Dhaka Univ. J. Sci. 66(1): 79-86, 2018 (January)

Structure Analysis of Tropical Cyclone Hudhud Over Bay of Bengal Using WRF Model

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(Received: 9 November 2017 ; Accepted : 20 December 2017)

Abstract

Tropical cyclones (TCs) over Bay of Bengal (BoB) have significant socio-economic impacts on the countries bordering the BoB. In this study, we have examined the structure and thermodynamic features of the TC Hudhud (7th -14th October, 2014) using WRF model. Simulated outputs are in good agreement with the available observations of India Meteorological Department and Joint Typhoon warning Center. At maximum intensity stage, the system's horizontal size is found around 690 km. Wind and vorticity distributions capture the circulation of the system very well. Most strong winds of 60 ms^{-1} are extended vertically from 850 hPa to about 700 hPa. Simulation has shown intensification of the system above 200 hPa with wind speed of about 30ms^{-1}. Relative humidity of the order of 90 % is found up to 400 hPa.

Key Words: TC, Horizontal size, Intensification, Vertical Profile.

I. Introduction

The Bay of Bengal (BoB) is the largest bay in the world situated in the eastern part of the North Indian Ocean (NIO). The tropical cyclones (TCs) over BoB have significant socio-economic impacts on the bordering countries especially Bangladesh, India and Myanmar. The shallow water of BoB, low flat coastal terrain and funneling shape of the coastline can lead to the most destructive TCs. So, it is very important to extend the lead time in the prediction of tropical cyclogenesis. A TC is a large, rapidly rotating system of clouds, winds, and thunderstorms characterized by a low pressure center near the earth's surface[1] that operates as a Carnot heat engine[2]. TCs have areas of positive near-surface vorticity[3]. The size[4] of TCs over the NIO varies from 100 to 2000 km with an average of 300-600 km. Numerical studies of TCs were started in the mid-1950s with the development of a two dimensional axisymmetric hurricane model[5]. A number of studies of TC wind structure were performed in 1960's and 1970's based on flight level data from aircraft observations[6]. In the present days, with the use of some high resolution three dimensional asymmetric numerical models (e.g. WRF model) the treatment of model governing equations and hence the cyclone research has improved a lot. Fovell *et al*.[7] simulated the hurricane 'Rita' by using WRF model with alternating Microphysical Parameterization (MP) and Cumulus Parameterization (CP) schemes. Environmental conditions such as sea surface temperature, vertical wind shear[8] and relative humidity (moisture) distribution[9] are the controlling parameters for the structure and intensity of a TC. Benjamin *et al.*[10] found that intensity and structure of the hurricane 'Katrina' was significantly depended on the surface flux by using WRF model. Basnayak *et al.*[11] and A. Imran *et al.*[12] simulated the structure and movement of cyclonic storms over the NIO by WRF-ARW model. Akhter *et al*.[13] found better performance of WRF model than MM5 model in simulating TCs over BoB.

In this study, the Advanced Research WRF (version 3.7.1) has been used to explore the structure (horizontal & vertical) and thermodynamic features of Very Severe Cyclonic Storm (VSCS) 'Hudhdud' that was formed over the BoB from 7th-14th October, 2014. The WRF model is suitable for extensive applications in the field of atmospheric research such as idealized simulations, real time weather forecasting, and data assimilation etc[14]. Improved knowledge of TC's structure & associated thermodynamics will improve the forecasting techniques of TCs over the BoB and this study may be helpful for this purpose.

II. Methodology

Data used

The Global Final (FNL) analysis data (6 hourly) on $1.0° \times 1.0°$ grids provided by the National Centre for Environmental Prediction (NCEP) has been used as the initial and lateral boundary condition. The simulated outputs are compared with the observed value from India Meteorological Department (IMD) and are visualized by using Grid Analysis and Display System. The model predicted rainfall is compared to the Tropical Rainfall Measuring Mission (TRMM) 3B42V7 rainfall data.

WRF model description [14]

WRF model is the composition of some fully compressible non-hydrostatic equations with different prognostic variables. Vertical grid coordinate is terrain following and dry hydrostatic pressure. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes. There are several options for spatial discretization, diffusion, lateral boundary conditions and nesting. Model initial conditions are three dimensional for real data and one to three dimensional for idealized data. The model has several options for CP, MP, surface layer physics, atmospheric radiation and planetary boundary layer physics. Fig. 1 represents the selected domain in WRF model for this study and the following table 1 contains the input details of the model.

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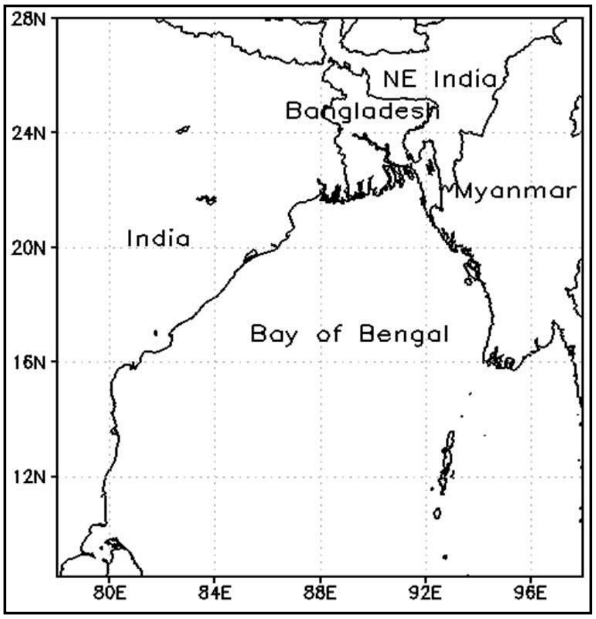

Fig. 1. Selected WRF Model Domain.

Table 1. List of WRF model inputs and domain configurations

No. of domain	1	**Horizontal grid**	Arakawa C-grid
Center of the domain	17.5°N, 87.5°E	**Time integration**	3rd order Runge-Kutta
Vertical co-ordinate	40 sigma levels	**Microphysics**	WSM 6-class (Hong and Lim)
No. of grid points & Resolution	W-E 100, S-N 100 & 20 km	**CP scheme**	Kain-Fritsch (new Eta)
Run time (120 hours)	2014-10-8_00 to 2014-10 13_00	**PBL scheme**	Yonsei University Scheme (YSU)
Map projection	Mercator	**Radiation scheme**	RRTM long wave; Dudhia's short wave

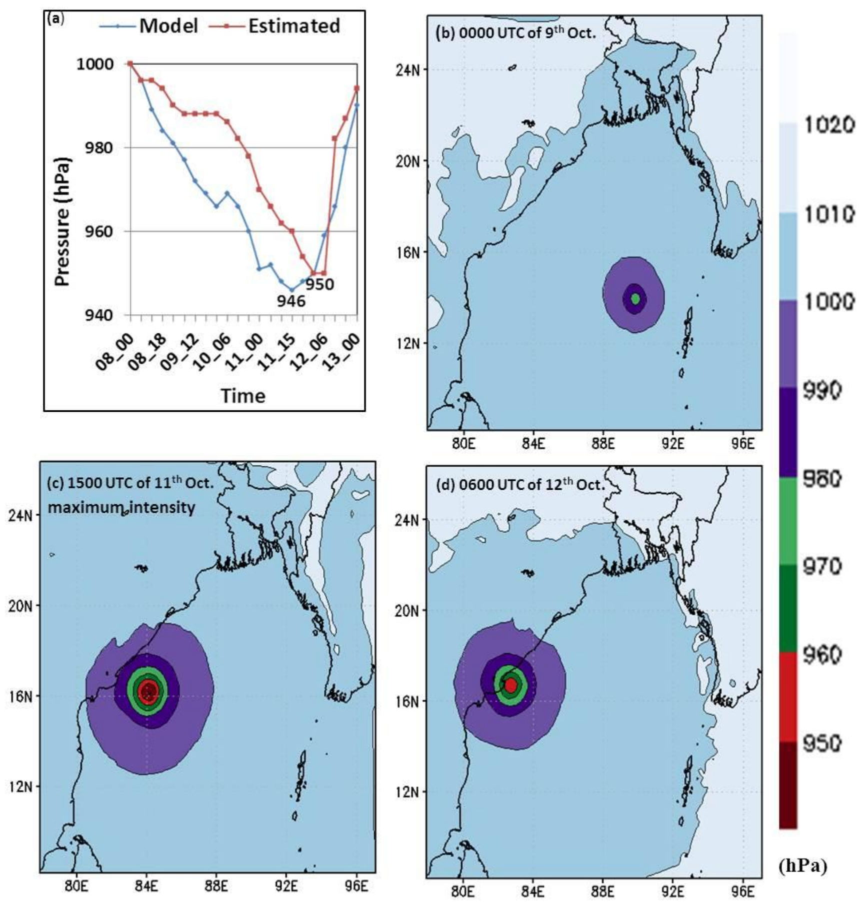

Fig. 2. (a) Comparison of MCP with the ECP (hPa)[15]. (b) - (d) MSLP (hPa) distribution based on 0000 UTC of 8th October, 2014.

III. Results and Discussion

Mean Sea Level Pressure (MSLP)

Comparison between the time evolution of the Estimated Central Pressure (ECP)[15] & simulated Minimum Central Pressure (MCP) of the TC Hudhud (Fig. 2a) shows that the simulated MCP falls more sharply than the ECP. The lowest simulated MCP of 946 hPa and the lowest ECP of 950 hPa are obtained at 1500 UTC of 11th October and 0000 UTC of 12th October respectively. Therefore, the model has predicted intensification of the system 09 hours in advance and overestimates in minimum pressure by only 4 hPa i.e. by only 0.42% (close to Douluri *et al.*[16]). From the distributions of simulated MSLP (Fig. 2b-2d), the lowest value is found at the center of the TC at its maximum intensity stage (Fig. 2c). At this stage, the system's horizontal size is estimated (considering the outermost closed isobar) around 6.25° (663 km) in the east-west (E-W) and 6.5° (722 km) in the north-south (N-S) directions. This result identifies Hudhud as an average sized[17] TC.

Wind flow analysis

Fig. 3a shows the variations of simulated Maximum Wind Speeds (MWSs) (at standard meteorological height of 10 m) and estimated maximum sustained surface wind[15] (MSSW) of the TC Hudhud. The highest simulated MWS of 45 ms^{-1} is obtained at 1500 UTC and the highest estimated MSSW of 51.44 ms^{-1} is obtained at 1800 UTC of 11th October. So, the model underestimates the highest MWS by 6.0 ms^{-1} i.e. by 12% (close to Douluri *et al.*[16]). The horizontal distributions of wind at surface (Fig. 3b-3d) shows strong cyclonic circulation with minimum wind at the center (eye of the TC). Strongest winds of around 30 ms^{-1} at the initial stage (Fig. 3b) & 40-45 ms^{-1} at the maximum intensity (Fig. 3c) both are found in the south-east sector of the TC. Near landfall (Fig. 3d), wind in the front side (northwest) of the system is slightly smaller compared to that in the other sectors due to landmass friction.

At 850 hPa level (Fig. 4), the distribution of wind is almost the same as that of at the surface level except the increase in wind magnitude to a value of around 60-70 ms^{-1}. At 200 hPa level, the cyclonic circulation is not well defined at the initial stage (Fig. 5a) but at the stage of maximum intensity (Fig. 5b); there is clearly a well-organized cyclonic circulation that makes the TC Hudhud VSCS.

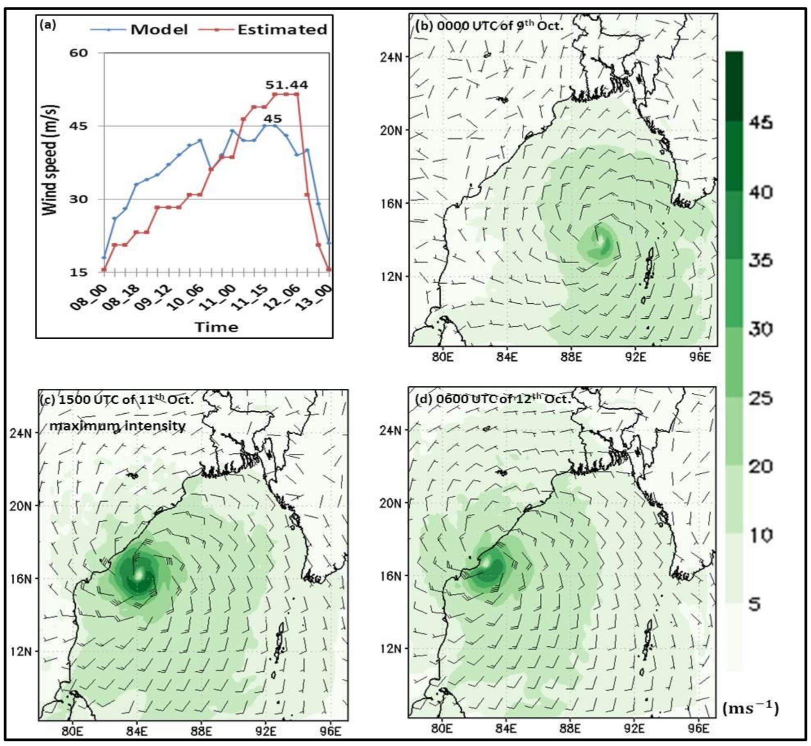

Fig. 3. (a) Comparison of simulated MWS (ms^{-1}) at surface with the estimated MSSW (ms^{-1}) [15]. (b) – (d) wind distribution (speed in ms^{-1}) at surface based on 0000 UTC of 8th October, 2014.

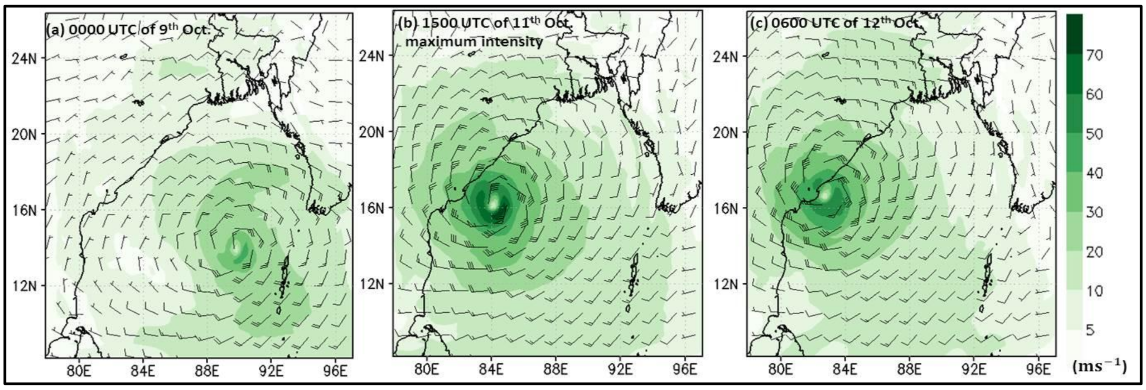

Fig. 4. Wind distribution (speed in ms^{-1}) at 850 hPa level based on 0000 UTC of 8th October, 2014.

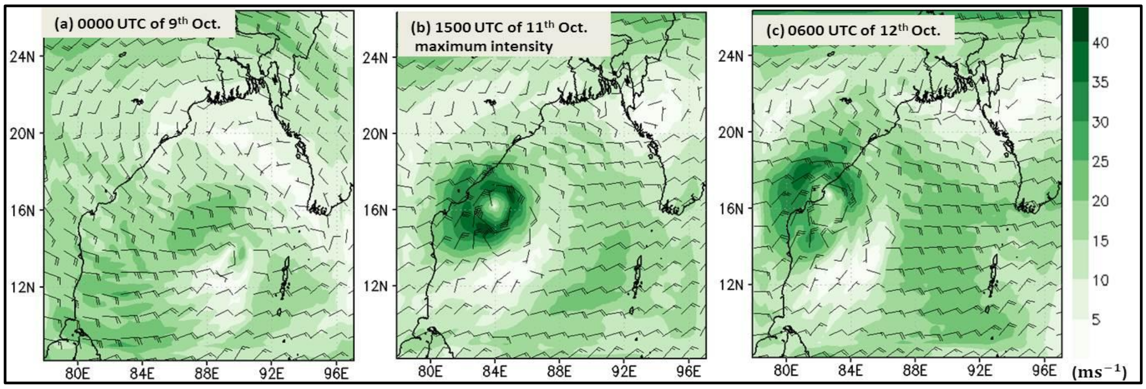

Fig. 5. Wind distribution (speed in ms^{-1}) at 200 hPa level based on 0000 UTC of 8th October, 2014.

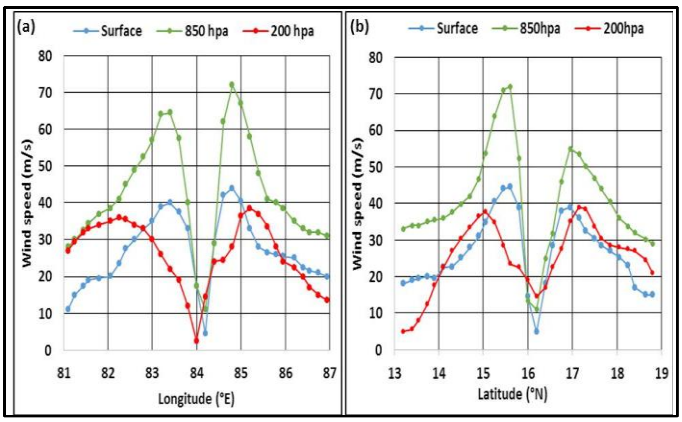

Fig. 6. Wind speed distribution (ms^{-1}) at 1500 UTC of 11th October (maximum intensity), along the center (16.19°N, 84.18°E).

Fig. 6 ((a) E-W, (b) N-S) shows the distributions of simulated wind of the TC Hudhud passing through its center at 1500 UTC of 11th October, 2014 (maximum intensity). The central region is relatively calm with feeble wind compared to that in the surrounding eyewall of the system. The radius of maximum wind of the system at surface, 850 hPa and 200 hPa are found to be around 60, 60 and 110 Km respectively.

Relative vorticity

The horizontal distributions of simulated relative vorticity (Fig. 7) at 850 hPa associated with the TC Hudhud shows positive relative vorticity close to the center that indicates strong cyclonic circulation[18] which contributes to the severe convective activities to maintain the supply of moisture into the system. The vorticity increases following the development of the TC and it is maximum (around $240\times 10^{-5}s^{-1}$) at the stage of maximum intensity (Fig. 7b). At 200 hPa level (Fig. 8), joint distribution of weak positive vorticity (around $110\times 10^{-5}s^{-1}$) along with negative vorticity indicates cyclonic circulation up to 200 hPa that correspondingly indicate the intensification of the system into a VSCS.

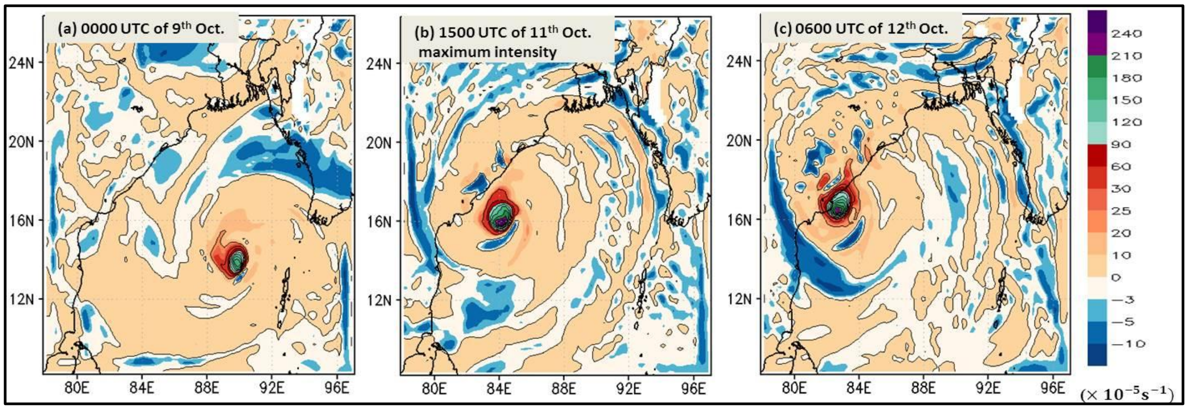

Fig. 7. The distribution of relative vorticity (unit: $\times 10^{-5}s^{-1}$) at 850 hPa based on 0000 UTC of 8th October, 2014.

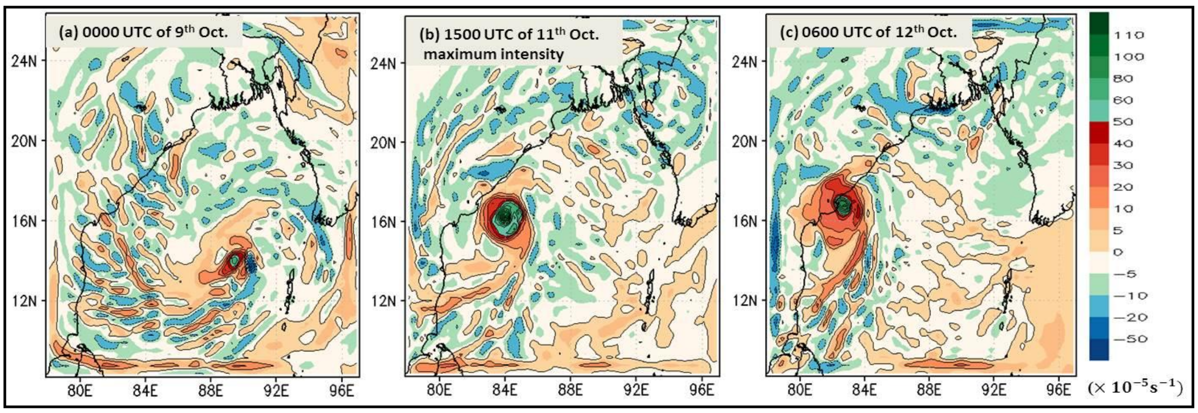

Fig. 8. The distribution of relative vorticity (unit: $\times 10^{-5}s^{-1}$) at 200 hPa based on 0000 UTC of 8th October, 2014.

Relative humidity (RH) and rainfall

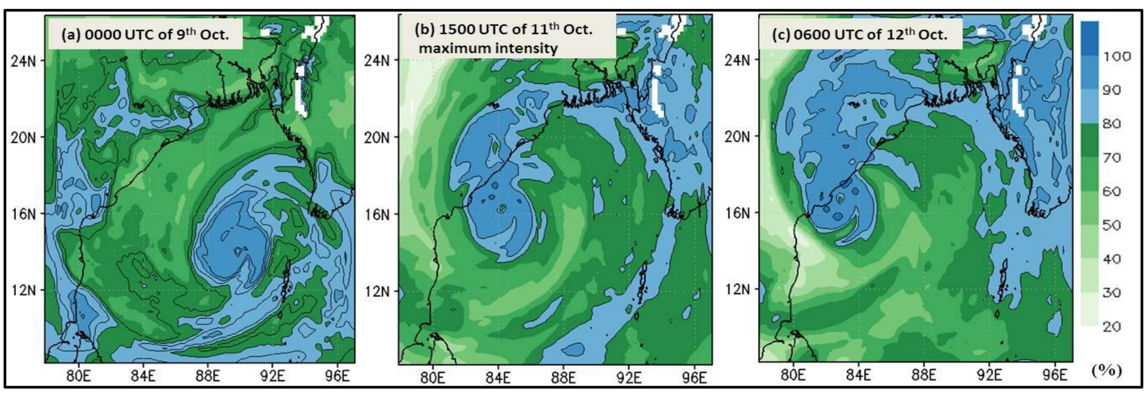

Fig. 9. The distribution of RH (%) at 850 hPa based on 0000 UTC of 8th October, 2014.

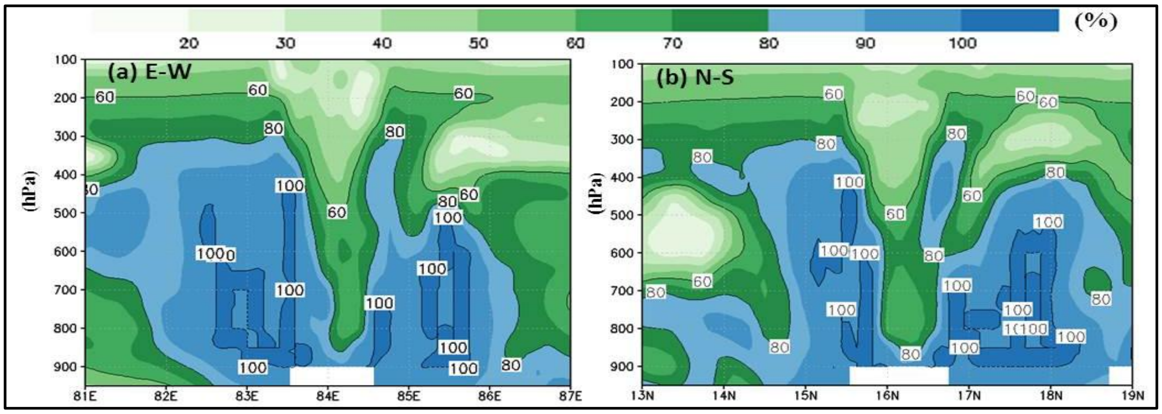

Fig. 10. Vertical profile of RH (%) at 1500 UTC of 11th October (maximum intensity), along the center (16.19°N, 84.18°E).

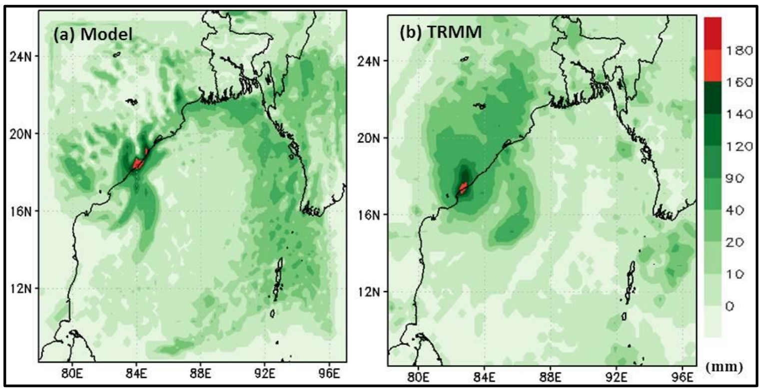

Fig. 11. Comparison of (a) simulated and (b) TRMM 24 hour accumulated rainfall (mm) on 12th October (landfall day), 2014.

The horizontal distributions of RH at 850 hPa (Fig. 9) indicate that southeasterly flow associated with the TC transports huge amount of moisture (80-100 %) which is favorable for heavy rainfall events near landfall. The vertical profile of RH along the center (Fig. 10) at 1500 UTC of 11th October (maximum intensity) shows lower values of RH at the center than the surroundings. Large RH (> 80 %) along the center of the system is extended up to 850 hPa. Above 500 hPa the air is relatively dry (RH $\leq$ 50 %). But in the peripheral region, high RH (90 %) is maintained up to 400 hPa[19].

The comparison between the spatial distribution of simulated and the TRMM 3B42V7 24 hour accumulated rainfalls (Fig.11) on 12th October (landfall day) shows that model simulated and TRMM rainfalls are nearly in good agreement in both spatial and quantitative perspective.

Zonal and meridional components of velocity

The vertical distributions of zonal and meridional wind (Fig. 12) at maximum intensity along the center capture a calm center (the eye) with feeble wind. Strong winds with different magnitudes are confined at different levels. In Fig. 12a, the negative (north side) and positive (south side) zonal velocities indicate easterly and westerly winds respectively. Maximum wind of 60 ms^{-1} is found to the south of the center that extends vertically from 850-700 hPa. In Fig. 12b, the positive (east side) and negative (west side) values of meridional wind represent southerly & northerly winds respectively. Maximum wind of 60 ms^{-1} is in between 950 to 800 hPa. Wind speed also decreases with increasing distance (radius) from the center[19].

Vertical component of velocity

The distributions of vertical velocity component (Fig. 13) at maximum intensity through the center of the TC show both upward (positive) and downward (negative) motions. In the E-W (Fig. 13a) and N-S (Fig. 13b) view, strong updraft with magnitude 0.5-2.5 ms^{-1} (western side) & 1-3 ms^{-1} (southern side) are found respectively along the peripheral region. So, the updraft is relatively stronger in the south-west sector. Upward motion through the troposphere maintains the feeding of necessary moisture to the system. Downdrafts are through the center and the regions in between rain bands of the TC i.e. downdrafts in between the updrafts[20].

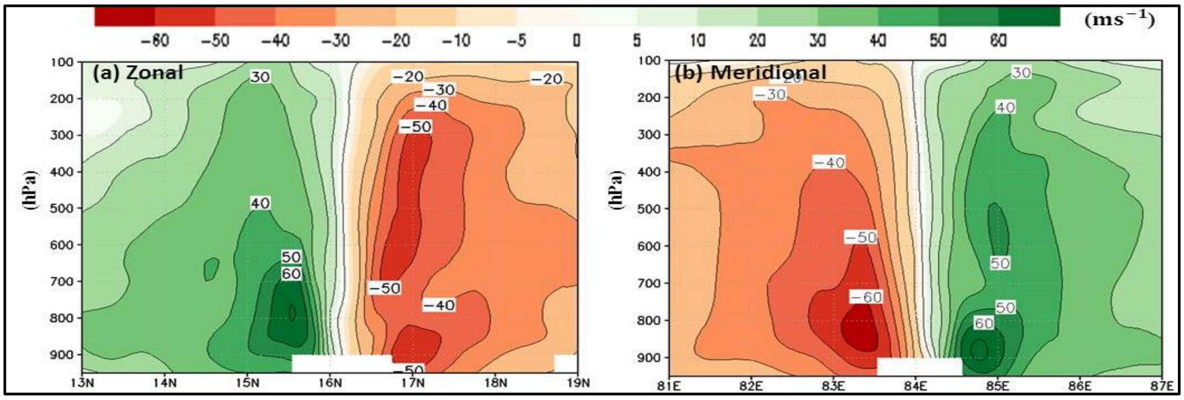

Fig. 12. Horizontal components of velocity at 1500 UTC, 11th October (maximum intensity) along the center (16.19°N, 84.18°E).

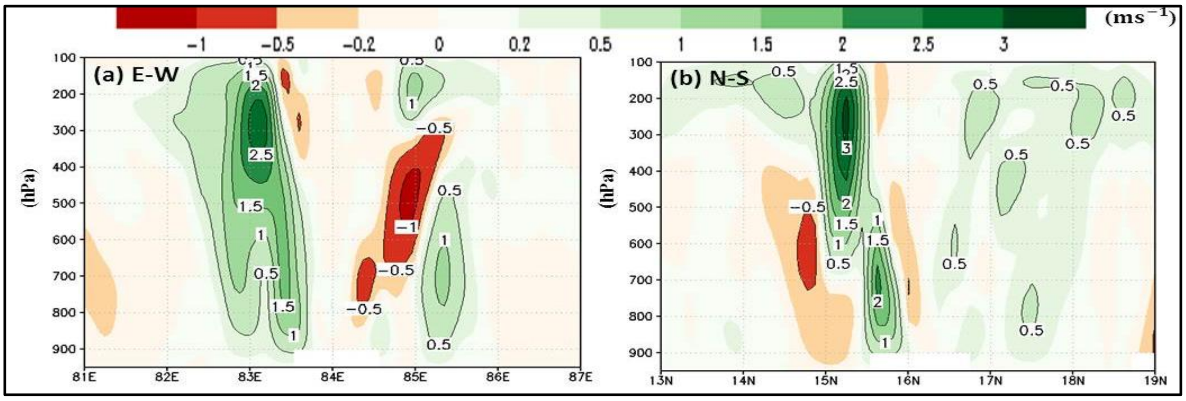

Fig. 13. Vertical component of velocity at 1500 UTC, 11th October (maximum intensity) along the center (16.19°N, 84.18°E).

IV. Conclusions

Lowest MCP for the TC Hudhud is 946 hPa and highest MWS at surface is 45 ms^{-1}. Average horizontal size of the TC at the most intense stage is found roughly 690 km. The wind speeds are found to be decreasing with increasing height but the size of the TC changes inversely. Favorable RH ($\geq$60 %) is found between 700 and 500 hPa. The wind and relative vorticity distributions show cyclonic circulation up to 200 hPa. Large vertical extension (entire troposphere) of the TC is found with strongest winds (60ms^{-1}) in between 850 to 700 hPa. The highest upward velocity is found around 3ms^{-1}.

Acknowledgements

The authors are grateful to National Center for Atmospheric Research and National Center for Environmental Prediction for providing the WRF model and analysis data sets respectively. We are also thankful to India Meteorological Department and Joint Typhoon Warning Center for observed data to validate our results.

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