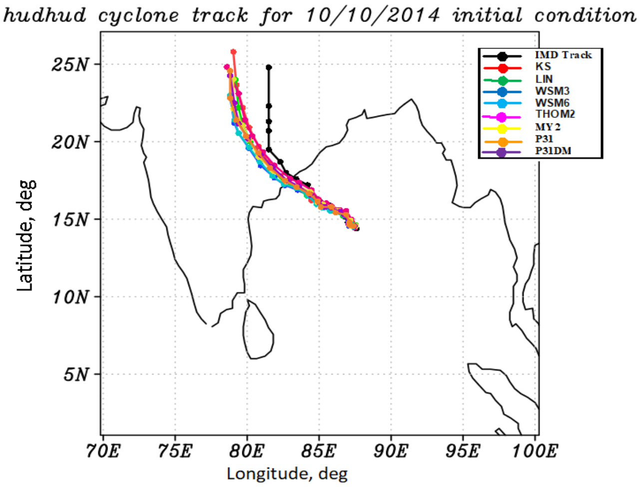


Figure 10. Hudhud Cyclone Track for different micro physics scheme

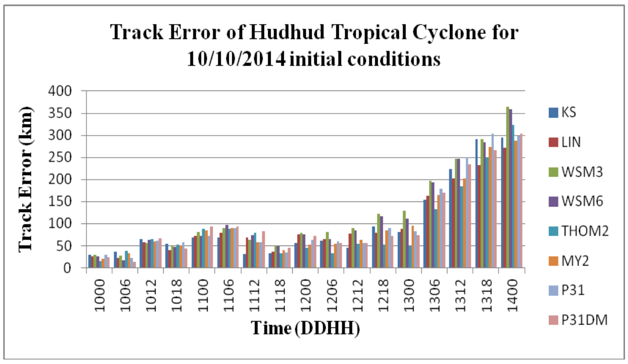


Figure 11. Hudhud Cyclone Track error for different micro physics scheme

The RMSE minimum for THOM2 microphysics scheme 65.52575 km and maximum for WSM3 scheme 92.43462 km.

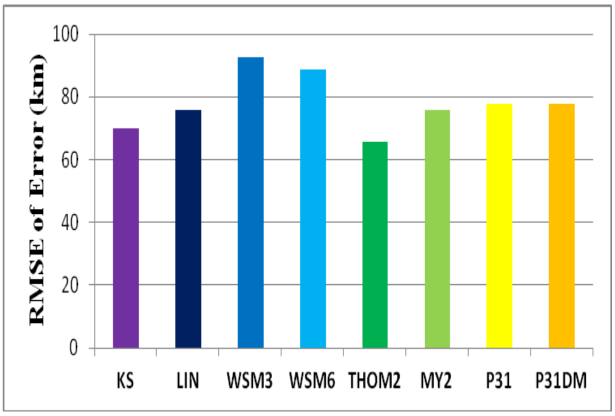


Figure 12. The RMSE of Hudhud Cyclone Track

Time variation of model-simulated central sea level pressure (CSLP) with IMD observations for Hudhud TC in hPa is plotted in Figure 13. All the schemes well simulated the initial position of the Minimum Sea Level Pressure but all the schemes under estimated the Maximum Sustained wind Speed.

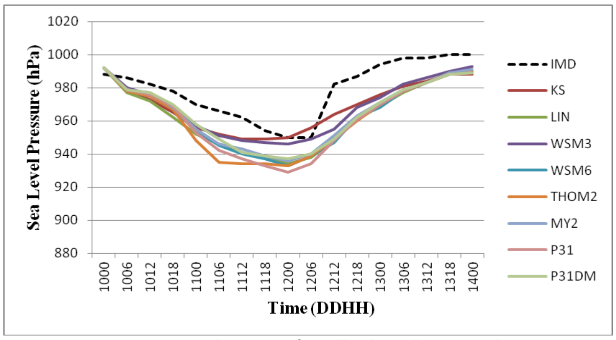


Figure 13. The SLP of Hudhud Cyclone Track

The 10-m Maximum Sustained Wind speed along with the IMD observations plotted in Figure 14.

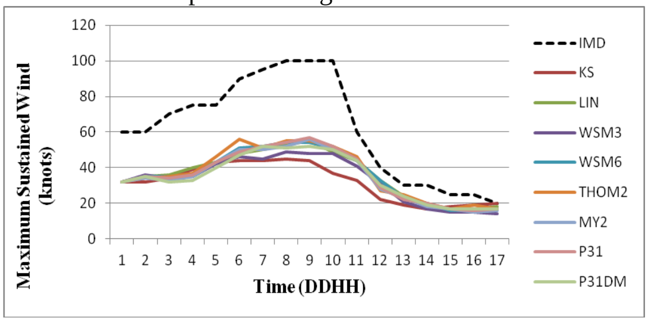


Figure 14. The MSW of Hudhud Cyclone Track

The scatter plot of Sea Level Pressure versus Maximum Sustained Wind Speed is plotted in Figure 15. The intensity of a tropical cyclone can be represented by the relationship between minimum sea level pressure (MSLP) and maximum sustained wind speed. The WRF-ARW model performs poorly in simulating the intensity of the Hudhud cyclone, in terms of central Pressure and maximum wind speed prediction

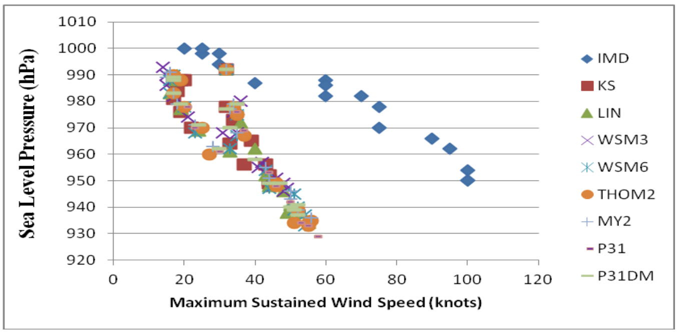
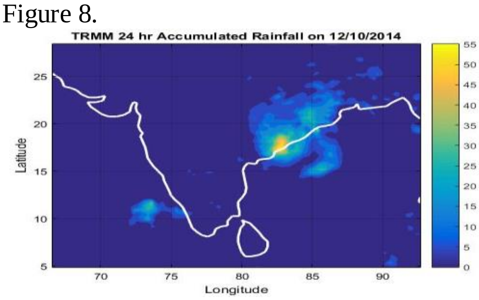


Figure 15. The scatter plot of SLP vs. MSW

The simulated 24 hr accumulated rainfall on 12/10/2014 with different mp and cu physics schemes along with the TRMM is shown in Figure 8.



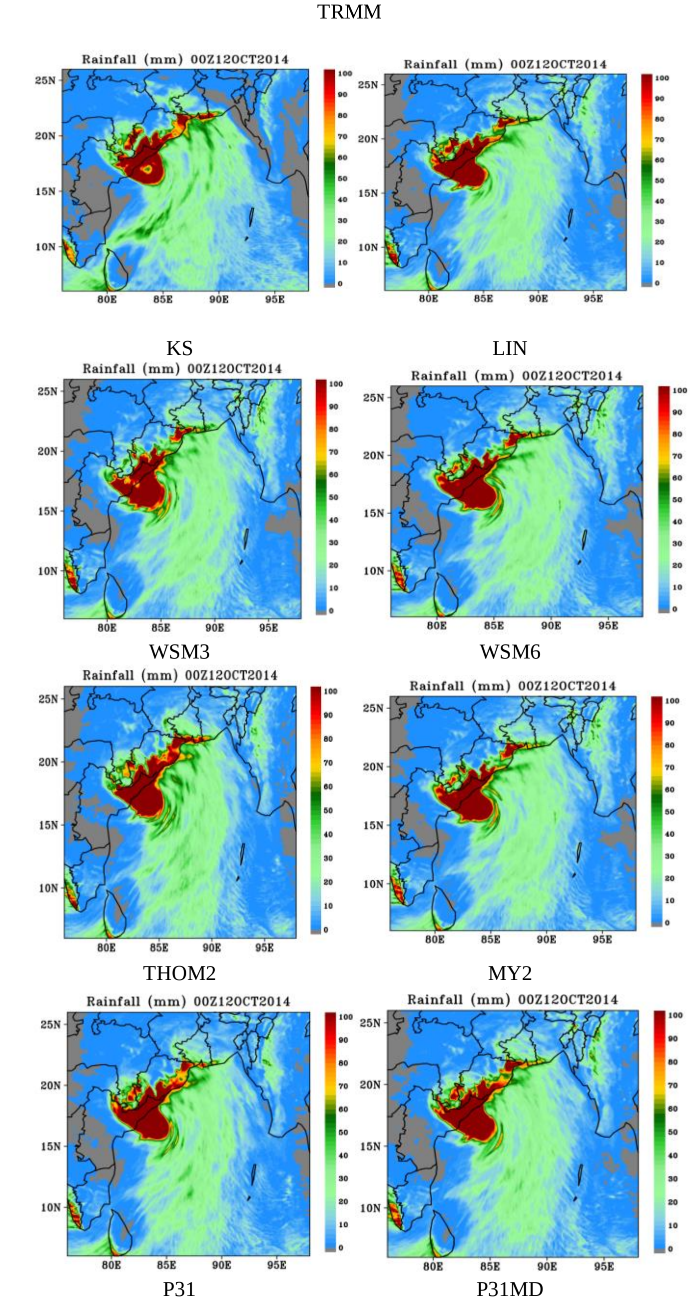


Figure 16. TRMM and different mp schemes 24 hr Accumulated rainfall in (mm)

CONCLUSION

The simulation of a tropical cyclone through WRF–ARW model is documented by studying the sensitivity of different model physics options and initial conditions. The investigated tropical cyclone is the Hudhud that formed recently over the North Indian Ocean. The simulated track and intensity of the Tropical Cyclone is assessed against best track data provided by IMD. The WRF–ARW simulations have performed well in predicting the propagation of the cyclone track. However, while using the 08/10/2014 initialization and boundary conditions, the Cyclone Track propagation error in distinctively high compared with the track error for 10/10/20014 initialization and boundary conditions. All the schemes well simulated the initial position of the storm but 08/10/2014 initial and boundary conditions are poorly simulated the initial MSLP and MSW. All the simulations have underestimated the strength of the cyclone to a larger extent. For Hudhud TC simulations with 08/10/2014 initial and boundary conditions WSM3 microphysics scheme in combination G3D cumulus scheme gives out the best results and TC simulations with 10/10/2014 initial and boundary conditions THOM2 microphysics scheme in combination G3D cumulus scheme gives out the best results which closely matches with the IMD track. The track error for this combination is the minimum of all the other combinations

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