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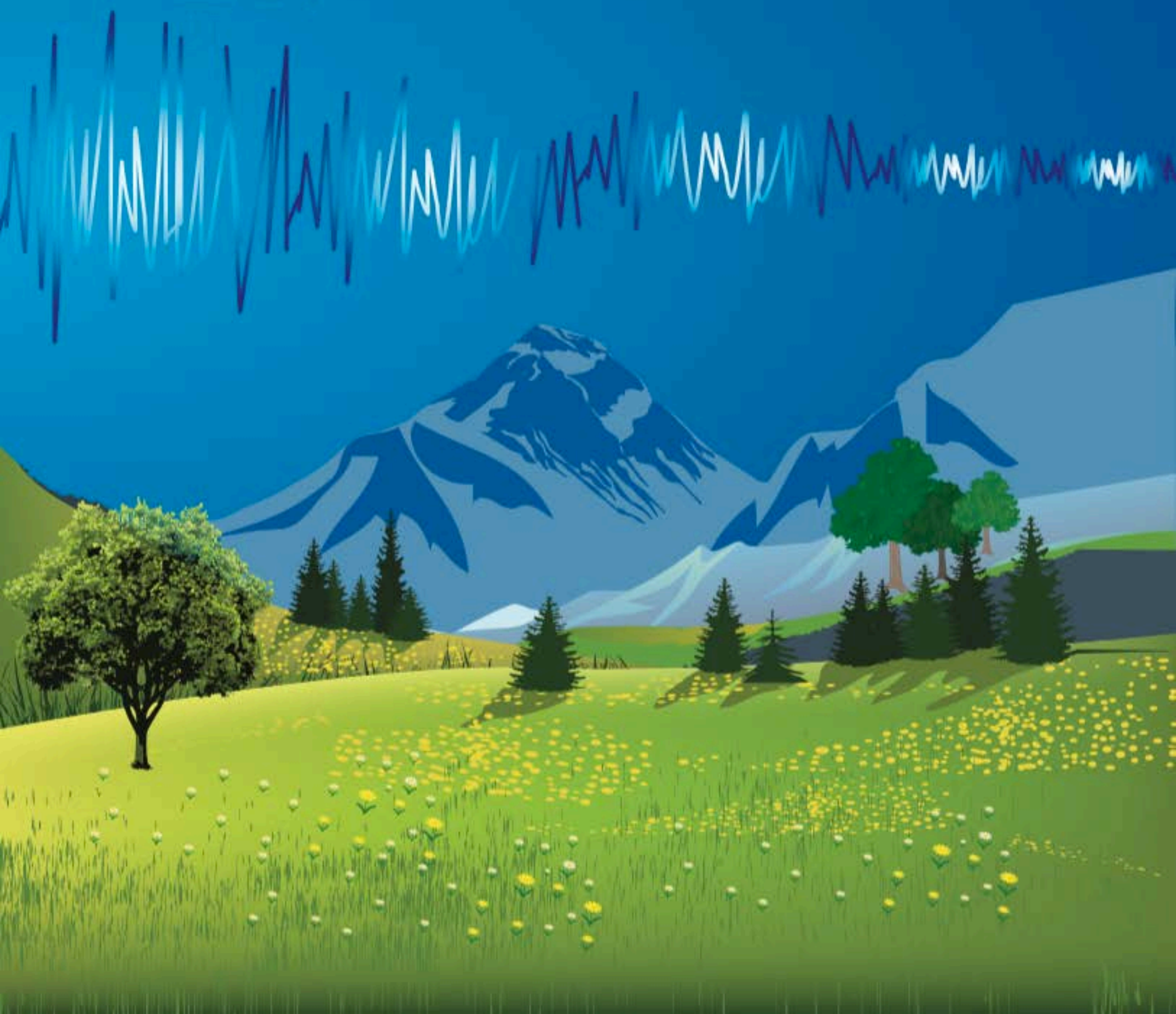

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NUMERICAL STUDY OF MESOSCALE CONVECTIVE SYSTEMS FOR RECURVING CYCLONE MADI AND NON-CURVING CYCLONE PHAILIN FORMED OVER THE BAY OF BENGAL IN 2013 USING WRF MODEL

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Abstract
A mesoscale convective system (MCS) is nothing but a cloud system which occurs in relation with an ensemble of thunderstorms. For tropical cyclone (TC) genesis, MCSs are the basic precursors. In this study, cyclone Phailin and Madi formed over the Bay of Bengal in 2013 are considered to simulate and analyze the characteristics of convective cells and their MCSs using WRF model. Cyclone Madi was a very severe cyclonic storm with maximum wind speed of 85 knots and during life time it changed its direction to the angle of almost 140 degrees from its original track, whereas, cyclone Phailin had maximum wind speed of 140 knots and its direction is almost straight during its lifetime. High unidirectional shear and moderate convective available potential energy (CAPE) suggests the possibility of supercell formation in the rainband of Madi whereas moderate CAPE and small shear are favorable for the development of ordinary convective cells in Phailin. At the mature stage of convective cells, the average length is ~30 km for both TCs and average speed is almost 9 ms^{-1}. The average lifetime of the cells in Madi (Phailin) has been found 3.5 (4.6) hours. The vortex pair within the cells indicates the existence of mesovortices, which is more intense in case of Madi than Phailin. Intense MCSs having maximum reflectivity >50 dBZ are found in the northern side of Madi and southwest side for Phailin. MCS length (height) before 1 hr of recurving of Madi is approximately 220 (9.8) km, which is reduced to ~180 (5.7) km during curving time even though cyclone has highest wind speed at that time. On the other hand, the MCS length (height) is found 275 (8.5) km for Phailin which remains almost constant. The low-level moisture flux inflow causes the variability of the MCS structure.

Keywords: Tropical cyclone, Raindband, Mesoscale convective system

1. Introduction:

The tropical cyclones (TCs) over the Bay of Bengal (BoB) are developed and restricted within the monsoon transition periods, with a highest frequency in October-November and second highest in May, therefore, formation of cyclones over the BoB is different from other ocean basins (Akter 2015, Akter and Tsuboki 2014; Camargo et al 2007; Kikuchi et al. 2011). In the boreal summer, the location of the monsoon trough (MT) is well inland and the prevailing southwesterly winds and upper-level easterly winds generate strong vertical shear which suppresses TCs development over the BoB (Jeffries and Miller 1993; McBride 1995).

The TC formation and intensity over the Ocean not only depends on the synoptic criteria but also mesoscale convective systems (MCSs) (Houze 2004). Barnes and Zipser (1983) observed mesoscale and convective structure of cyclone rainband for cyclone 'Floyd' formed in Atlantic basin. Using radar observations they have showed that the band has both a stratiform and convective structure . The upwind end of the band is mainly convective and the band gradually becomes less convective and more dominated by stratiform precipitation toward its downwind end. The structure and dynamics of tropical squall-line system over Atlantic Ocean area were investigated by Houze (1977) and the study was found that the squall-line system consisted of convection at the leading edge of the system and a trailing anvil cloud region.
Along with the other basin, a few works about the MCSs in the TCs is also done in the NIO. Goyal et al. (2016) observed the interaction of multiple mesoscale structures during different stages of TC Using satelite kalpana-1. Mesoscale convection associated with bimodal cyclogenesis over the BoB was studied by Akter (2015). The study found that mature MCSs associated with bimodal cyclone formations were quasi linear, and they featured leading-edge deep convection and a trailing stratiform precipitation region, which was very narrow in the postmonsoon cases. Akter and Tsuboki

(2010) observed the characteristics of supercells in the rainband of numerically simulated cyclone Sidr. The study explained that Supercells in the outer axis were classical supercell which are more intense and well-structured and persisted for a longer period and supercells of the inner axis are mini-supercells which usually formed in the moist environment of TC. Akter and Tsuboki (2012) investigated the characteristics of an outer rainband for cyclone Sidr and found that downwind portion of the band consisted of convection with stratiform rain, whereas the upwind and middle portions comprised active convective cells without stratiform rain. So far, no study has been done before for the individual cell and MCS characteristics during curving time of a cyclone. According to Hima (2017), 64.55% cyclones formed over the BoB changes the track from its original path (re-curving) during 1991-2015. Therefore it is important to know the characteristics of convective cells as well as associated MCS for the formation and intensity of TC. In this study, re-curving cyclone Madi (2013) and non-curving cyclone Phailin (2013) occurred in postmonsoon have been selected. The objective of this study is to characterize convective cells and associated environment in the rainband, and to analyze MCSs at the time of recurvature of cyclone Madi and the same analysis for cyclone Phailin at the time when it has similar intensity as Madi.

2. Synoptic Description of Cyclones:

Very severe cyclonic storm Madi is a category 2 cyclone according to Saffir-Simpson Hurricane Scale, formed 06 December in 2013. The cyclone Madi reached a maximum intensity of 85 knots (43.72 ms^{-1}) at 0000 UTC of 10 December 2013 near the region of latitude 15.4° N and longitude 85.3°E. Figure 1 (a) shows the track of cyclone Madi (2013). The extremely severe cyclonic storm (as IMD scale) 'Phailin' is a category 5 cyclone which formed in 05 October 2013 from a remnant cyclonic circulation over the South China Sea. The cyclone Phailin attained its maximum intensity of 140 knots (72 ms^{-1}) at 1200 UTC of 11 October 2013 over the region near latitude 16.7° N and longitude 87.7° E. After landfall the system weakened gradually. Figure 1 (b) shows the track of cyclone Phailin (2013).

3. Model Set-up and Data Used:

The Advanced Hurricane Weather Research and Forecasting (WRF) model (AHW) (version 3.7.1) has been used. National Centers for Environmental Prediction. (NCEP) Final Analysis (FNL) Operational Global Analysis data at 6-hour intervals with a resolution of 1° x 1° has been used for the model initial and boundary conditions. The model has been configured on two-way nested domains with 12 km for the outer domain D1 and 4 km for the innermost domain D2 (Davis et al. 2008). In the model, the horizontal grid points for parent domain (D1): 861 × 595 and inner nest domain (D2): 1064 × 996. The center of the domain is selected to be at 90°E and 15°N. The physical parameters are chosen according to Raju et al. (2011) and Osuri et al. (2012) because they have customized the parameters for the cyclone formed over the BoB. Vertical co-ordinate and time integration are chosen 29 pressure level and 72 respectively. Microphysics, cumulus parameterization, PBL parameterization, land surface parameterization and surface layer are selected respectively from Ferrier scheme, Kain-Fritsch, Yonsei University scheme, Noah land-surface model and Monin-Obukhov scheme. Output is taken for 30 minutes intervals.
The Joint Typhoon Warning Center (JTWC) best track data is used to determine the positions, intensities and duration of these two tropical cyclones. National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) Data with 0.5° × 0.5° has been also used to verify and analyze environmental parameter.

4. Validation:

Fig 1(a) and (b) shows that the simulated tracks of the cyclone Madi and Phailin have been found almost near to the same tracks with JTWC data. The average root mean square error (RMSE) of the simulated track is found approximately 50 km for Phailin whereas 60.5 km for Madi. The trends of minimum sea level pressure (MSLP) of simulated cyclones Phailin and Madi are almost matched with that in JTWC data shown in Fig. 1(c) and 1(d). The average RMSE of MSLP is found 27.60 hPa for Phailin whereas 9.51 hPa for Madi. The simulated maximum winds of cyclones Phailin and Madi are also similar with that in the JTWC data. The vorticity at 850 hPa level for both cyclones has been compared with the JTWC data in figure 1(e), 1(f)). During the maximum intensity of the cyclone Madi, the simulated maximum vorticity is found nearly about 30×10^{-4} s^{-1} and the same for NCEP-CFSR is 10×10^{-4} s^{-1}.On the other side, the simulated maximum vorticity of cyclone Phailin (2013) is found almost 20×10^{-4} s^{-1} which is 6×10^{-4} s^{-1} for reanalysis data. The values of vorticity in the reanalysis data is low because of lower resolution compared to the model. However, the rotation of wind is in good agreement with NCEP-CFSR wind for both simulated cyclones.

5. Result and Discussion:

In this study, the time has been chosen at the same intensity for these two cyclones. The convective cells along the northern rainband have been taken within the time at 0630 UTC 10 December 2013 to 1200 UTC 10 December 2013. Convective cells (named as a, b, c and d) as well as MCS in the rainband of cyclone Madi has been shown in figure 2 (i, ii, iii). The convective cells of cyclone Phailin along the rainband have been analyzed within the time at 1100 UTC 10 October 2013 to 2100 UTC 10 October 2013 shown in figure 2 (iv, v, vi). For cyclone Madi, the cell 'a' is started from 0630 UTC and merged with the northern side of the MCS after 1000 UTC. Cell 'b' and 'c' are started respectively from 0830 UTC and 0900 UTC and are combined with each other at 1130 UTC and finally merged to MCS. The cell 'd' is started 0900 UTC and merged with the northern side of the MCS after 1200 UTC. On the other hand, cell 'a' and 'b' are started respectively from 1100 UTC and 1130 UTC 10 Oct 2013 and is merged with each other at 1500 UTC 10 Oct 2013 and finally merged to eye wall surrounded MCS after 1600 UTC 10 Oct 2013.

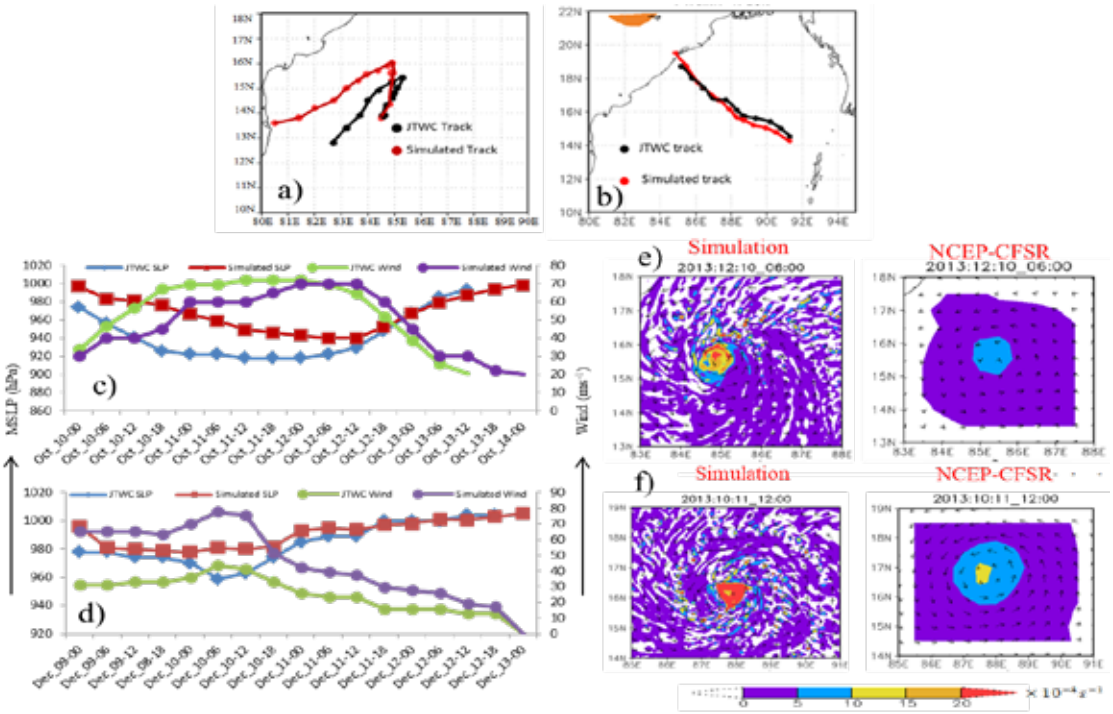

Fig.1.Validation of (a) track of cyclone Madi , (b) track of cyclone Phailin. MSLP and max. wind speed of (c) cyclone Phailin for 0000 UTC 10 Oct to 0000 UTC 14 Oct 2013, d) cyclone Madi for 0000 UTC 09 Dec to 0000 UTC 13 Dec 2013, Vorticity (shaded) and 850 hPa wind (vector) for (e) cyclone Madi at 0600 UTC 10 Dec 2013 and (f) cyclone Phailin at 1200 UTC 11 Oct 2013

The cells 'c' and 'd' are started from 1730 UTC 10 Oct 2013 and merged with the northern side of the MCS after 2100 UTC 10 Oct 2013. All cells are merged with northern portion of the MCS in the rainband for both cyclones. All convective cells are analyzed individual in the study, but, for convenience all parameters are discussed and shown only for convective cell 'a' for both cyclones. However, the summery for all convective cells is given later in the table.

5.1 Environmental Condition for the Formation of the Convective Cells:

Environmental condition has been observed 30 minutes before the initiation of the cells a, b, c and d of both cyclones Madi and Phailin. The environment condition for the formation of the convective cell such as lifting condensation level (LCL), level of free convection (LFC), convective available potential energy (CAPE), convective inhibition (CIN), vertical wind shear between 0 to 3 km and 0 to 6 km height are analyzed in this study. For both cyclones, LCL of cells a, b, c and d is found 273 ~ 377 m which indicates lower value above the surface. The LFC value is found at low level of 274 ~ 420m which indicates unstable environment for the convection. The height difference between LCL and LFC is very low that indicates the probability of deep convection. The CIN is found almost near about zero indicating the high probability for the development of deep convective thunderstorm. CAPE is 1362 ~ 2480 jkg^{-1} for both cyclones which indicates moderate value. For cyclone Madi vertical wind shear between 0

to 6 km is found approximately 26 to 35 ms^{-1} which are high but for cyclone Phailin is found 2.59 to 5.19 ms^{-1} which are low. Moderate CAPE values and high vertical wind shear are important criteria for the formation of supercell (Blustein 2000) and moderate CAPE values and low vertical wind shear are criteria for the formation of ordinary cell. Another most important parameter for environmental study is hodograph which characterize the convective cell by the wind motion. In the hodograph (Fig. 3) 'sfc', '3 km' and '6 km' are indicated by three points marked by small red colored circle. In the hodograph for cyclone Madi, the motion of the wind is started from negative x-axis and thereafter changed the co-ordinate to positive x-axis and the wind is turned clockwise or veers with height. It shows curvature and unidirectional motion of wind. The vertical wind shear is very high between 0 to 6 km above ground level (AGL). So, the characteristics of the vertical wind direction indicate about the formation of supercell (Weisman and Klemp 1986). On the other hand, for cyclone Phailin, the hodograph shows that the direction of the wind motion is random. It also shows that the vertical wind shear between 0 to 6 km AGL is low. So, the characteristics of the vertical wind direction favours for the ordinary cell (Weisman and Klemp 1986). Therefore, the above analysis of environment condition for initiation of the convective cells of cyclone Madi (2013) indicates that the LCL, LFC, CIN, CAPE, vertical wind shear and hodograph are favorable for the formation of supercell, whereas, the same analysis are favorable for the formation of ordinary cell in the rainband of cyclone Phailin (2013).

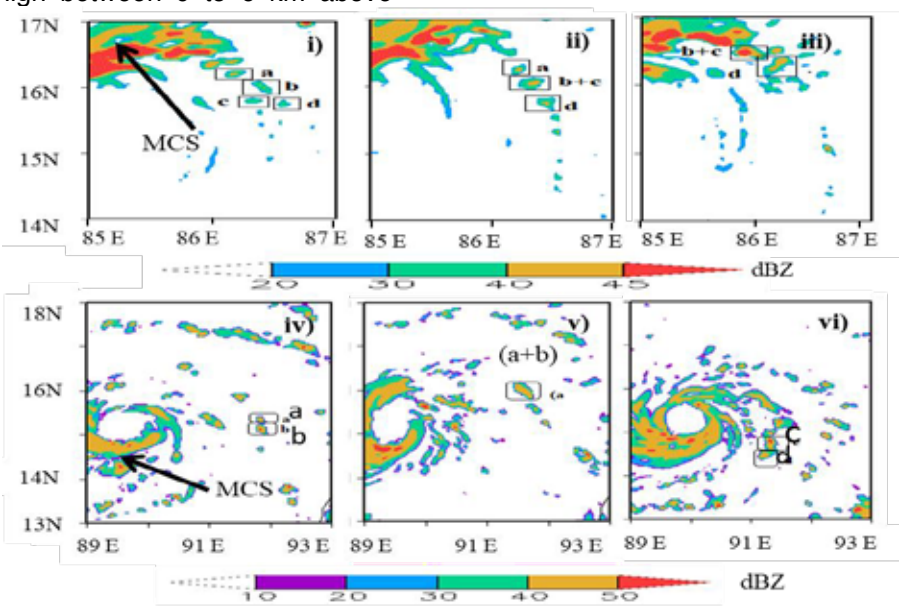

Fig. 2. Convective cells (a,b,c and d) and associated MCS in the rainband of cyclone Madi (2013) at i) 0900 UTC ii) 1000 UTC iii) 1100 UTC 10 Dec 2013 and Phailin at iv) 1330 UTC v) 1500 UTC vi) 2100 UTC 10 Oct 2013.

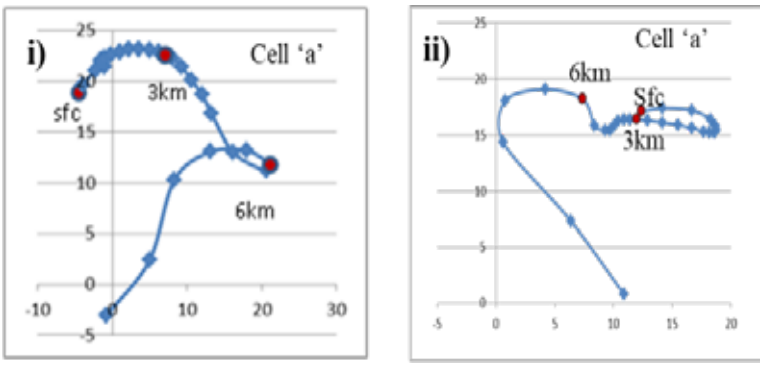

Fig. 3. Hodograph for convective cells 'a' in the rainband of i) cyclone Madi (2013) and ii) cyclone Phailin (2013).

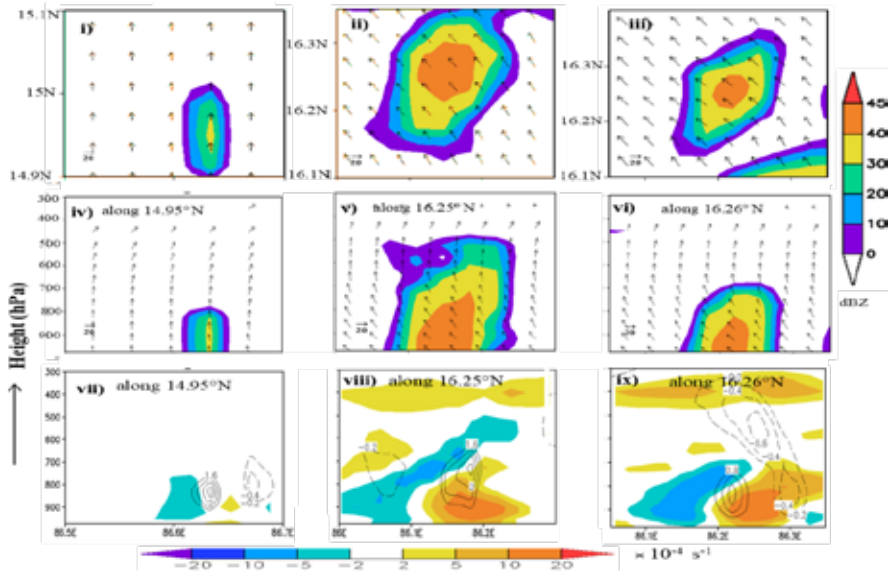

Fig. 4. Horizontal distribution of reflectivity at 925 hPa (shaded, dBZ) and wind at 850 hPa (vector, ms-1) for i) initial stage at 0630 UTC, ii) mature stage at 0930 UTC and iii) before merging stage at 1000 UTC 10 Dec 2013 for cell 'a' of cyclone Madi (2013). Vertical cross section of reflectivity (shaded, dBZ) and wind (vector, ms-1) at iv) initial stage, v) mature stage and vi) before merging stage. Vertical distribution of vorticity (shaded, ×10-4s-1), updraft (contour; solid line , 0.2 ms-1 interval) and downdraft (contour; solid dash line, 0.2 ms-1 interval) at vii) initial stage viii) mature stage ix) before merging stage.

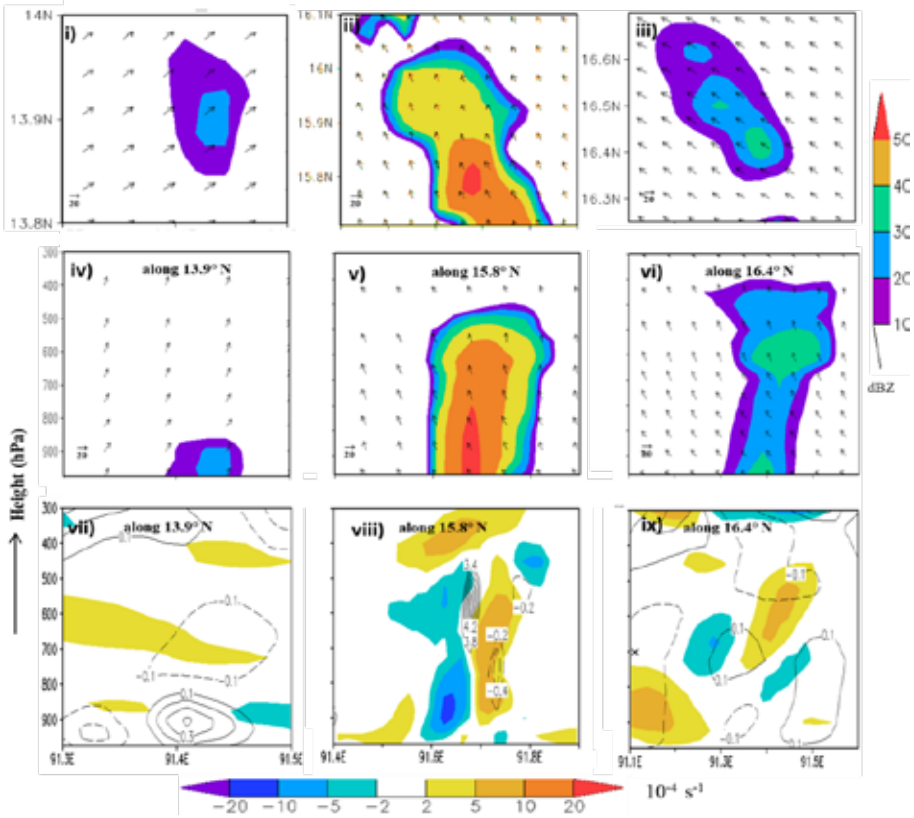

Fig. 5. Horizontal distribution of reflectivity at 925 hPa (shaded, dBZ) and wind at 850 hPa (vector, ms-1) for i) initial stage at 1100 UTC, ii) mature stage at 1430 UTC and iii) before merging stage at 1600 UTC 10 Oct 2013 for cell 'a' of cyclone Phailin (2013). Vertical cross section of reflectivity (shaded, dBZ) and wind (vector, ms-1) at iv) initial stage, v) mature stage and vii) before merging stage. Vertical distribution of vorticity (shaded, ×10-4s-1), updraft (contour; solid line , 0.2 ms-1 interval) and downdraft (contour; solid dash line, 0.2 ms-1 interval) at vii) initial stage viii) mature stage ix) before merging stage.

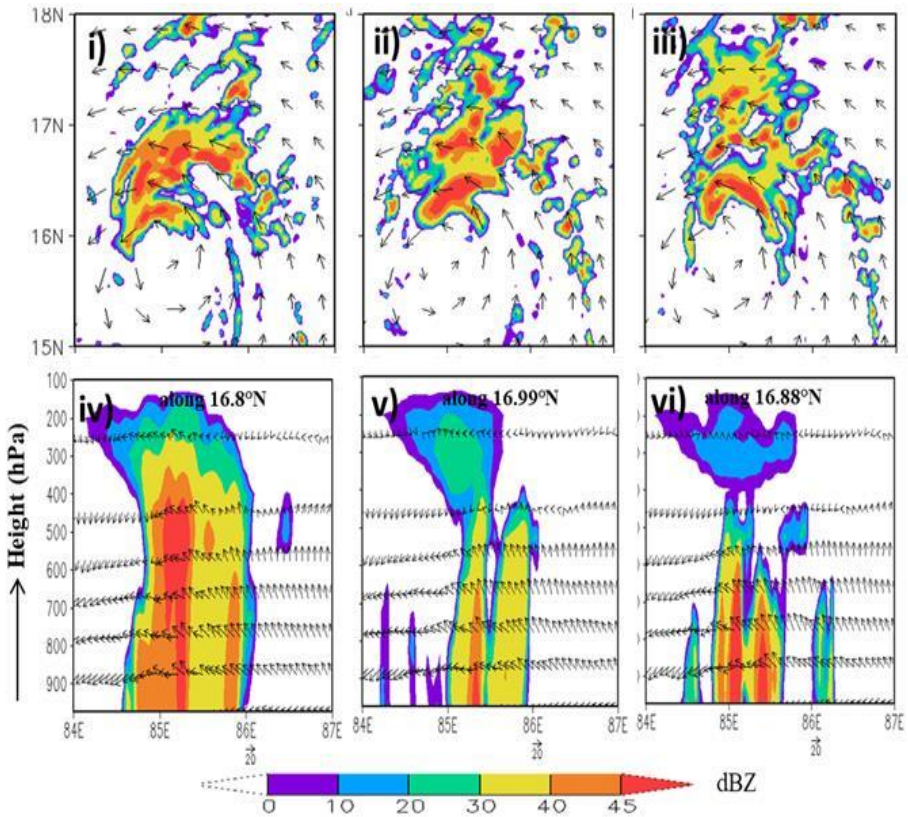

Fig. 6. Horizontal distribution of reflectivity at 925 hPa (shaded, dBZ) and wind at 850 hPa (vector) at i) one hour before of curving time at 1100 UTC, ii) curving time 1200 UTC and iii) one hour after of curving time 1300 UTC 10 Dec 2013 of cyclone Madi (2013). Vertical cross section of reflectivity (shaded, dBZ) and wind (vector) at iv) one hour before of curving time at 1100 UTC, v) curving time at 1200 UTC and vi) one hour after of curving time at 1300 UTC 10 Dec 2013 of cyclone Madi (2013).

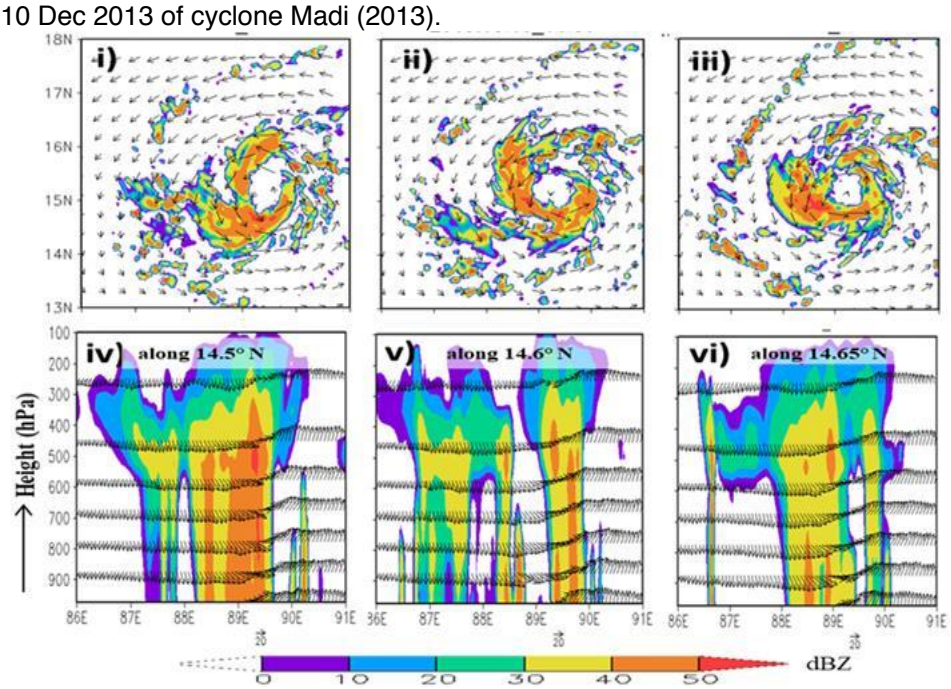

Fig. 7 Horizontal distribution of reflectivity at 925 hPa (shaded, dBZ) and wind at 850 hPa (vector) at i) tp-1at 1500 UTC, ii) tp at 1600 UTC and iii) tp+1 at1700 UTC 10 Oct 2013 of cyclone Phailin (2013). Vertical cross section (along XY line in the first row) of reflectivity (shaded, dBZ) and wind (vector) at iv) tp-1at 1500 UTC, v) tp at 1600 UTC and vi) tp+1 at1700 UTC 10 Oct 2013 of cyclone Phailin (2013)

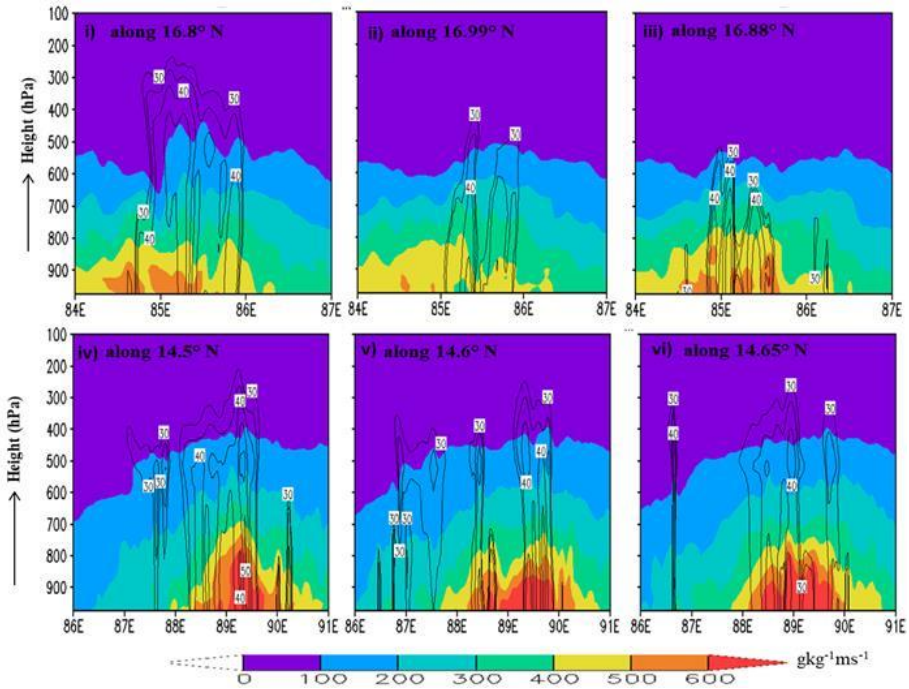

Fig. 8: Vertical distribution of moisture flux (shaded, gkg-1ms-1) and reflectivity (contour, 5-dBZ interval) at i) one hour before of curving time at 1100 UTC, ii) curving time at 1200 UTC and iii) one hour after of curving time at 1300 UTC 10 Dec 2013 of cyclone Madi (2013) using same time and cross section as fig. 6. The sameat iv) tp-1 at 1500 UTC, v) tp at 1600 UTC and vi) tp+1 at 1700 UTC 10 Oct 2013 of cyclone Phailin (2013) using same time and cross section as fig. 7.

5.2 Horizontal and Vertical Characteristics of the Convective Cells Formed in the Rainband:

Under the horizontal and vertical characteristics, reflectivity, vorticity, updraft and downdraft have been discussed for the convective cells formed in the rainband of cyclone Madi (2013) and Phailin (2013). The horizontal reflectivity at 925 hPa and wind at 850 hPa for cell 'a'of cyclone Madi has been shown in the figure 4 (i, ii, iii). For the convenience of the study; initial, matured and before-merging stage have been taken for characterizing the parameters of this convective cell. For cyclone Madi, the initial, matured and before-merging stages are found at 0630 UTC, 0930 UTC and 1000 UTC shown in the figure 4 (i, ii, iii). At the initial stage, the length of the cell 'a' has been found 12.1 km. The length is found 24.2 km at the matured stage which is double than the initial stage. At the before-merging stage, the length is 22 km.The lifetime of the cell is noticed for 4 hours. At the initial stage, the cell speed is found 21.38 ms^{-1}. But then the cell speed is decreased slowly. At the matured stage, the cell speed is found very less (3.23 ms^{-1}) which is almost 85% less than the initial stage. At the beginning of the cell, the southerly wind is observed which gradually turns south easterly for mature and before-merging stages. The vertical cross-section along the center of the cell 'a' has been shown in the figure 4 (iv, v, vi) for initial, matured and before-merging stage. At the beginning of time, the cell height and diameter has been found 1.65 km and 4 km respectively. The values have been found 5.30 km and 18.7 km at the matured stage. Finally, for the before-merging stage, the height and diameter is found 2.84 km and 14.3 km, respectively. At initial stage, maximum reflectivity is shown 30 dBZ which indicates light to moderate rainfall. But in mature and before merging stage maximum reflectivity is 44 dBZ that specifies moderate to heavy rainfall.

Table 1: Summary for the characteristics of cells of cyclone Madi (2013) at matured stage.

Cells	Diameter (km)	Length (km)	Height (km)	Max. Reflectivity (dBZ)	Max. Updraft (ms^{-1})	Max. Downdraft (ms^{-1})	Cell Speed (ms^{-1})	Max. Vorticity (s^{-1})
a	18.7	24.2	5.30	44	2.2	0.2	3.23	12×10^{-4}
Merged (b+c)	30.8	36.3	6.5	48	3.4	0.4	5.19	25×10^{-4}
d	28.6	33	6.08	45	1.8	0.2	13.44	18×10^{-4}

Table 2: Summary for the characteristics of cells of cyclone Phailin (2013) at matured stage.

Cells	Diameter (km)	Length (km)	Height (km)	Max. Reflectivity (dBZ)	Max. Updraft (ms^{-1})	Max. Downdraft (ms^{-1})	Cell Speed (ms^{-1})	Max. Vorticity (s^{-1})
a	22	39	8.5	50	4.6	0.3	7.35	12×10^{-4}
b	20	22	11.35	52	5	0.5	9.49	19×10^{-4}
c	22	33	6.96	52	5	0.5	15.35	18×10^{-4}
d	24	27.5	9.79	47	2	0.5	30.26	6×10^{-4}

Table 3: Summary for the characteristics of MCS

	Madi (2013)			**Phailin (2013)**		
Parameter	Before 1hr. of Curving	Curving Time	After 1hr. of Curving	t_p-1	t_p	t_p+1
MCS Length (km)	~220	~180	~220	~250	~275	~264
Height (km)	~9.8	~5.7	~4.28	~8.5	~8.5	~8.5
Max. Reflectivity (dBZ)	48	46	52	50	45	45
Max. Vorticity (s^{-1})	25×10^{-4}	25×10^{-4}	30×10^{-4}	30×10^{-4}	15×10^{-4}	10×10^{-4}
Max. updraft (ms^{-1})	13	8	12	10	8	11

Again, for cyclone Phailin, the horizontal reflectivity at 925 hPa and wind at 850 hPa for cell 'a' are shown in the figure 5 (i, ii, iii). In the figure 2 (v), it has showed that the cell 'a' and cell 'b' are merged with each other at 1500 UTC 10 Oct 2013 and continued to move before merging to the MCS. At the initial stage the cells 'a' is found very small in size. It is gradually increased in size and reached at the matured stage at 1430 UTC 10 Oct 2013. The initial stage of cells 'a' is found at 1100 UTC. The mature stage of cell 'a' is found at 1430 UTC 10 Oct 2013 whereas the before-merging stage at 1600 UTC 10 Oct 2013. At the initial stage, the length of the cell 'a' is found 14.3 km. The length of the cell 'a' is found 39 km at the matured stage which is two times (173% more) than the initial stage. The length of merged cell '(a+b)' is found 35 km at the before-merging to MCS. The lifetime of the cell 'a' is found 5.5 hours. The maximum cell speed is estimated as 7.35 ms^{-1}.

The vertical cross-section of the cell 'a' is shown in the figure 5 (iv, v, vi). The initial height of cell 'a' is found 1.02 km. On the other hand, the diameter is found 5.5 km. The height and diameter of the cell 'a' at the matured stage are found 11.35 km and 22 km, respectively. The initial stage reflectivity of cell 'a' is found 10 dBZ. But in the mature stage it is found 50 dBZ which indicates heavy rainfall.

Vertical vorticity, updraft and downdraft have been plotted for cell 'a' of cyclone Madi and cyclone Phailin in the figure 4(vii, viii and ix) and 5 (vii, viii and ix) (Third row) respectively. In every stage i.e. at initial, matured and before-merging both positive and negative vorticity are found in the cell. The positive vorticity of the cell of both cyclones are happened in the southeast portion along the wind direction and negative vorticity is existed in northwest side of the cell. Maximum area of the positive vorticity is found in the matured stage. This vortex pair present in the cell indicates the possibilities of supercell. This result shows the same result as Akter and Tsuboki (2010) in which they found supercell in the rainband of cyclone Sidr (2007) formed over the BoB. The height of the vortex pair is increasing from initial to before-merging stage through mature stage. For cyclone Madi, The maximum height of the cell 'a' for both vortex pair is upto 700 hPa whereas 500 hPa for cyclone cell 'a' of cyclone Phailin. The maximum positive vorticity is found 15×10^{-4} s^{-1} and the maximum negative vorticity is found 6×10^{-4} s^{-1} at the before-merging stage. Maximum updraft of cell 'a' for cyclone Madi and cyclone Phailin has been found 2.2 ms^{-1} and 4.6 ms^{-1} respectively. Summary of the characteristics of convective cells for cyclone Madi and Phailin are given in the table 1 and 2 respectively.

5.3 Horizontal and Vertical Characteristics of the MCS:

The convective cells in the eastern side rainband of cyclone Madi (2013) moving northward with the cyclone movement and form MCS in the north of the cyclone which is above the north of the eyewall. On the other hand, the convective cells in the rainband of cyclone Phailin (2013) moving northwest direction with the cyclone movement and form intense MCS in the southwest side of the cyclone. For detail study about the MCS of cyclone Madi (Phailin), the north (South) side MCS has been taken. Fig. 6 shows the MCS at recurving (t_m), before one hour of curving time (t_m-1) and after one hour of curving time (t_m+1) for cyclone Madi (2013). The curving time is found at 1200 UTC 10 December 2013. Both horizontal and vertical characteristics of MCS have been observed at every stage. In this study, MCS of cyclone Phailin (2013) is considered at time t_p= similar intensity time as curving time of cyclone Madi (2013). Where, t_p-1= 1 hr. before of t_p and t_p+1= 1 hr. after of t_p. The horizontal and vertical distribution of reflectivity and wind graph is plotted for curving time, before one hour of curving time and after one hour of curving time in the figure 6. On the other hand, the horizontal and vertical distribution of reflectivity and wind graph of cyclone Phailin is plotted for t_p-1, t_p and t_p+1 in the figure 7.

The MCS size and intensity of the reflectivity of cyclone Madi is decreased at the curving time. The maximum intensity area is found at one hour before of curving time for cyclone Madi. At the one hour before of curving time and after one hour of curving time, the maximum MCS reflectivity is found 48 and 52 dBZ whereas 46 dBZ at the curving time. The MCS length is found ~220 km at the one hour before of curving time and after one hour of curving time. But at the curving time, the MCS length is found ~180 km. The intense horizontal wind is coming from the south-easterly direction (Fig: 6). For cyclone Phailin, The highest reflectivity is found at t_p -1. After that the MCS intensity of the reflectivity is decreased at the time of t_p and t_p+1. The maximum reflectivities are found 45 dBZ, 45 dBZ and 50 dBZ for the time of t_p -1, t_p, and t_p+1, respectively. At the time of t_p-1, t_p and t_p+1 the MCS length is found ~250 km, ~275 km and ~264 km severally. The intense horizontal wind is coming from the north-easterly direction (Fig: 7).

The height of the MCS of cyclone Madi is decreased significantly at the curving time than that of the before one hour of curving time (Fig. 6). The height of the MCS has been found at one hour before of curving time is approximately 9.8 km. At the curving time, the height is found 5.7 km approximately. After one hour of curving time, the height is found 4.28 km approximately. The strong south-easterly wind upto 600 hPa is found east side of the MCS. Again for cyclone Phailin, the height of the MCS has been found approximately 8.5 km for all three stages of time. The strong south-westerly wind upto 300 hPa is blown south side of the MCS. Overall summary of the characteristics of the MCS is given in the table 3. To study the moisture flux within the MCS, vertical cross-section has been taken for both cyclones in the figure 8. Here, the moisture flux is shaded and reflectivity is in contour with 5 dBZ interval. Figure 8 indicates that the low-level moisture is more intense in the west side of the MCS of cyclone Madi. Before one hour of curving time, lower level moisture flux is significant and it is extended upto 550 hPa level. The maximum amount of moisture flux is almost 600 $gkg^{-1}ms^{-1}$ which may help the MCS to become intense. But at the curving time, the intensity of moisture flux is decreased little bit. Almost 200 $gkg^{-1}ms^{-1}$ moisture flux is decreased at the curving time than that of the one hour before of curving time. The decreasing of moisture flux decreases the height of the reflectivity . After the curving time the vertical distribution of moisture flux is again increased little. However, for the cyclone Phailin (Fig. 8), at the time of t_p-1, lower level moisture flux is significant and moisture flux is found upto 450 hPa level and the maximum amount of moisture flux is above 600 $gkg^{-1}ms^{-1}$ which may favor the MCS to become intense. But at the time of t_p, the intensity area of moisture flux is decreased significantly. At the time of t_p+1, the intensity of the moisture flux is started to increased. The height of the moisture flux is found also upto 450 hPa level for both t_p, and t_p+1. The maximum amount of moisture flux is found above 600 $gkg^{-1}ms^{-1}$ for both t_p, and t_p+1.

6. Conclusion:

The formation and intensity of TCs not only depend on the synoptic criteria but also MCSs formed over the Ocean. In this study, two cyclones i.e. cyclone Phailin and cyclone Madi formed over the BoB in 2013 are considered for study. According to JTWC the intensity of the Phailin is 140 knots (72 ms^{-1}) and the intensity of Madi is 85 knots (43.72 ms^{-1}). Both the cyclones are formed in postmonsoon season but the track of the cyclone Madi has recurved whereas the Phailin has an almost straight cyclone track. Cyclone Madi has changed its direction to the angle almost 140 degrees from its original track. A high resolution WRF simulation has been performed to characterize convective cells and associated environment in

the rainband of the TCs. In addition MCSs during the time of recurvature of cyclone Madi is analyzed and tried to find the differences in characteristics of MCSs for non-curving cyclone Phailin. The simulated cyclones are verified with JTWC data and 6 hourly NCEP-CFSR reanalysis data (0.5° x 0.5° resolution). The simulated tracks of the cyclone Phailin and Madi have been found almost near to the same tracks with JTWC data. The average RMSE of the simulated track is found approximately 50 km for Phailin whereas 60.5 km for Madi. The trends of MSLP of simulated cyclones Phailin and Madi are almost matched with that in JTWC. The average RMSE of MSLP is found 27.60 hPa for Phailin whereas 9.51 hPa for Madi. The simulated maximum winds of cyclones Phailin and Madi are also similar with that in the JTWC data. The vorticity at 850 hPa level for both cyclones has been compared with the JTWC data. The values of vorticity in the reanalysis data is less because of soft resolution compared to model data resolution. However, the rotation of wind is in good contract with NCEP-CFSR wind for both simulated cyclones.

To characterize the convective cells in the rainband, four individual cells (a, b, c and d) are selected randomly for both cyclones Madi and Phailin. As Phailin (2013) is more intense cyclone than Madi (2013) so cells are considered during the time when both cyclones have almost similar intensity. The environment condition for every four cells has been studied 30 minutes before the initiation. The value of CAPE for the formation of convective cells in the rainband is found moderate for both cyclones. Wind shear from surface to 6 km AGL is found almost 8 times higher in Madi . The wind direction is clockwise and unidirectional for Madi whereas, it is random for Phailin. Therefore, moderate CAPE and clockwise veering unidirectional vertical wind represents the favourable environment for the formation of supercells in the rainband of Madi (2013) whereas environment are favourable for ordinary cells for Phailin (2013). The structure and intensity of the convective cells are more prominent in case of Phailin (2013) than that in Madi (2013) for the same intensity (80-85 knots) of the TCs. Speed and lifetime of the cells are also high in cyclone Phailin (2013) than that in Madi (2013). Vortex pair in both cyclones indicates the presences of mesovortices associated with the cells in the rainband. The advection of low-level deep moisture helps to develop an intense MCS in cyclone Phailin than the MCS in Madi. At the curving time of cyclone Madi, the MCS length, height and intensity are found less in value than that before one hour of recurving time though it has highest intensity in the recurving time . On the other hand, no significant changes is found to the structure of MCS formed in the cyclone Phailin (2013) within consecutive time. The difference in low level moisture flux may cause the variation of the structure of MCS.

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