

# Formation, Structure and Movement of Tropical cyclone in monsoon and post-monsoon season over North Indian Ocean

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## Abstract

The North Indian Ocean is highly vulnerable to tropical cyclogenesis and the tropical cyclone is one of the most disastrous atmospheric phenomena in the tropics, which forms over the warm oceans and ravage life and property especially over the coastal belt due to extremely strong winds and associated storm surges at the time of landfall. To save the life and minimize the damages it is necessary to make advance warning and prediction of tropical cyclone quite ahead of time and a study has been conducted to investigate the formation, structure and movement of tropical cyclone by analyse some important parameters; sea level pressure, pressure drop, maximum wind speed, pressure field, and tracks movement using Weather Research and Forecasting (WRF) model with a horizontal resolution of 24 km. In this study cyclonic storm Komen and Cyclonic Storm Murjan are consider and the model predicts well the parameters and probable areas at the time of landfall of the selected tropical cyclones with high accuracy of prediction. In CS Komen the actual landfall position (23.5°N 88.8°E) but simulated of that (23.8°N, 88.9°E) with time errors 3 hrs early and in CS Murjan the actual landfall position (9.5°N 51.5°E) but simulated of that (9.1°N, 51.2°E) with time errors 6 hrs delayed which are better than previous studies. The forecast error was much lower than the errors of the previous studies

**Keywords:** Cyclonic Storm (CS); Tropical cyclone (TC); Genesis; Structure; Tracks movement; Advanced Research WRF model; Simulation; North Indian Ocean (NIO); Advance warning

## 1. Introduction

A tropical cyclone (TC) is the generic term for a non-frontal warm core synoptic scale low-pressure system originating over tropical or sub-tropical waters with organized convection and definite cyclonic surface wind circulation- counter clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The tropical cyclones are perhaps the most devastating of natural disasters of the tropics because of the loss of human life they cause and the large economic losses they induce [1, 2, 3, 27, 28]. A single storm in Bangladesh in 1970 killed nearly half a million people [4, 5]. Vulnerability to tropical cyclones is becoming more pronounced because the fastest population growth is in tropical coastal regions. In recent years, attempts to associate tropical cyclone trends with climate change resulting from greenhouse warming has led to additional attention being paid to tropical cyclone prediction [6, 11]. It is a low-pressure system with maximum sustainable winds over 62 km/hr; this can go up to around 300 km/hr. A mature tropical cyclone has a horizontal dimension of around 500-1500 km and extends through the depth of the troposphere, about 15 km [1, 4, 9]

### 1.1 Aspects of the study

Several researchers reported modeling experiments to predict the performances of North Indian Ocean tropical cyclones in the recent years [7, 8-12, 24, 31]. For prediction of tropical cyclone it is necessary to understand the physical mechanism of its evolution. Some researchers have superimposed artificial vortex using bogussing technique based on satellite information in the initial field so that the models are able to predict further intensification and evaluation of the systems. There is a research gap in prediction of the tropical cyclonic evaluation accurately and this research gap motivated us to find out evaluation more accurately. In this way the present study has immense social values and economic importance. This is the first time an attempt has been made to simulate the pre-monsoon and monsoon tropical cyclonic disturbance with initial field condition. Besides, the knowledge gained through this research will create new avenues for further studies for improving the WRF model. This paper is arranged under section 2 on methodology, section 3 on results and discussions, and section 4 on conclusion.

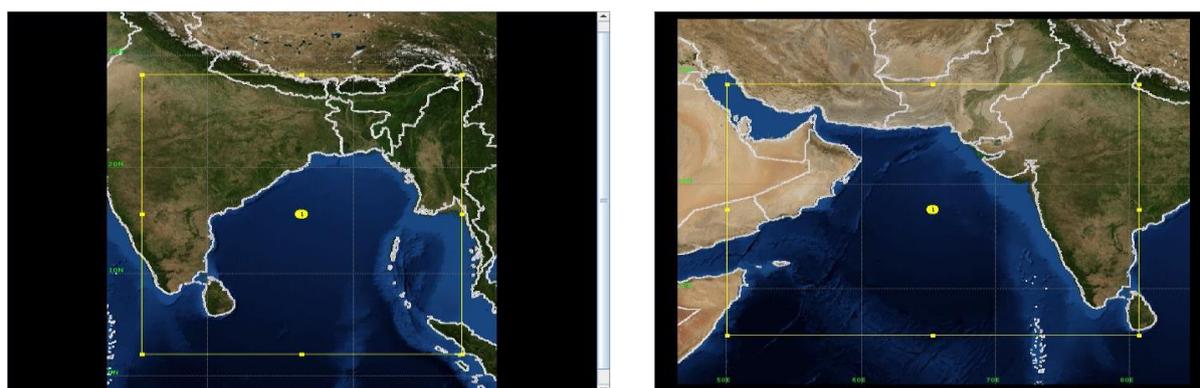
## 2. Methodology

This study was conducted using Advanced Research WRF (ARW) model with a horizontal resolution of 24 km. The (WRF) is a new generation mesoscale numerical weather forecasting community model which has the potential to simulate meteorological phenomena ranging from meters to thousands of kilometers and ARW is a dynamic solver [1, 6, 13-25] which is compatible with the WRF system to simulate broad spectrum of meteorological phenomena. ARW was developed by the Mesoscale and Microscale Meteorological (MMM) Division of National Centre for Atmospheric Research (NCAR), USA. This model integrates the compressible,

non-hydrostatics Euler equation, which are cast in flux form (UCAR, 2006) with terrain-following mass vertical coordinates [21-23] form and simulated results can be presented in the graphical and tabular forms. Grid Analysis and Display System (GrADS) software provides facility for visualization of model outputs. Figure 1 shows the horizontal domain of the model. The model domain consists of 127 ×127 grid points. Marcator map projection has been used. WRF model was run for 96 hrs, 72 hrs, 48 hrs and 24 hrs to study the evolution of tropical cyclones developed over North Indian Ocean. National Centre for Environment Prediction (NCEP), Final Reanalysis (FNL) data (1°×1° resolution) was utilized as initial and lateral boundary conditions (LBCs) which are updated at six hourly intervals. The model was initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. To study the evolution of tropical cyclones the prediction experiments were performed up to 96 hrs using the initial field before the landfall of the system [22-31]. Finally, the model outputs were compared with Joint Typhoon Warning Center (JTWC) best track data to demonstrate the performance of the modeling study and the discussions of the results are provided with necessary physical interpretation.

**2.1 Domain selection**

To simulate above selected tropical cyclones a domain of dimension (3.0-24.0)°N and (69.0-98.0)°E was selected to cover the Bay of Bengal basin and a domain of dimension (4.0-30.0)°N and (49.0-82.0)°E was selected to cover the Arabian Sea basin at 24 km horizontal resolution with 27 vertical η levels.



**Figure 1:** Model domain with 24kmX24km horizontal resolution (a) Bay of Bengal (b) Arabian Sea

**3. Result and Discussion:**

**3.1 Minimum Sea Level Pressure**

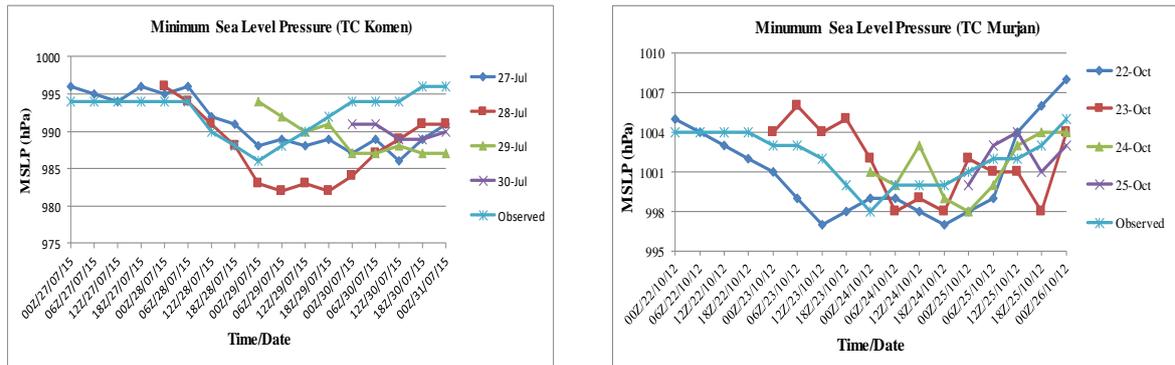
Minimum sea level pressure (MSLP) of a tropical cyclone is of great importance as it helps to measure the intensity of a cyclone. Since tropical cyclones develop over the vast oceanic areas, where observations are sparse or not available, it is of great difficulty to make any validation of model simulated MSLP with sea truth data before the landfall. The model simulated and observed MSLP of all selected cyclones at the stage of their highest intensity are summarized in Table 1. In the Table, initial conditions are written in column 2 and the corresponding simulated lowest values of MSLP along with its obtaining time are written in column 4. The observed MSLP at the time of lowest simulated MSLP is written in column 5. Finally, the lowest observed value of MSLP is written in column 6.

**Table 1:** Minimum Sea Level Pressure (MSLP) at the stage of highest intensity

Name of Cyclone	Initial Date/Time (UTC)	Forecast Hours	Simulated MSLP (hPa) [Date/Time]	Observed MSLP(hPa) [Date/Time]	Full track observed MSLP (hPa) [Date/Time]
Komen (2015)	27 July/0000	96	986 [30 July/1200]	994 [30 July/1200]	986 [29 July/1800]
	28 July/0000	72	982 [29 July/1800]	992 [29 July/1800]	
	29 July/0000	48	987 [30 July/1800]	996 [30 July/1800]	
	30 July/0000	24	989 [30 July/1800]	996 [30 July/1800]	
Murjan (2012)	22 October/0000	96	987 [23 October/1200]	1002[23 October/1200]	998 [24 October/0000]
	23 October/0000	72	998 [25 October/1800]	1003[25 October/1800]	
	24 October/0000	48	998 [25 October/0000]	1000[25 October/0000]	
	25 October/0000	24	1000 [25 October/0000]	1000 [25 October/0000]	

More conclusion from table: 1 that for Cyclonic Storm Komen among all simulated MSLP values, the 72 hrs predicted MSLP 982 [29 July/1800] is nearest the observed value 986 [29 July/0000] and for Cyclonic Storm Murjan among all simulated MSLP values, the 96 hrs predicted MSLP 997 [23 October/1200] is nearest the observed value 998 [24 October/0000]. So it is also seen that the model underestimates the intensity in terms of MSLP for tropical cyclones under consideration. It appears from figure 2 that model simulated and observed

MSLP gradually drops with time for all cases and attains peak intensity just before the landfall time and thereafter its MSLP increases.



**Figure 2:** Model simulated and observed minimum sea level pressure with time of Cyclonic Storm Komen and Cyclonic Storm Murjan.

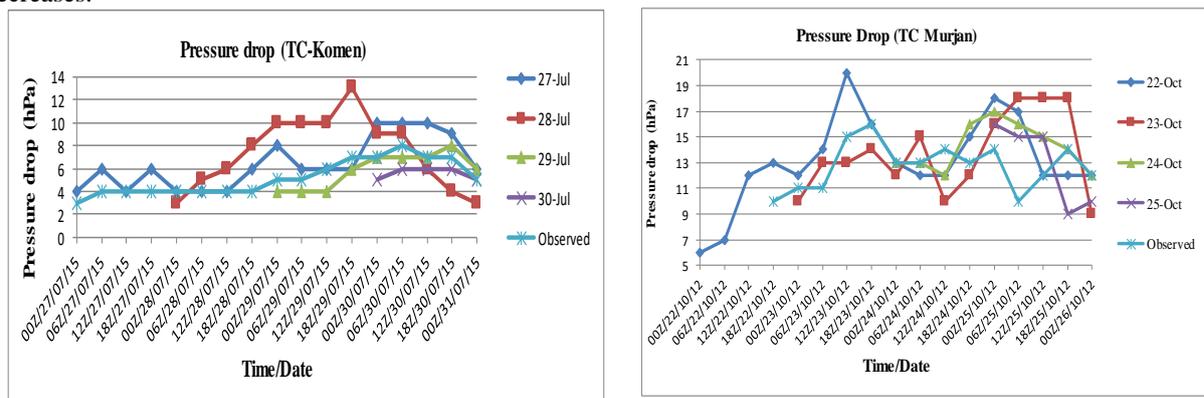
### 3.2 Pressure Drop

Pressure drop ( $\Delta p$ ) is another important parameter of tropical cyclone in measuring its intensity. Pressure drop of the tropical cyclone is determined as the difference between pressure of the outer most closed isobar and minimum sea level pressure. The model simulated and observed pressure drop of all selected cyclones at the stage of their highest intensity are summarized in Table 2. In the Table, initial conditions are written in column 2 and the corresponding simulated highest values of pressure drop along with its obtaining time are written in column 4 and its estimated ( $\sqrt{\Delta p}$ ) is in column 5. The observed pressure drop at the time of highest simulated pressure drop is written in column 6. Finally, the highest observed value of Pressure drop is written in column 7.

**Table 2:** Maximum pressure drop ( $\Delta p$ ) at the stage of highest intensity

Name of Cyclone	Initial Date/Time (UTC)	Forecast Hours	Simulated ( $\Delta p$ ) [Date/Time]	Estimated ( $\sqrt{\Delta p}$ ) [Date/Time]	Observed ( $\Delta p$ ) [Date/Time]	Full track observed ( $\Delta p$ ) [Date/Time]
Komen (2015)	27 July/0000	96	10 [30 July/1200]	3.16[30 July/1200]	7 [30 July/1200]	8 [30 July/0600]
	28 July/0000	72	13 [29 July/1800]	3.60[29 July/1800]	7 [29 July/1800]	
	29 July/0000	48	8 [30 July/1800]	2.82[30 July/1800]	7 [30 July/1800]	
	30 July/0000	24	6 [30 July/1800]	2.44[30 July/1800]	7 [30 July/1800]	
Murjan (2012)	22 October/0000	96	20 [23 October/1200]	4.47[23 October/1200]	15[23 October/1200]	16 [23 October/1800]
	23 October/0000	72	18 [25 October/1800]	4.24[25 October/1800]	14 [25 October/1800]	
	24 October/0000	48	17 [25 October/0000]	4.12[25 October/0000]	14 [25 October/0000]	
	25 October/0000	24	16 [25 October/0000]	4.00[25 October/0000]	14 [25 October/0000]	

From table 2 that for Cyclonic Storm Komen among all simulated  $\Delta P$  values, the 48 hrs predicted  $\Delta P$  8 [30 July/1800] is same with the observed value 8 [30 July/0600] and for Cyclonic Storm Murjan among all simulated  $\Delta P$  values, the 24 hrs predicted  $\Delta P$  16 [25 October/0000] is same with the observed value 16 [23 October/1800]. So it is also seen that the model underestimates the intensity in terms of  $\Delta P$  for all the selected tropical cyclones under consideration. It appears from figure 3 that model simulated and observed  $\Delta P$  gradually drops with time for all cases and attains peak intensity just before the landfall time and thereafter its  $\Delta P$  decreases.



**Figure 3:** Model simulated and observed pressure drop with time of Cyclonic Storm Komen and Cyclonic Storm Murjan.

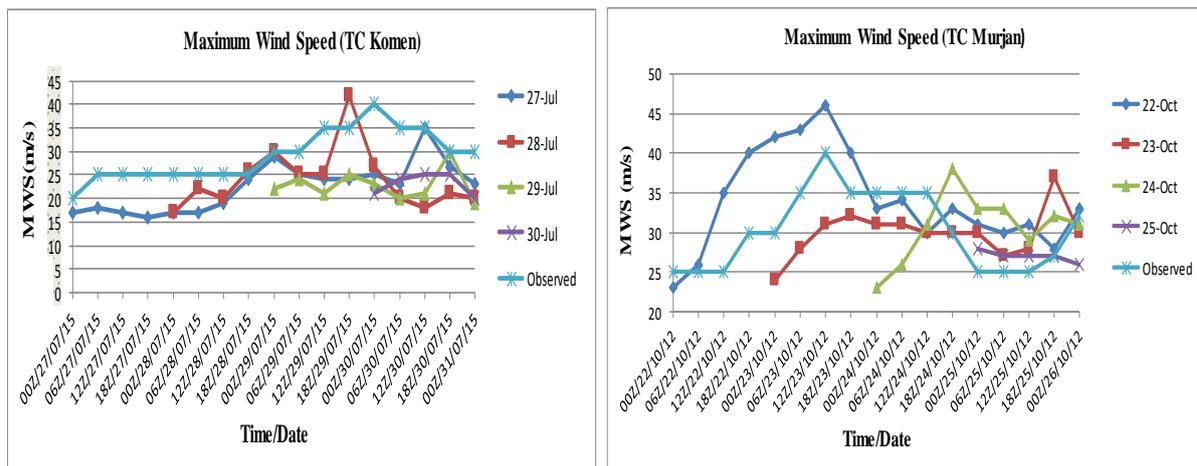
### 3.3 Maximum Wind Speed

Maximum wind speed (MWS) is another important parameter of tropical cyclones for measuring its intensity. It is of importance as it directly devastates the affected area at the time of landfall, it is the most active driving force of generating storm surge over the area of landfall. These surface winds are taken at the standard meteorological height of 10 meter in an unobstructed exposure. The model simulated and observed MWS of all selected cyclones at the stage of their highest intensity are summarized in Table 3 and initial conditions are written in column 2, the corresponding simulated highest values of MWS along with its obtaining time are written in column 4, estimated values in column 5. The observed MWS at the time of highest simulated MWS is written in column 6. Finally, the highest observed value of MWS is written in column 7. MWS has been estimated by modified Fletcher’s formula (1995) [29],  $V_{max}=13.6\sqrt{\Delta p}$ , [30] using modeled pressure drop ( $\Delta p$ ). Here  $\Delta p$  is in hPa and  $V_{max}$  is in knots.

**Table 3:** Maximum wind speed (MWS) of selected tropical cyclones at the stage of highest intensity

Name of Cyclone	Initial Date/Time (UTC)	Forecast Hours	Simulated MWS in m/s [Date/Time]	Estimated MWS in knots [Date/Time]	Observed MWS in m/s [corresponding simulated Date/Time]	Full track observed MWS in m/s [Date/Time]
Komen (2015)	27 July/0000	96	35[30 July/1200]	68.60[30 July/1200]	35[30 July/1200]	40[30 July/0000]
	28 July/0000	72	42[29 July/1800]	82.32[29 July/1800]	35[29 July/1800]	
	29 July/0000	48	30[30 July/1800]	58.80[30 July/1800]	30[30 July/1800]	
	30 July/0000	24	25[30 July/1800]	49.00[30 July/1800]	30[30 July/1800]	
Murjan (2012)	22 October/0000	96	46[23 October/1200]	90.16[23 October/1200]	40[23 October/1200]	40 [23 October/1200]
	23 October/0000	72	37[25 October/1800]	72.52[25 October/1800]	27[25 October/1800]	
	24 October/0000	48	33[25 October/0000]	64.68[25 October/0000]	25[25 October/0000]	
	25 October/0000	24	28[25 October/0000]	54.88[25 October/0000]	25[25 October/0000]	

Conclusion from Table 3 that for Cyclonic Storm Komen among all simulated MWS values, the 72 hrs predicted MWS 42[29 July/1800] is nearest with the observed value 40 [30 July/0000] and for Cyclonic Storm Murjan among all simulated MWS values, the 72 hrs predicted MWS 37 [25 October/1800] is nearest with the observed value 40 [23 October/1200]. So it is also seen that the model underestimates the intensity in terms of MWS for all the selected tropical cyclones under consideration. It appears from figure 4 that model simulated and observed MWS gradually increases with time for all cases and attains peak intensity just before the landfall time and thereafter its MWS decreases.



**Figure 4:** Model simulated and observed MSW with time of Cyclonic Storm Komen and Cyclonic Storm Murjan

But for all the cases and at all the time points’ model simulated MSLP,  $\Delta P$  and MWS are more or less systematically higher and lower than the observed values and for all cases it increases with time up to the highest maturity stage of the respective cyclones and it is more or less in good agreement with the observed values.

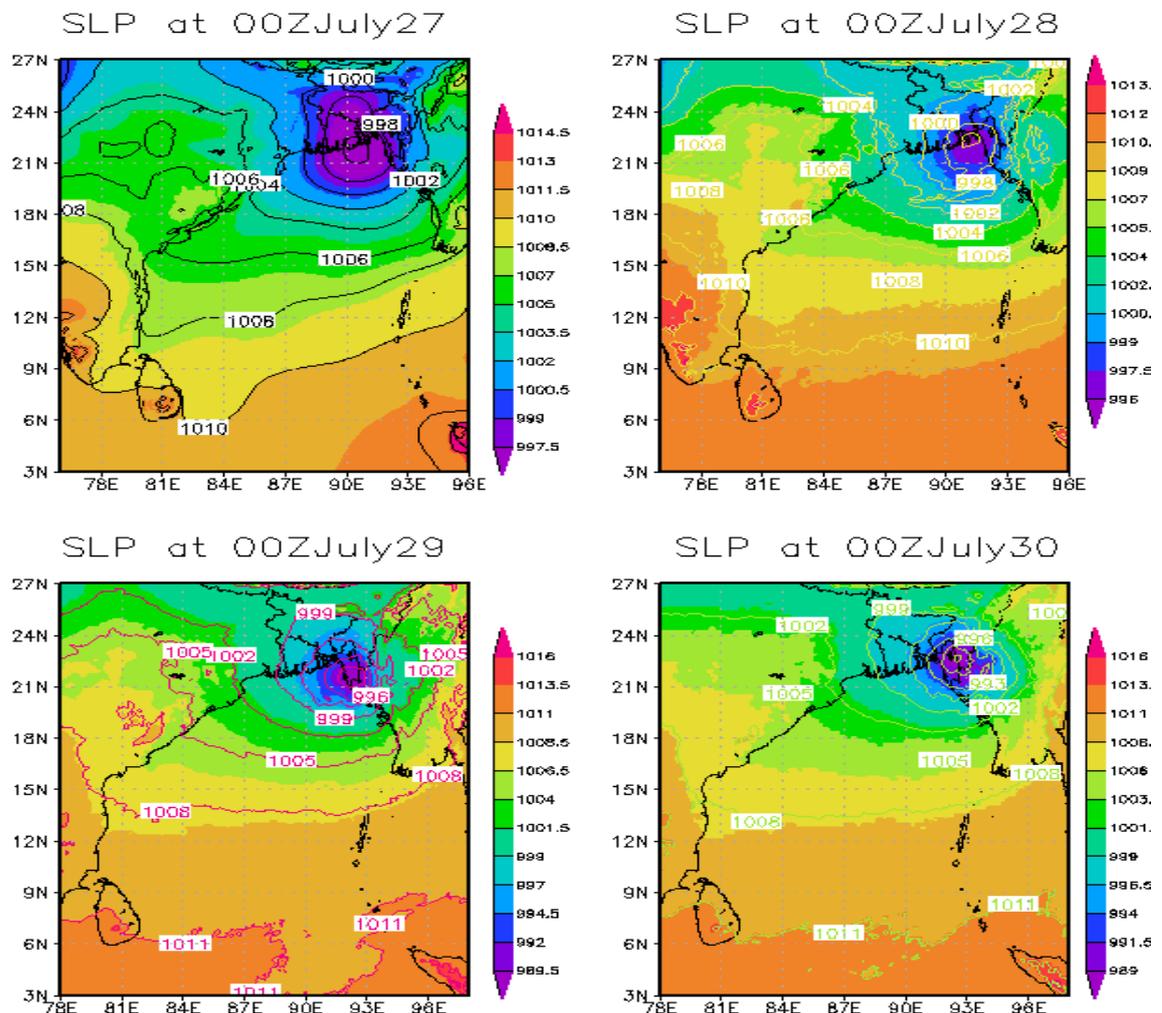
### 3.4 Structure of Tropical Cyclone

In this section the pressure field is discussed and the model results are presented in the graphical forms with necessary physical interpretations to demonstrate the performance of the modeling exercise. To analyze the structure of tropical cyclones the different meteorological parameters obtain from the model are discussed as

possible in the following sub-section. Model simulated results are compared with available data obtained from Joint Typhoon Warning Centre (JTWC).

### 3.4.1 Cyclonic Storm Komen

Pressure field is an important parameter of tropical cyclones to investigate the pressurised condition because it measures the intensity of cyclones. The pressure field of the Cyclonic Storm Komen is discussed based on model results. The horizontal distribution of pressure field at its mature stage has been shown in Figure 5 and the MSLP is 996 hPa also show that the isobar has near circular arrangements around the cyclone center. The contour interval is 2 hPa. Considering the outermost closed isobar, the system's horizontal size is estimated as Lon. 2.0°E (220 km) in the east-west direction and Lat. 2.0°N (220 km) in the north-south direction on 00Z of 27<sup>th</sup> July 2015.



**Figure 5:** Distribution of model simulated SLP (hPa) of Cyclonic Storm Komen at different stages: at 00Z of 27 July, 00Z of 28 July, 00Z of 29 July, 00Z of 30 July 2015

### 3.4.2 Cyclonic Storm Murjan

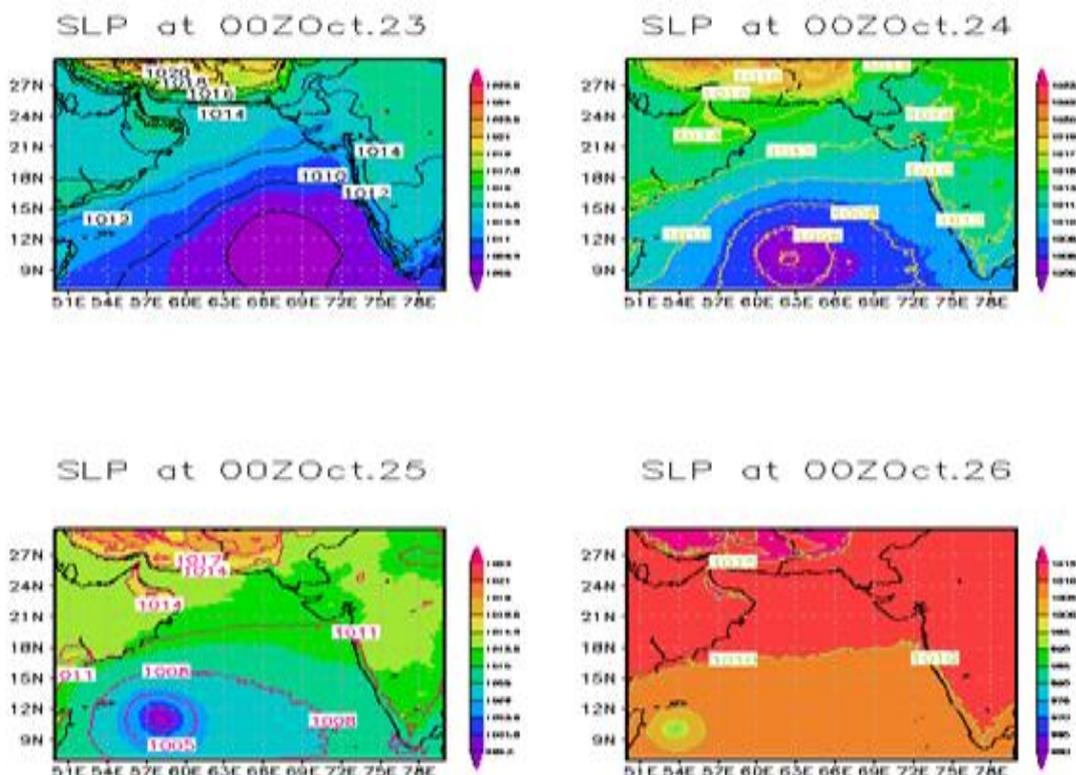
To analyse the pressure field of Cyclonic Storm Murjan the model was run with the initial field at 00Z UTC of 23 October 2012 and the pressure field is discussed based on model results. The horizontal distribution of pressure has been shown in figure 6 and the MSLP is 1005 hPa and contour interval is 3hPa. Considering the outermost closed isobar, the system's horizontal size is estimated as 6°E Lon (660 km) in the east-west direction and 5°N Lat (550 km) in the north-south at 00Z UTC of 25 October 2012.

In the front of the cyclone the isobaric lines are denser compared to the rear side of the cyclone and demonstrating a strong spatial asymmetry in its circular shape with elongation in the direction of the movement of the cyclone. The model simulated Minimum Sea Level Pressure with corresponding observed Minimum Sea Level Pressure are given in the Table 4.

**Table 4:** Model simulated and observed minimum sea level pressure (MSLP) of tropical cyclones

Name of tropical cyclones	Minimum Sea Level Pressure (MSLP) in hPa	
	Simulated	Observed
Cyclonic Storm Komen	989 hPa	996 hPa
Cyclonic Storm Murjan	991 hPa	1000 hPa

From above discussion and in the Table 4, it is seen that simulated values are closer to the observed values. Therefore, the ARW model not only provides improved Minimum Sea Level Pressure but it has provided highly encouraging results in 96 hrs prediction. This shows the advantage of using ARW model with high resolution for monsoon and post-monsoon season over North Indian Ocean cyclone prediction.



**Figure 6:** Distribution of model simulated SLP (hPa) of Cyclonic Storm Murjan at different stages: at 00Z UTC of 23 October, at 00Z UTC of 24 October, at 00Z UTC of 25 October and at 00Z UTC of 26 October 2012

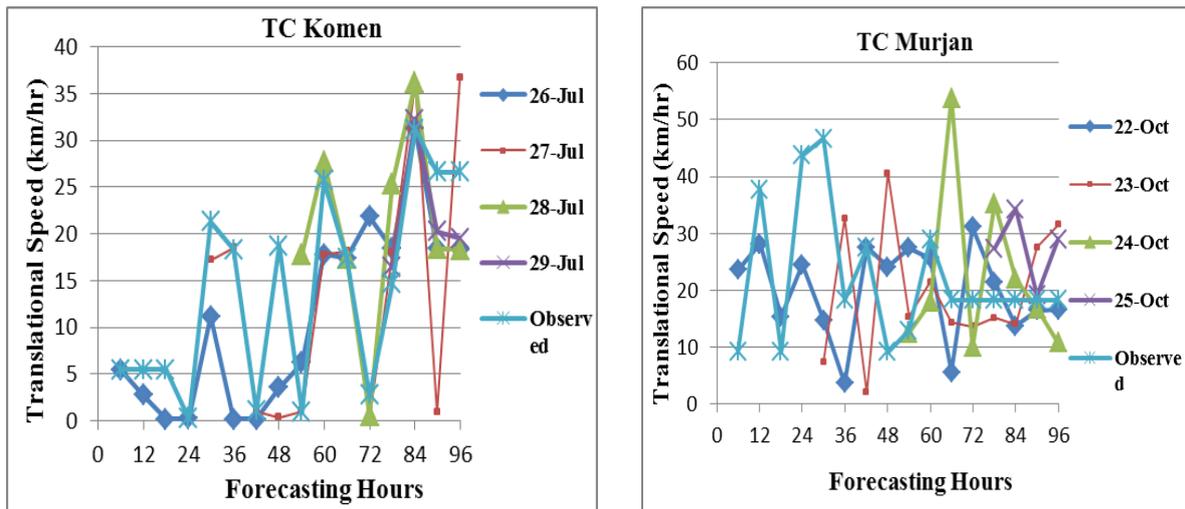
### 3.5 Movement of Tropical Cyclone

Movement forecasting has been a challenging task for meteorologists over the last few decades in spite of the rapid development of numerical weather prediction techniques. The simulated average translational speed is calculated for respective model forecast hour and observed full track average translational speed. Observed track average implies that the average simulated translational speed is about 11.40 km/hr -28.90 km/hr but full track observed is about 13.48 km/hr -23.97 km/hr. shown in Table 5.

**Table 5:** Average translational speed of tropical cyclones

Name of Cyclone	Initial Date/Time (UTC)	Forecast Hours	Simulated Average Translational Speed (km/hr)	Observed Average Translational Speed (km/hr)	Errors of Translational Speed (km/hr) [corrospending Forecasting Hours]
TC Komen	27 July/0000	96	11.40	13.87	-2.47
	28 July/0000	72	13.84		-0.03
	29 July/0000	48	20.20		6.33
	30 July/0000	24	22.10		6.23
TC Murjan	22 October/0000	96	19.99	23.97	-3.98
	23 October/0000	72	19.66		-4.31
	24 October/0000	48	21.28		-2.69
	25 October/0000	24	27.44		3.47

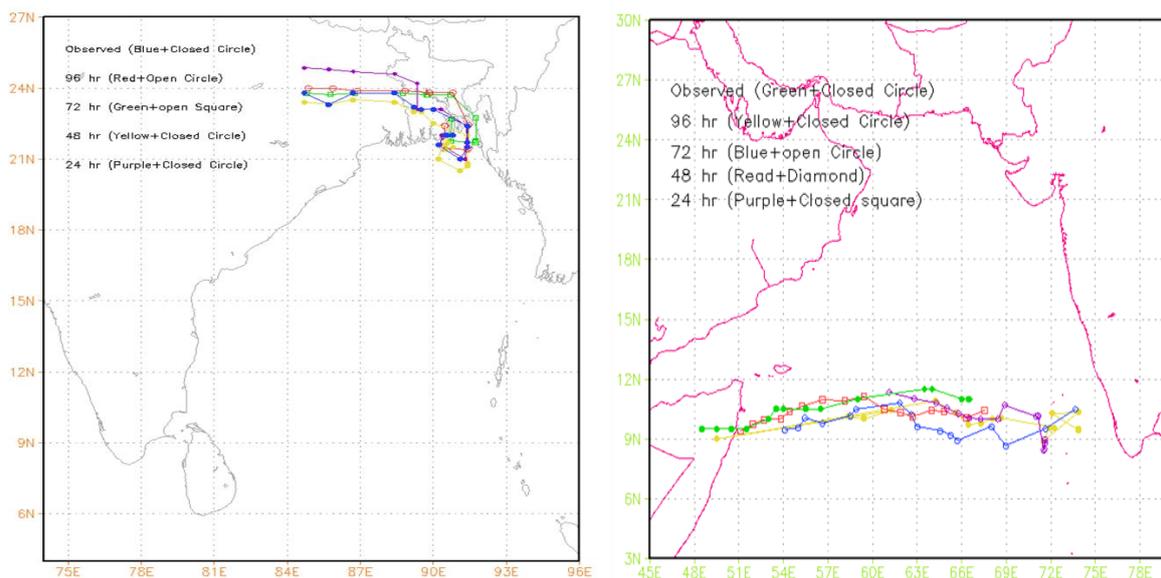
Figure 7 demonstrate that in general the translational speed of the system increases as it intensifies and moves towards landfall position of Cyclonic Storm Komen and Cyclonic Storm Murjan and also found that, there is a close similarity between the simulated translational speed and observed translational speed.



**Figure 7:** Time variation of model simulated and observed six hourly average translational speed of tropical cyclones.

### 3.6 Tracks of Cyclonic Storm Komen and Cyclonic Storm Murjan

The tracks of Cyclonic Storm Komen show that the prediction experiments captured well the direction of motion and probable areas of landfall in Figure 8(a). The forecast tracks agreed well with the observed track and indicated landfall at Myanmar coast fairly close to the actual. 96 hrs and 72 hrs predicted tracks finally deviated to northeast from the observed track and landfall points departed. It is noted from observed information that the Cyclonic Storm Komen remained stationary near 23.1°N/89.5°E for some time and abruptly changed its direction and started to move towards the north-east direction.



**Figure 8:** (a) Model simulated tracks of cyclonic storm Komen. (b) Cyclonic storm Murjan.

In Cyclonic Storm Murjan the tracks of cyclonic storm Murjan show that the prediction experiments captured well the direction of motion and probable areas of landfall Figure 8(b). The forecast tracks agreed well with the observed track and indicated landfall and crossed the coast of Somalia by late 25 October and gradually weakened into a depression and fairly close to the actual. It is noted from observed information that the cyclonic storm Murjan remained stationary near 9.5°N/49.5°E for some time on 24 October 2012 and abruptly changed its direction and started to move towards the north-east direction that is Bosaso city in Somalia. The storm

brought strong winds and heavy but beneficial rains within the areas of Bari region (Bossasso, Ishkushban and Bandar Beyla) according to the Somalia Water and Land Information Management.

It has been seen that the model forecast also captured well this recurvature area of movement and the stationary feature of the track which indicating the remarkable success of the model.

### 3.7 Landfall forecast errors

As landfall of tropical cyclones is very important to the cyclone forecasters, the landfall position and time errors are investigated for evaluating the model performances. The results are presented in Tables 6-7 and variations in the landfall and time errors.

**Table 6:** Landfall position and time errors of Cyclonic Storm Komen

Base Date/Time (UTC)	Forecast hrs	Landfall Forecast		Actual Landfall		Errors	
		Position Lat <sup>o</sup> N/Lon <sup>o</sup> E	Date/Time (UTC)	Position Lat <sup>o</sup> N/Lon <sup>o</sup> E	Date/Time (UTC)	Distance (km)	Time (hrs)
27/0000	96	23.8/88.9	30/1900	23.5/88.8	30/2200	35 ne	3 E
28/0000	72	23.7/89.8	30/1800	-do-	-do-	114 ne	4 E
29/0000	48	23.3/88.4	30/1600	-do-	-do-	45 sw	6 E
30/0000	24	24.7/88.4	30/1900	-do-	-do-	139 nw	3 E

\*D: Delay and E: Early

**Table 7:** Landfall position and time errors of Cyclonic Storm Murjan

Base Date/Time (UTC)	Forecast hrs	Landfall Forecast		Actual Landfall		Errors	
		Position Lat <sup>o</sup> N/Lon <sup>o</sup> E	Date/Time (UTC)	Position Lat <sup>o</sup> N/Lon <sup>o</sup> E	Date/Time (UTC)	Distance (km)	Time (hrs)
22/0000	96	9.1/51.1	25/1800	9.5/51.5	25/1200	62 sw	6 D
23/0000	72	9.7/51.9	25/2100	-do-	-do-	101 ne	9 D
24/0000	48	9.2/52.2	25/1600	-do-	-do-	84 sw	4 D
25/0000	24	10.7/51.3	25/1500	-do-	-do-	133 nw	3 D

\*D: Delay and E: Early

The mean landfall position and time errors of selected cyclones are calculated considering only the magnitude. The mean landfall errors are shown in the Table 8. The mean landfall position errors for 96 hrs, 72 hrs, 48 hrs and 24 hrs are 48.5 km, 107.5 km, 64.5 km, and 136 km respectively and respective mean time errors are 4.5 hrs, 6.5 hrs, 5.0 hrs, and 3.0 hrs.

**Table 8:** Mean landfall position and time errors of selected tropical cyclones

Forecast predictions	Mean Landfall Positio Errors (km)	Mean Landfall Time Errors (hrs)
96 hrs	48.5	4.5
72 hrs	107.5	6.5
48 hrs	64.5	5.0
24 hrs	136	3.0

In track prediction of some previous studies Mathur and Ruess (1993) [22], in an evaluation of the QLM's forecast track guidance in NMC Washington during the period 1998-90 reported mean forecast errors in the range of 180-190 km for 24 hrs, 300-370 km for 48 hrs, and 400-540 km for 72 hrs forecasts. Rao and Prasad (2005) [31] have reported mean position errors of around 167 km for 24 hrs, 367 km for 48 hrs and 433 km for 72 hrs forecasts in respect of the QLM experiments carried out earlier. Goerss (2000) [25] has reported mean position errors in track prediction with GFDL of about 142 km for 24 hrs, 246 km for 48 hrs and 364 km for 72 hrs predictions. After making cyclone track prediction experiments with QLM at 40 km horizontal resolution for nine cyclonic storms developing during the period 1997-2000, Prasad (2004) [12] have reported the mean position errors of about 122 km for 24 hrs, 256 km for 48 hrs and 286 km for 72 hrs predictions. Though this level of forecast errors in quite large, particularly in the higher forecast range, from the point of view of dependability of WRF guidance for operational cyclone track prediction, this aspect should be viewed in light of the fact that uncertainties of forecasts based on purely subjective methods using synoptic data and satellite observations are much larger and could still be minimized with the help of numerical guidance.

## 4. Conclusions

The model results indicate that it simulates the realistic genesis, structure and movement forecasting process and more or less realistic intensification of tropical cyclones. the longer range prediction provides better intensity

forecasting of the tropical cyclones with high spatial details without use of any idealized vortex in the initial condition. One of the outstanding findings of this study is that the model has successfully predicted the probable areas and time of landfall of the selected tropical cyclones with high accuracy of predictions. The genesis, structure and movement of the cyclones are well predicted with fair accuracy and the stationary feature of the track which indicates the remarkable success of the model. So it may finally be concluded that the WRF model used in the present study with high resolution has high potential to predict the formation, structure and movement of the tropical cyclones in monsoon and post-monsoon season. It appears from the above discussion that the WRF model is high potential to forecast position and time of landfall in monsoon and post-monsoon season over North Indian Ocean cyclones with the certain amount of uncertainty. However, further studies on sensitivity experiments with model resolution, boundary layer formulation, model physics and cumulus parameterization schemes on track prediction are required for proper tuning of the model to improve the reduce landfall error and prediction accuracy.

### Acknowledgements

Acknowledgements are due to Bangladesh Meteorological Division (BMD), and Meteorological Research Laboratory of Khulna University of Engineering and Technology (KUET) for providing the laboratory facilities, data and cordial cooperation.

### References

- [1] Abbott, P.L., 2004: Natural disasters (4<sup>th</sup>ed.), McGraw-Hill, New York, pp.302-333.
- [2] Anthes, R.A., 1982: Tropical Cyclones: Their Evolution, Structure and Effects. *Meteo Monogr. No. 41*, Amer. Meteor. Soc.
- [3] Gray, W.M., C.W. Landsea, P.W. Jr. Mielke, and K. J. Berry, 1993: Predicting Atlanti seasonal tropical cyclone activity by 1 August. *Wea. Forecasting*, 8, 73-86.
- [4] Tonkin, H., C. Landsea, G.J. Holland, and S.Li, 1997: Tropical cyclones and climate change: A preliminary assessment. *Assessment Climate change: Results from the Model evaluation consortium for climate assessment*, W. Howe and A. Henderson-Sellers, Eds., Gordon and Breach, Sydney, Australia, 327-360.
- [5] Choudhury, M.A., 2009: *Protecting Bangladesh from Natural Disasters*, Academic Press and publishers Library, Dhaka.
- [6] Quadir, D.A., and M.A. Iqbal, 2008: Investigation of the variability of tropical cyclones impacting on the livelihood of coastal inhabitants of Bangladesh, report of IUCN, Bangladesh.
- [7] Hossain, M.A., 2003: Prediction of Cyclonic Events over Bay of Bengal Using Numerical Weather Prediction Model with High Resolution, Ph. D. Thesis, Department of Mathematics, University of Rajshahi, Bangladesh.
- [8] Krishnamurti, T. N., and B. Jha, 1998: Cyclone track prediction. *Sadhana*, 23,563-684.
- [9] Rao, G.V., and D.V.B Rao, 2003: A review of some observed mesoscale characteristics of tropical cyclones and some preliminary numerical simulation of their kinematics features, *proc. of Ind. Nat. Sci. Acad.*, 69A, 5, 523-541.
- [10] Yang, M. -J., and L. Ching, 2005: A Modeling study of typhoon Toraji (2001): Physical Parameterization sensitivity and topographic effect. *Terrestrial, Atmospheric and Oceanic Sciences*, 16(1), 177-213.
- [11] Debsarma, S.K., 2003: Cyclone Forecasting and its Constraint for the Bay of Bengal. *Journal of BAKP The Atmosphere* 2, 40-52.
- [12] Prasad, K., (Quadir, D.A. ed.), 2004: Cyclone track prediction experiments with a Quasi-Lagrangian model. SAARC Meteorological Research Centre (SMRC) Report No. 9, Dhaka, Bangladesh.
- [13] NASA, 2008:<http://earthobservator.nasa.gov>
- [14] WMO, 2009: Tropical Cyclone Operational Plan for Bay of Bengal and the Arabian Sea. World Meteorological Organization Technical Document, WMO/TD No. 84. Tropical Cyclone Program Report Not. TCP21, Geneva, Switzerland.
- [15] IMD, 1979: *Traks of Storms and Depressions in the Bay of Bengal and Arabian Sea (14877-1970)*. Cyclone Atlas, Indian Meteorological Department, Regional Meteorological Centre, Chennai, India.

- [16] JTWC, 2010: Joint Typhoon Warnig Center (JTWC) best track data available on: [http://www.unso.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best\\_tracks/ioindex.html](http://www.unso.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/ioindex.html).
- [17] Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Barker, M.G. Duda, X-Y. Huang, W. Wang and J.G. Powers, 2008: A description of the Advanced Research WRF Version 3. NCAR Technical Notes, NCAR/TN-475+STR, Boulder, Colorado, USA.
- [18] World Atlas, 2009: <http://www.worldatlas.com/aatlas/infopage/baybengal.htm>.
- [19] Banglapedia, 2006: [http://www.banglapedia.org/httpdocs/HT/C\\_03\\_97.HTM](http://www.banglapedia.org/httpdocs/HT/C_03_97.HTM).
- [20] UCAR, 2006: Cyclone Glossary, University Corporation for Atmospheric Research (UCAR) (<http://meted.ucar.edu/>)
- [21] Choudhury. A.M., D.A Quadir and M. Nessa, 1998: Monitoring of TropicalCyclone of May 1979 that Hit Bangaladesh Using Data from GMS-5 Satellite, *Journal of Remote Sensing and Environment*. 2,51-69.
- [22] Mathur, M.B., and J. Ruess, 1993: Further evaluation of the quasi-Lagrangion model's forecast track guidance, *Mon. Wea. Rev.*, 121, 1514-1530.
- [23] Sadharam, Y., B. P. Rao, D.P. Rao, P.N.M. Shastri, and M.V. Subrahmanyam 2004: Seasonal Variability of Cyclone Heat Potential in the Bay of Bengal, *Natural Hazards*: 32 (2):191-209.
- [24] Prasad, K.and Rama Rao, Y.V., 2003: Cyclone track prediction by a quasi-Lagrangian model, *Meteorol, and Atoms. Phys.*, 83, 173-185.
- [25] Goerss, J.S., 2000: Tropical Cyclone Track Forecasts Using an Ensemble Dynamical Models, *Mon. Wea. Rev.*, 128, 1187-1193.
- [26] Anthes, R.A., 1982: Tropical Cyclones: Their Evolution, Structure and Effects. *Meteo Monogr. No. 41*, Amer. Meteor. Soc.
- [27] M. A. E., Akhter, Prediction of high impat precipitation event over Bangladesh and its surrounding area using NWP models, Ph. D. Thesis, Department of physics, Khulna University of Engineering and Technology, Bangladesh, 2012.
- [28] M. S. Haque, 2010: A PhD Thesis of "A Study of Formation, Evolution and Track of Tropical Cyclones of the Bay of Bengal Using Numerical Weather Prediction (NWP) Modeling Techniques"
- [29] Fletcher, R.D., 1955: Computation of maximum surface winds in hurricane. *Bull.Amer. Meteo. Soc.*, 36, 247-250.
- [30] Nessa, M. and A.M. Choudhury, 1981: Estimation of maximum wind speed in tropical cyclones of Bay of Bengal from observed pressure drop. *Geophysics*, I, 63-66.
- [31] Rao, Y.V.R., and K. Prasad, 2005: Further evaluation of the quasi-Lagrangian modelfor cyclone track prediction if the Noth Indian Ocean, SAARC Meteorological Research Centre Publication No. 12, Dhaka, Bangladesh.