Evolution of Dynamic Parameters during the Development of Tropical Cyclones over North Indian Ocean using WRF Model

A.H.M. Fazla Rabbi[1], Ishtiaque M. Syed[1], Md. Abdullah Elias Akhter[2], M A K Mallik[3]

[1]*Department of Physics, University of Dhaka, Dhaka, 1000, Bangladesh*
[2]*Department of Physics, Khulna University of Engineering and Technology, Khulna, Bangladesh*
[3]*Bangladesh Meteorological Department, Agargaon, Dhaka., Bangladesh*

Corresponding Author's mail: rabbiphy@gmail.com

Abstract

The development of tropical cyclones (TC) has remained a complex phenomenon to the meteorologist from the very beginning. Analysis of dynamic parameters may provide significant insights concerning the development of tropical storms (TS). In the present study, we used Weather Research and Forecasting (WRF) Model version 4.0.3 to simulate the dynamic parameters of TCs Amphan, Titli, Ashoba and Mekunu over the North Indian Ocean (NIO). Among them Amphan and Titli formed over the Bay of Bengal(BOB) and two others over Arabian Sea(AS).All the simulations were done by following the time and status of the events issued by the Indian Meteorological Department (IMD) satellite observation. A coupling of the Kain-Fritsch (new Eta) cumulus scheme and the WSM6-class graupel microphysics parameterization scheme used to run the model. The westerlies dominate the upper air three days before reaching a mature TC. The low-level wind speed continued to increase with time, reaching 35 knots and becoming a cyclonic storm in the final moments of the model run. At the same time, cyclonic and large-scale anti-cyclonic circulation systems are observed in the upper atmosphere to the left and right sides of the cyclone centre, respectively. A rapid decline in central pressure begins two days before the cyclone develops. The trend of increasing upper and lower relative vorticity throughout the whole period of the model run favours the intensity of TC. The wind shear becomes positive and weak from about 6 hours before reaching a mature TC. However, the acquisition of negative values of wind shear during the 72-h period before turning into a TC could not hinder the genesis and development of the TC. Therefore, the WRF model has captured very plausible dynamic features of tropical cyclone over NIO.

Keywords: Dynamic, WRF, NIO, Vorticity and Shear**.**

1. Introduction

Tropical cyclones are the most devastating natural calamity. Quick preparedness and efficient early warning systems can reduce high mortality and natural hazards caused by TC. For a better prediction of TC, a complete understanding of tropical cyclogenesis is significantly required. Physics for the genesis of the tropical cyclone (TC) is very complex. Lack of upper air routine observation is one of the dominant factors obstructing the complete understanding of cyclogenesis. In tropics, pre-existing tropical disturbance (TD) is the triggering mechanism for the genesis of TC [1]. TDs are the distinctly organized cloud and wind patterns in the horizontal scale of 100 to 600 km [2]. The life span of TDs is a day or more. In the North Indian Ocean (NIO), the average distance between the points of the initial location of TD and the position of high-intensity TC in any direction is approximately 7^0 lat. No TC can develop in the vicinity of the equator. An area of positive vorticity associated with low-level convergence favours cyclogenesis [2]. Gray (1968) defines TC as a warmed core cyclonically rotating wind in which the maximum sustained winds speed is 35 knots(40 m.ph.) or higher. The development of TC follows the same basic physical process in all locations [3].In the genesis stage, a vortex of weak relative vorticity extending through about the whole of the troposphere exists at pre-existing TD [4]. In low latitudes intensifying upper trough produce a sharp downstream wave trough. In this downstream wave trough, resultant pressure fall set up a low-level cyclonic disturbance. This type of disturbance is sufficient to initiate the development of TC [5].

Instability in the trade wind belt of the northern hemisphere commences the development of TC. Such instability set wave troughs in the easterlies of the lower troposphere. This type of instability also set the broad-scale ridge in the westerlies of the upper troposphere. A tropical cyclone can develop from a disturbance under that ridge of the upper troposphere. This ridge facilitates the upper-level outflow [6]. This upper-level outflow is subjected to a narrow channel and directed towards the higher latitudes [18]. The prerequisites for the development of TC exist in the locations more than 5^0 latitudes over tropical ocean [17].

In the early stage of TC formation, a midlevel cyclonic vortex is formed and undergoes downward expansion towards the boundary layer. A warmed core and surface flux driven TC develop within this vortex. This mid-level vortex increases the mid-level relative humidity. That results in higher precipitation with enhanced low-level inflow and vertical mass fluxes [7,8]. Erickson has shown that low-level positive vorticity and upper-level negative vorticity are significantly higher in developing TDs[9]. The poleward flow aloft with anticyclonic vorticity is more favourable for tropical cyclogenesis [10, 19].

According to Frank and Roundy (2006), TCs form in the regions that meet the following climatological conditions: 1) sea surface temperatures not less than 26.5°C 2) low-level positive relative vorticity and planetary vorticity 3) weak to moderate zonal vertical wind shear, and 4) broad-scale ascending motion with intense convection in an area and high mid-tropospheric relative humidity [11].

Michio Yanai (1968) has divided the cyclogenesis process into three stages (i) wave stage: a low-level disturbance with high-level anticyclonic circulation (ii) warming stage: gradual warming at the upper troposphere and transformation of the cold-core to the warm-core (iii) developing stage: the system establish as a warm-core structure throughout the whole troposphere [12]. In the pre cyclone, small-scale vortical hot towers work as building blocks for the large-scale cyclogenesis process. Low-level convergence provides the necessary favourable spin-up condition that exceeds the spin-down tendency due to available surface friction [13].

Weaker vertical wind shear and more anticyclonic upper troposphere are necessary characteristics for the development of TDs [14]. The threshold value of vertical wind shear that prevents the formation and intensification of TC is 12.5 ms^{-1} [15].

The TCs are formed usually in pre and post-monsoon seasons in the BOB region. During these periods, there exist upper-level westerlies and minimum zonal vertical wind shear. In monsoon, zonal vertical wind shear becomes large enough due to the surface westerlies and strong upper-level easterlies. This condition prevents any development of TC in this region. Inside a developed TC, low-level convergence and compensating upper-level divergence provides sufficient moisture to maintain a warmed core vortex [3].

This study aims to analyze the role of dynamic parameters in creating favourable conditions for the development of TC over the NIO. The evolution of dynamic parameters of TCs will examine as well.

2. Data and methods

The WRF model version 4.0.3 used to simulate the dynamic parameters of TC. The 72 hours model run conducted from the low pressure area as initial conditon to the cyclonic storm (CS) stage as end condition. The model run took place following the best track position and status provided by the satellite observations of the Indian Meteorological Department(IMD). We used NCEP FNL reanalysis 1x1 degree data in the simulations. One-way nesting method is used to set up the domains. The horizontal resolutions of parent and child domains were 21 and 7 Kms. Arakawa C-grid staggering as grid distribution with mercator map projection used in the model runs. A coupling of the Kain-Fritsch (new Eta) scheme and WSM 6-class graupel scheme as cumulus and microphysics option applied in the runs. We calculated wind speed at 850hPa, central pressure and vertical wind shear between 850 and 200 hPa within the corresponding area of the inner domain. We visualized the model outputs using the GrADS software. The model outputs compared with the European Centre for Medium Range Weather Forecast (ECMWF) Reanalysis 5th Generation (ERA5) hourly data of 0.25° x 0.25° horizontal resolution.

Table1. Studied events for which model runs took place following the time and rank issued by IMD.

Event Name	**72 hours run**		**Location**	**Initial condition**	**End condition**	**Maximum intensity during their life cycle**
	Initial time and date	**End time and date**				
Amphan	1200UTC_ 13/05/2020	1200UTC_16 /05/2020	South-east BOB	LPA	CS	SuCS
Titli	0600UTC_ 06/10/2018	0600UTC_09 /10/2018	East-central BOB	LPA	CS	VSCS
Ashoba	0600UTC_ 05/06/2015	0600UTC_08 /06/2015	East-central AS	LPA	CS	CS
Mekunu	1200UTC_ 19/05/2018	1200UTC_22 /05/2018	South-east AS	LPA	CS	ESCS

*LPA: Low Pressure Area, *CS: Cyclonic Storm, *VSCS: Very Severe Cyclonic,*ESCS: Extremely Severe Cyclonic Storm,*SuCS: Super Cyclonic Storm.

3. Result and Discussion

3.1. Wind Field

Wind speed and direction are very significant for the prediction of the formation and development of TC over the tropical ocean. Generally, wind speed is used to measure the intensity of TC. In our study, the low-level wind speed around the centres of TCs increased with time. The wind speed measured by model found very close to ECMWF values for Ashoba and Mekunu. In last 36 hours spell model simulated wind speed found slightly higher than that of ECMWF in case of Amphan and Titli [Fig. 1]. At the end stage of the run wind speeds reached 35 to 40 knots and comparable to that of the ECMWF values. This result was also found consistent with the theoretical value of Gray (1968) as well as the IMD's satellite observed value for TC. The existence of westerly upper wind was observed three days ahead of the CS stage in the north and northeast sides of the centres of the events. The cyclonic and large scaled anti-cyclonic upper wind dominated the left and right sides of the centres in the CS stage [Fig.2-9]. These upper wind conditions favoured the development of our studied events. These upper pole-ward, westerly and large scaled anti-cyclonic wind (circles indicate the centre) found consistent with the theories of Erickson (1977), Colon et al. (1963) and Holland (1997) over the North Pacific region [9,10,18].

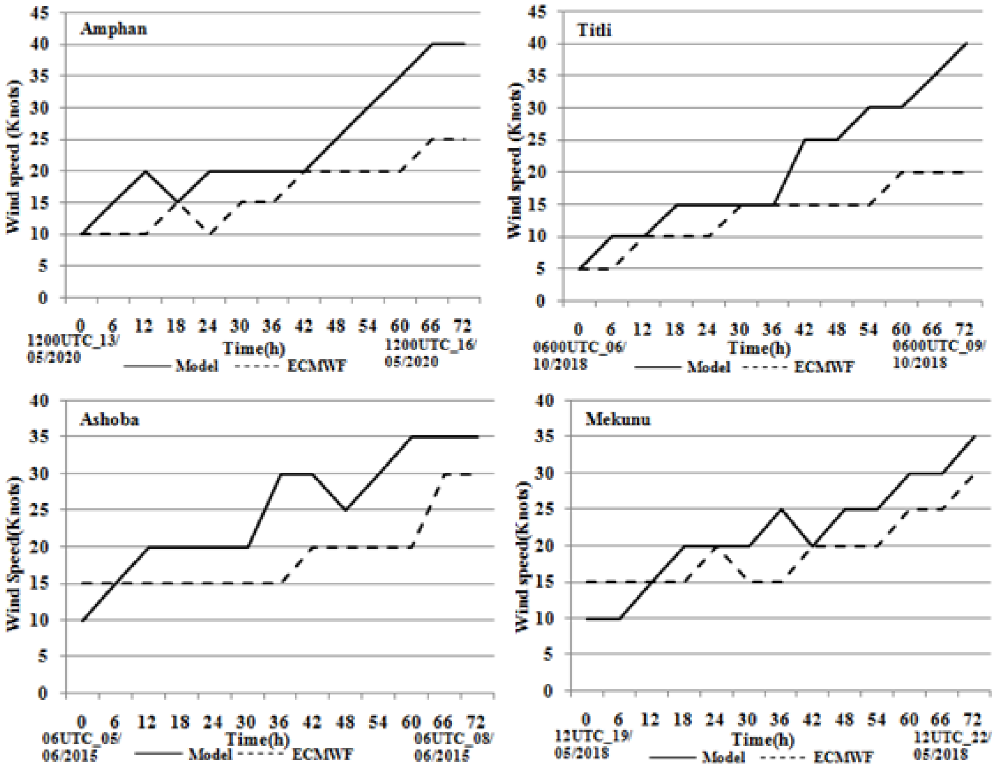

Figure 1: Variation of low level (850 hPa) wind at every six hours in Amphan, Titli, Ashoba and Mekunu.

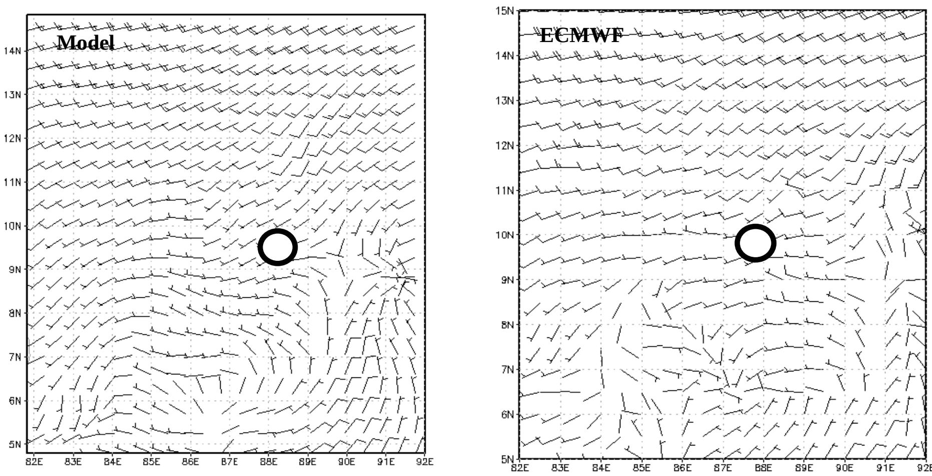

Figure2: Upper level (200 hPa) wind at 1200UTC of May 13, 2020, three days before the CS stage of Amphan.

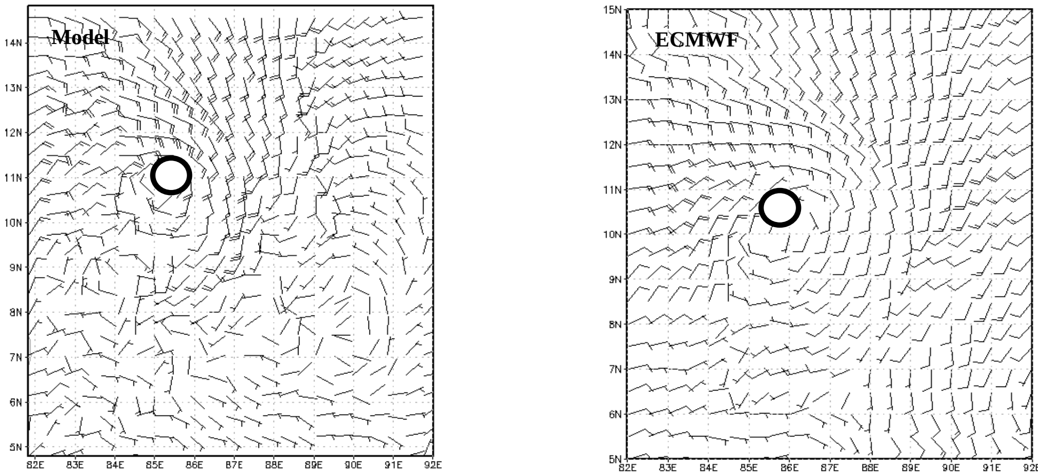

Figure 3: Upper level (200 hPa) wind at 1200UTC of May 16, 2020, in the CS stage of Amphan .

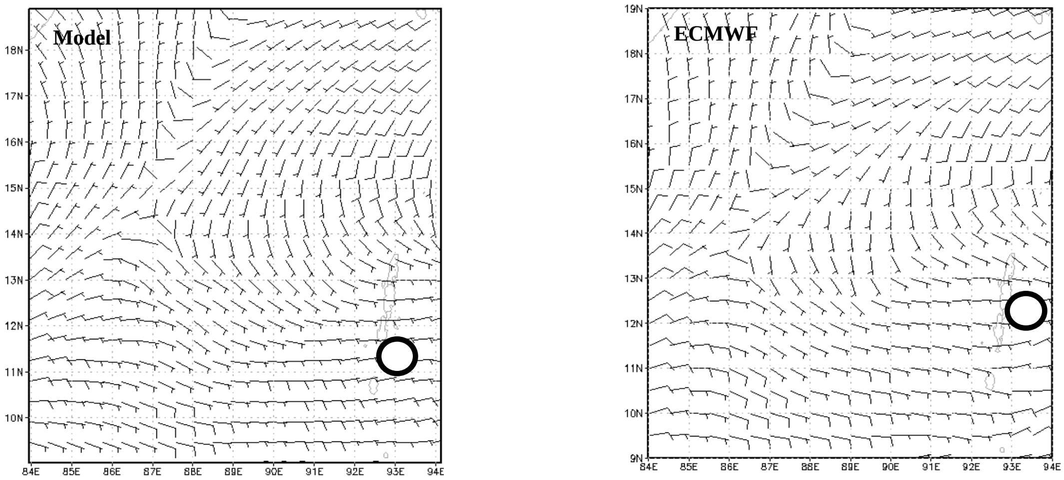

Figure 4: Upper level (200 hPa) wind at 06 UTC of October 06, 2018, three days before the CS stage of Titli. .

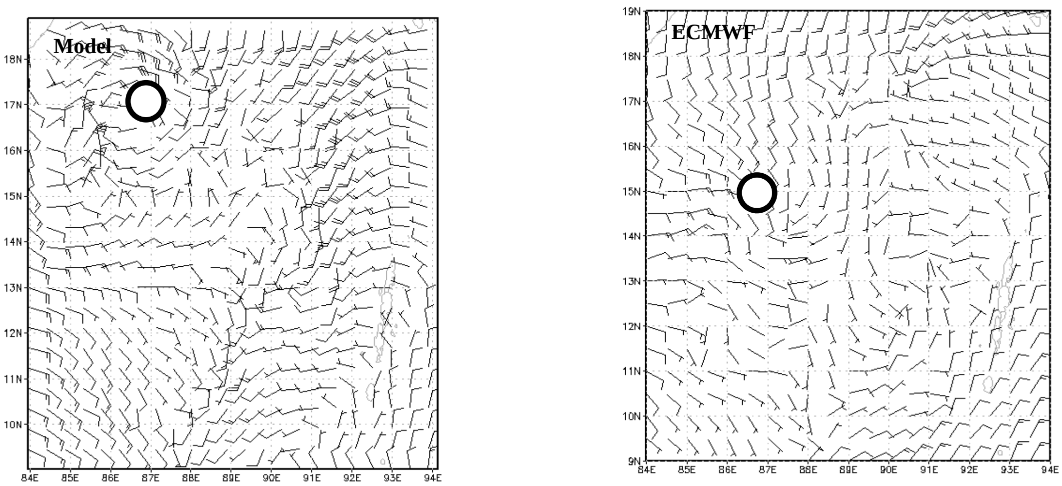

Figure 5: Upper level (200 hPa) wind at 06 UTC of October 09, 2018, in the CS stage of Titli.

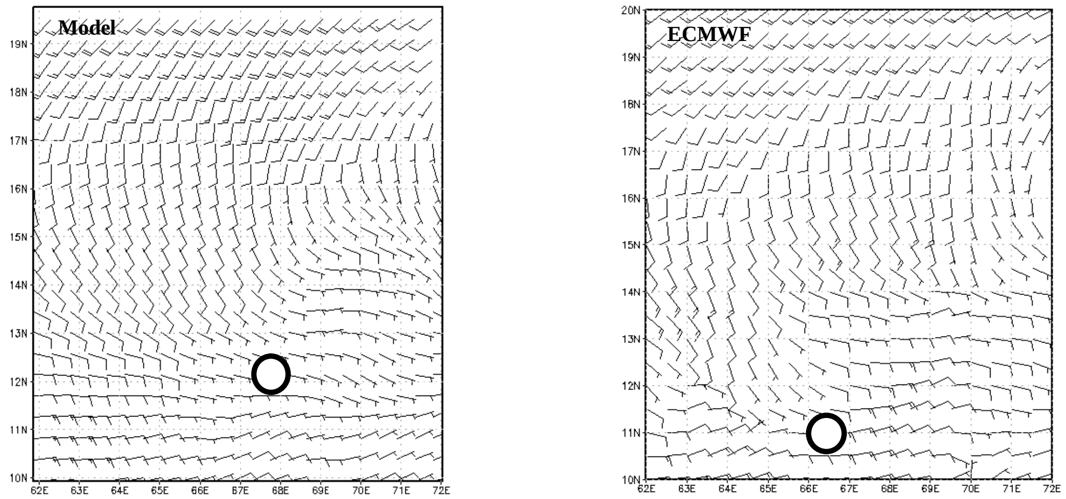

Figure 6: Upper level (200 hPa) wind at 06 UTC of June 05, 2015, three days before the CS stage of Ashoba

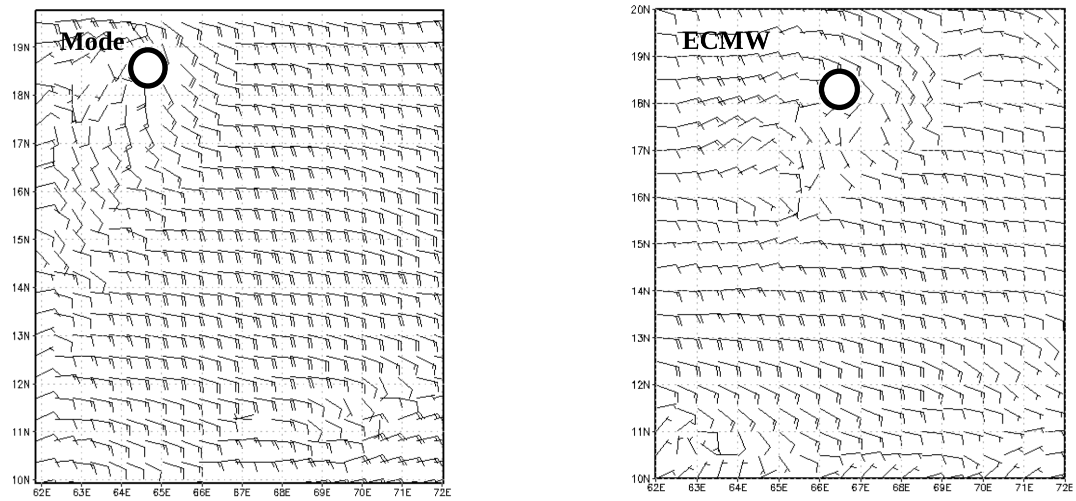

Figure 7: Upper level (200 hPa) wind at 06 UTC of June 08, 2015, in the CS stage of Ashoba.

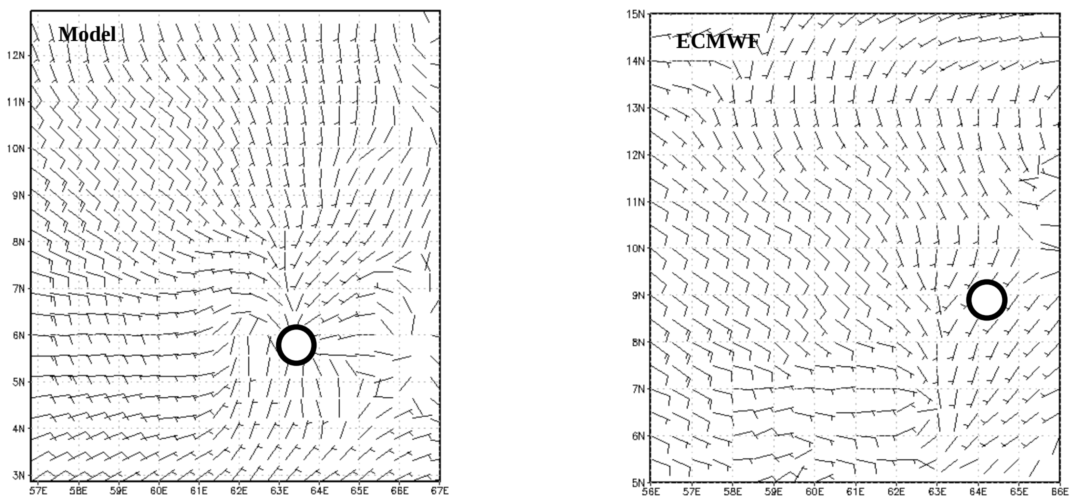

Figure 8: Upper level (200 hPa) wind at 12 UTC of May19, 2018, three days before the CS stage of Mekunu.

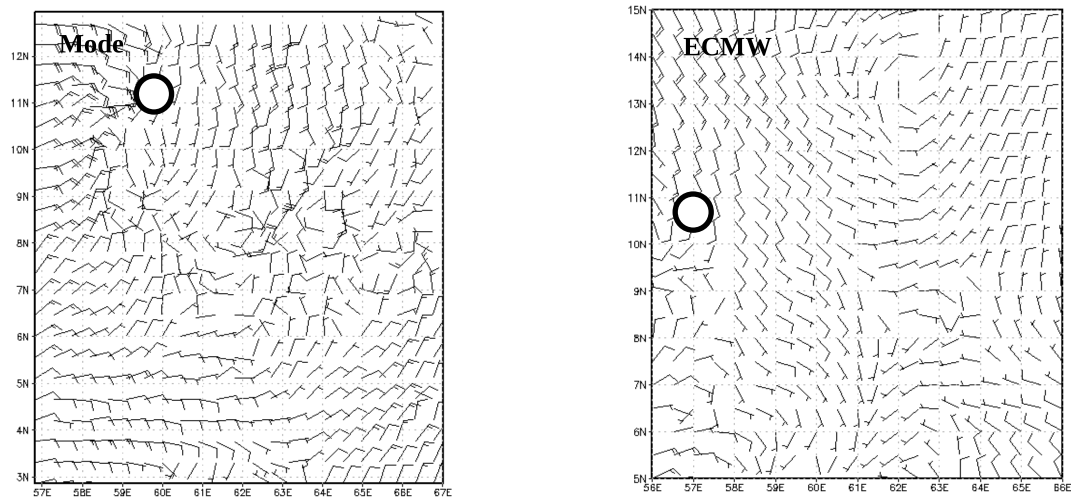

Figure 9: Upper level (200 hPa) wind at 12 UTC of May 22, 2018, in the CS stage of Mekunu .

3.2. Central Pressure

The decline of central pressure is crucial for the formation of TC over tropical oceans. Pressure drop through the centre enhances the low-level moisture inflow. Central pressure can also be a measurement of the intensity of storms. Model-derived central pressure was close to ECMWF during the first 24 hours. After that, the model has shown a rapid decline in central pressure. However, the model-measured pressure drop for Mekunu almost coincides with the ECMWF. Among our events, super-cyclone Amphan has the highest central pressure drop. A rapid decline in the central pressure of TCs begins approximately two days before reaching the CS stage [Fig.10]. The pressure drop obtained from the model is near to or less than the statistical threshold pressure 995 hPa for the maturity of TC over the Western North Pacific Ocean [19]. Therefore, the WRF model has succeeded in measuring the central pressure decline of TC.

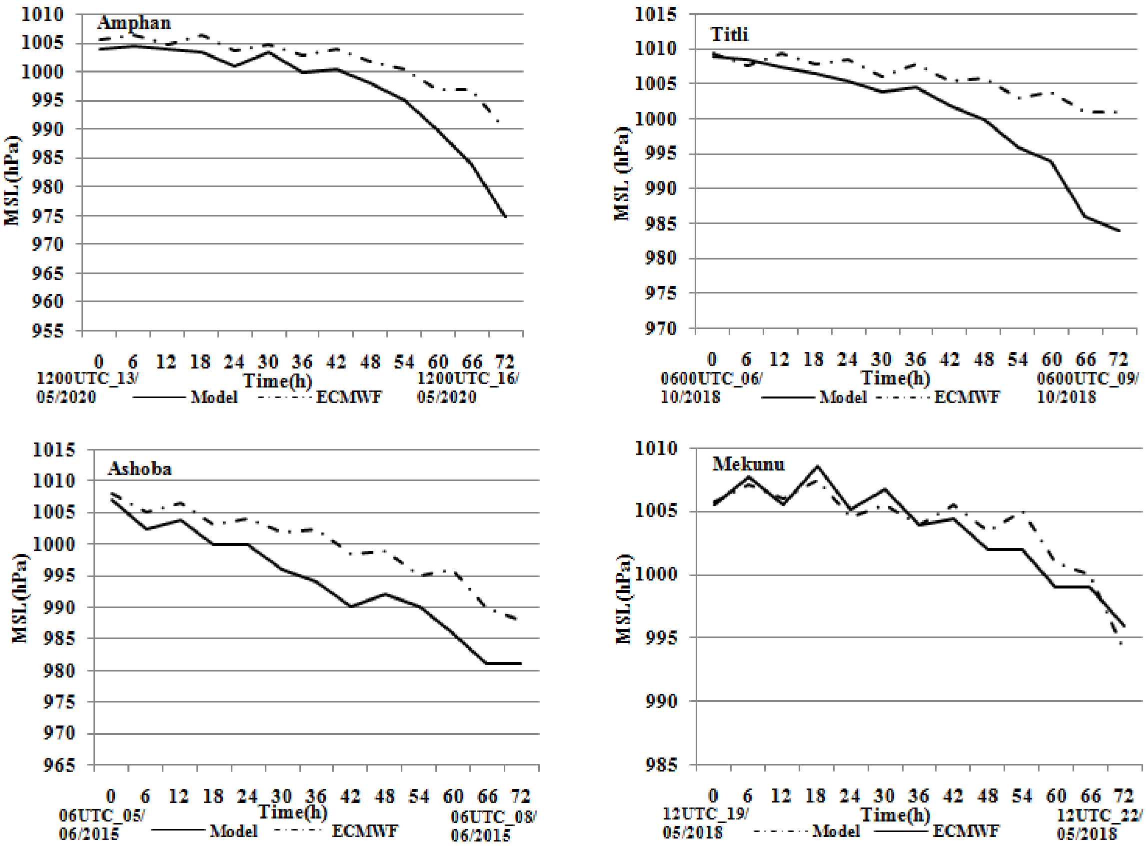

Figure 10: Variation of central pressure at every six hours of 72 hours model run in Amphan, Titli, Ashoba and Mekunu..

3.3. Relative Vorticity

Relative vorticity is one of the influential primary genesis parameters. Low-level relative vorticity plays a pivotal role in the flow of moisture into the low-pressure centers. Such inflow generates favorable conditions for the development of TC. In the tropics, the region with positive vorticity is the most breeding zone of TC. There is no controversy among meteorologists regarding this issue. The figures [11-12] depicted that the model overestimates the upper and lower relative vorticity than ECMWF. But the evolution of relative vorticity over time in the model and ECMWF shows the same pattern. In other words, the temporal increase of upper and lower relative vorticity persists in both model and ECMWF. This trend of increasing upper and lower relative vorticity is consistent with the intensity of TC. The figures [11-12] show that the magnitude of the TCs has changed to the CS stage [Fig.1] in the last moments of the model run. So, it can say that the model captures this trend of increasing intensity very effectively. In this study, the model-derived low-level positive relative vorticities were found ≥180×10-5s^{-1} for lower-level and ≥ 120×10-5s^{-1} for upper-level at the moment of CS stage [Fig.1,11and12]. These vorticities are greater than Gray's (1975) threshold value of 10×10-6s^{-1} for TC genesis.

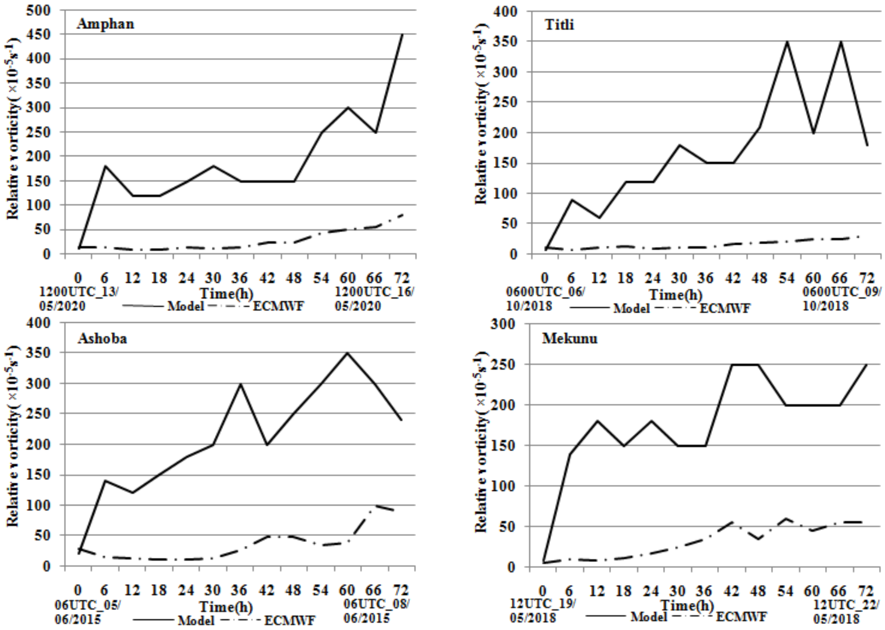

Figure 11: Variation of (850 hPa) relative vorticity after each six hours in 72 hours

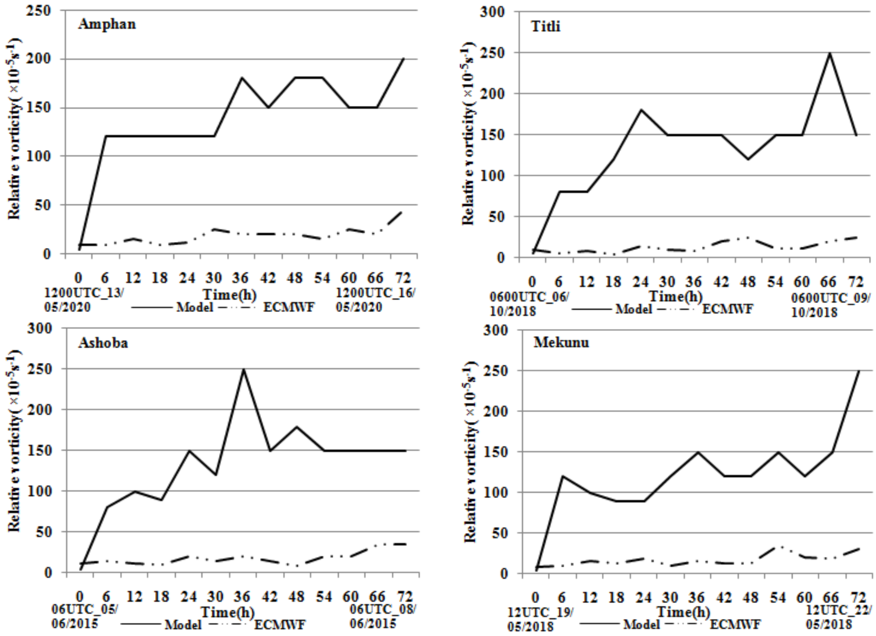

Figure 12: variation of upper (200 hPa) relative vorticity in 72 hours run.

3.4. Zonal Vertical Wind Shear

Zonal vertical wind shear is another dominant primary genesis parameter. Most meteorologists suggest that weak to moderate zonal wind shear favours the genesis of TC. In both model and ECMWF, vertical shear values didn't exceed 10 ms^{-1} through the whole period of runs. The temporal variation of shear values ≤0 ms^{-1} during the examined period didn't prevent the development of our studied events. The shear values between 0 to 5 ms^{-1} were more frequent. From six hours ahead of the CS stage, vertical shear persisted with positive values. Therefore, shear values during the intensification to the matured stage (CS) found positive and were less than the threshold value of 12.5 ms^{-1}[15].

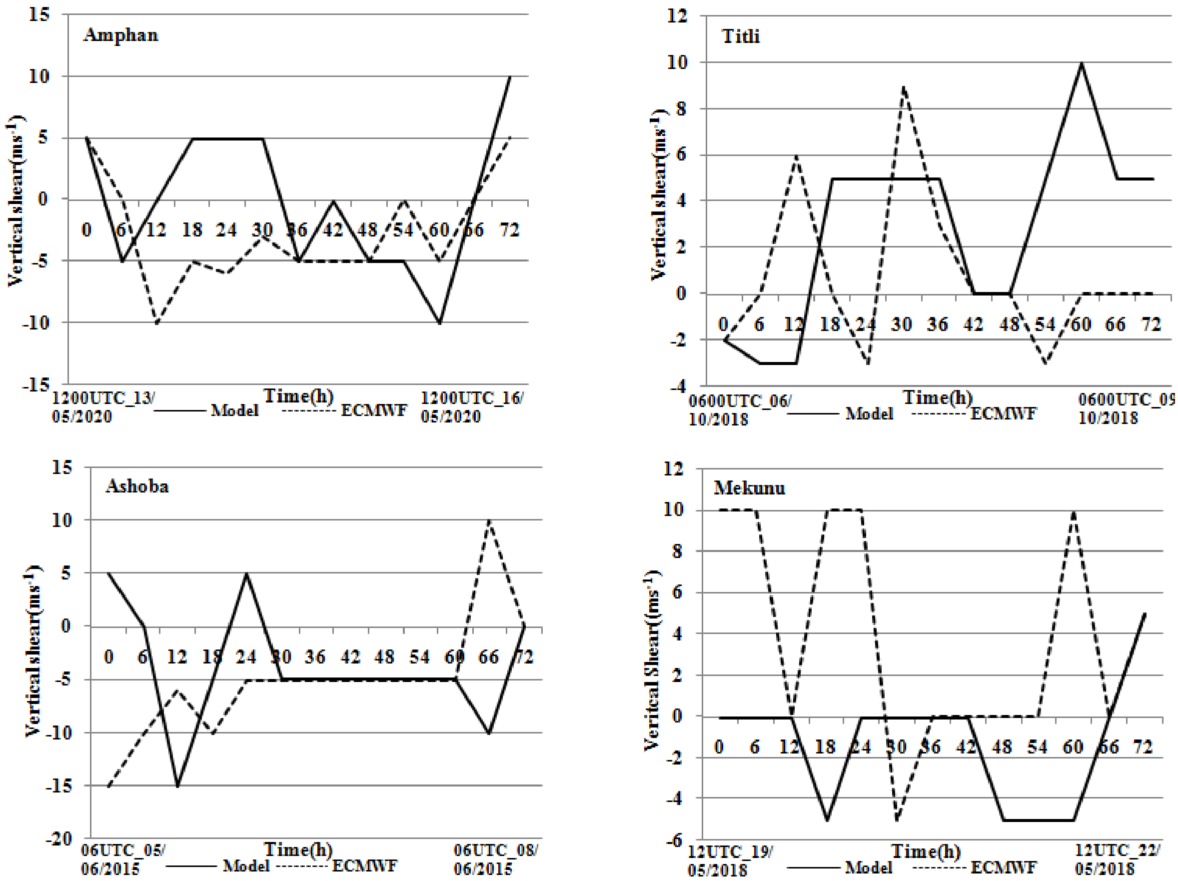

Figure 10: Temporal variation of zonal vertical wind shear at the centre of respective events.

4. Conclusion

Much discussion and research has been and is still ongoing to unravel the complexities of the origin and development of TC. But so far, meteorologists have not been able to reach any conclusion about the genesis and development of TC. So, we still have many challenges in tropical cyclone forecasting. Although mathematical models have come a long way in predicting TC, forecasting is impeding due to insufficient data or lack of observational accuracy. As a result, there is a need for more work on mathematical models. In particular, as the NIO basin is highly sensitive to the origin and development of TCs, research in this area is much required. Factors affecting the genesis and development of TCs in the NIO region have been neglected in all studies, especially in the BOB. So, we have to concentrate to the TC development in this region. With these considerations, we have conducted our current study to analyze the dynamic environmental essential for TC development in the NIO basin using the WRF4.0.3 model following the one-way nesting method. Some appreciable insights that favor TC development have emerged from current research. The westerlies dominate the upper air three days before reaching a mature TC. The low-level wind speed continued to increase with time, reaching 35 knots and becoming a cyclonic storm in the final moments of the model run. At the same time, cyclonic and large-scale anti-cyclonic circulation systems are observed in the upper atmosphere to the left and right sides of the cyclone center, respectively. A rapid decline in central pressure begins two days before the cyclone develops. The trend of increasing upper and lower relative vorticity throughout the whole period of the model run favors the intensity of TC. The wind shear becomes positive and weak from about 6 hours before reaching a mature TC. However, the negative values of wind shear during the 72-h period before turning into a TC could not hinder the genesis and development of the TC. Compared to the ECMWF and other theoretical values, the results found in this study are almost reliable. Therefore, the evolution of dynamic parameters in TC captured by the WRF model is credible.

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Reference

[1] Shapiro L.J.: Tropical Storm Formation from Easterly Wave: A Criterion for Development, Journal of the Atmospheric Science, Vol. 34, July 1977.

[2] Palmen E.: On the Formation and Structure of Tropical Hurricanes, Research Paper, University of Chicago.

[3] Gray W.M.**:** Global view of the Origin of Tropical Disturbances and Storms, Monthly Weather Review, Vol. 96, No. 10, October 1968.

[4] Gray W.M.: Tropical Cyclone Genesis, Department of Atmospheric Science Colorado State, University Fort Collins, Colorado, Atmospheric Science Paper No. 234, March, 1975.

[5] Ramage C.S.: Hurricane Development, Journal of Meteorology, Vol. 16, June 1959.

[6] Riehl H.: On the Formation of Typhoons, Journal of Meteorology, Vol. 5, No. 6, December 1948.

[7] Raymond D. J., Sessions S. L., and Carrillo C. L.: Thermodynamics of Tropical Cyclogenesis in the Northwest Pacific, Physics Department and Geophysical Research Center, New Mexico Tech Socorro, NM 87801 USA, May 18, 2011.

[8] Bister M. and Emanual K.A.: The Genesis of Hurricane Guillermo: Texmex Analyses and a Modelling Study, Monthly Weather Review, Vol. 125, December 6, 1996.

[9] Erickson S. L.: Comparison of Developing Vs. Non-developing Tropical Disturbances, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, Atmospheric Science Paper No. 274 July, 1977.

[10] Colon J.A. and Nightingale W.R.: Development of Tropical Cyclones in Relation to Circulation Patterns at the 200-Millibar Level, Monthly Weather Review, July 1963.

[11] Frank W. M., Roundy P. E.: The Role of Tropical Waves in Tropical Cyclogenesis, Monthly Weather Review, Vol. 134, September 2006.

[12] Yanai M.: Evolution of a Tropical Disturbance in the Caribbean Sea Region, Journal of the Meteorological Society of Japan, Vol. 46, No. 2, April 1968.

[13] Hendrics E. A., Montgomery M. T. ERIC and Davis C. A.: The Role of ‘‘Vortical’’ Hot Towers in the Formation of Tropical Cyclone Diana (1984), Journal of Atmospheric Sciences, Vol. 61, No. 11, June 1,2004.

[14] Elsberry R.L. and Jeffries R.: Vertical Wind Shear on Tropical Cyclone Formation and Intensification during TCM-92 and TCM-93, Monthly Weather Review, Vol. No. 124, July 1996.

[15] Zehr R.: Tropical Disturbance Intensification, Department Atmospheric Science, Colorado State University, Fort Collins, Colorado, Atmospheric Science Paper No. 259, December 1976.

[16] Sadler J.C.: A Role of the Tropical Upper Tropospheric Trough in Early Season Typhoon Development, Monthly Weather Review, Vol. 104, 29 July 1976.

[17] Ramage C.S.: Monsoonal Influences on the Annual Variation of Tropical Cyclone development over the Indian and Pacific Oceans, Monthly Weather Review, Vol. 102, No. 11, November 1974.

[18] Holland J.G.: The Maximum Potential Intensity of Tropical Cyclones, Journal of the Atmospheric Siences, Vol. 54, November 1997.

[19] Ozawa H. and Shimokawa S.: Thermodynamics of a tropical cyclone: generation and dissipation of mechanical energy in a self-driven convection system, Tellus A: Dynamic Meteorology an Oceanography, ISSN: (Print) 1600-0870 (Online) Journal homepage: https://www.tandfonline.com/ loi/zela20.