

REVIEW

Environmental Energetics aspects of anomalous Cyclogenesis over Indian Ocean during 2013

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ABSTRACT

An attempt has been made to understand the dynamics behind anomalous cyclogenesis over North Indian Ocean during 2013 cyclone seasons, from an atmospheric energetics point of view. For that various energy terms, their generation and conversion terms have been computed using NCEP/NCAR reanalysis data during different phases of the intense cyclonic vortices formed in 2013 over North Indian Seas. It is observed that maximum intensification of all the intense cyclonic vortices was associated with an enhancement in both conversions viz., from eddy available potential energy (AE) to eddy kinetic energy (KE) and zonal kinetic energy (KZ) to eddy kinetic energy (KE). Energetics analysis suggested that during intensification of the storms, dissipation of both eddy available potential energy (AE) and zonal available potential energy (AZ) have taken place, suggesting the intensification of storms at the cost of AE and AZ. For all of these systems baroclinic eddy kinetic energy conversions i.e. from AE to KE dominates over barotropic eddy kinetic energy conversions i.e. from KZ to KE. Anomalous cyclogenesis in 2013, was partly attributed to a positive anomaly in moist static energy of the environment along with positive anomaly in baroclinic and barotropic eddy kinetic energy conversions during cyclone seasons over the region under study. Release of convective instability in the atmosphere can be partly attributed for anomalous cyclogenesis in 2013.

1. Introduction

Meteorologists have always shown keen interest in observing and studying cyclonic storms (CS). As per the UN Economic and Social Commission for Asia and the Pacific (UNESCAP)-World

Meteorological Organization (WMO) Panel on Tropical Cyclone in Feb, 2013; in the North Indian Ocean (over the Bay of Bengal and Arabian Sea), the average number of CS formed in a year are just around 5 which accounts for only 6% of the total global average. However, the loss of

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life, damage to the property and human suffering caused by these tropical cyclones and associated storm surges is very high as compared to the other regions. Despite the adverse impact, tropical cyclones are also the main source of precipitation and water availability. Dynamical understanding of the processes leading to the intensification or weakening of these systems is very much essential.

Atmospheric energetics is a very useful tool for dynamical understanding of different atmospheric processes. The inflowing air to a hurricane acquires enthalpy from underlying surface leading to conversion of potential energy to kinetic energy^[15]. The study about the energetics of hurricane Hilda (1964) showed that the total generation of available potential energy within the hurricane scale, compares favourably with estimated kinetic energy production in mature hurricanes^[1]. There are significant relation between latent heating and production of kinetic energy as well as available potential energy^[2]. The Available Potential Energy (APE) is maintained primarily by the release of latent heat in the highly convective core region and the kinetic energy is generated at all levels by the down-gradient flow and tropical cyclones act as strong sources of Kinetic Energy (KE) which can play important roles in the energetics of the general circulation^[6]. A cyclonic storm initially acquires KE in the lowest layers southwest of the centre and later, the largest KE increases south of the centre at intermediate levels^[16]. The movement and the intensity of the cyclones in the tropics depend mostly on sea surface temperature (SST)^[9]. The frontal collapse of the eye wall is a key process in the evolution of tropical cyclones^[5]. When the 850 hPa wind anomalies associated with the Madden-Julian Oscillation (MJO) are westerlies, small-scale, slow-moving eddies grow through barotropic Eddy Kinetic Energy (K_E) conversion from the mean flow^[12]. The role of energy fluxes is to govern the atmospheric circulation as well as the physical processes for formation of the Tropical cyclones^[11]. A study of the interaction between the seasonal mean circulation and the transient eddies over the Western North Pacific (WNP) during El Niño-Southern Oscillation (ENSO) warm and cold years by analysing the three dimensional Eddy Kinetic Energy (K_E) and Eddy Available Potential Energy (A_E) budget equations for total eddy, high-frequency (< 10 days) and low-frequency (20–70 days) components indicated that low-level anomalous cyclonic circulation, westerly jet and ascending motion associated with the eastward extension of warm SST during warm ENSO years are favourable for eddy barotropic energy conversion [$C(K_z, K_E)$] and eddy baroclinic energy conversion [$C(A_E, K_E)$]^[7]. The enhancement of these two eddy kinetic energy conversions might provide KE for the growth of high- and low-frequency transient eddies in-

cluding Tropical Storms (TSs) from the Philippine Sea to the International Date Line over the tropical WNP during warm ENSO years. In contrast, high- and low-frequency eddies convert K_E to seasonal mean circulation over the subtropical and mid-latitude WNP during warm years. Enhanced eddy baroclinic energy conversion plays an important role in the maintenance and enhancement of the subsequent development of transient eddies including TSs as they propagate northward. The loss of A_E to K_E due to the eddy baroclinic energy conversion is mainly supplemented by the generation of AE associated with eddy diabatic heating. However, the energy conversion from Mean Available Potential Energy (MA_E) to AE is also important due to the eddy vertical heat transport which is neglected in the two-dimensional AE budget equation. It is suggested that high and low frequency eddies including TSs may be in-situ developments which intensify through their enhanced diabatic heating and vertical heat transport. The analysis of the kinetic energy budget of the Asian summer monsoon using the daily averaged (0000 and 1200 UTC) reanalysis data for forty-year (1960–99) period produced by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) elucidated the features associated with evolution and established phases of the monsoon^[14].

While analysed 58 cyclogenesis cases occurred during 2003–2011 over the southern Brazilian coast, using NCEP data, it was reported that the genesis of these cyclones was associated with baroclinic conversion processes^[13]. The barotropic energy conversion by the meridional gradient of the basic zonal flow was an important energy source for the growth of the tropical cyclone NARGIS in 2008^[8]. While studying the energetics aspects of the Super Cyclonic Storm (GONU) and the Very Severe Cyclonic Storm (SIDR), formed over North Indian Ocean in 2007, it was found that intensification of 'GONU' is characterized by an enhancement in vertically integrated Moist Static Energy and baroclinic eddy kinetic energy conversion, whereas the intensification of 'SIDR' appeared to have more similarity to that of a typical growing mid-latitude baroclinic wave^[17].

Table 1 shows the details about cyclonic disturbances formed over Indian Ocean from the year 2000 to 2013. It can be seen from the table that during the year 2013, 10 cyclonic disturbances developed over Northern Indian Ocean, out of which 5 intensified into Cyclonic Storm and all of these were in Bay of Bengal. Table 1 indicates that 2013 can be classified as a year with anomalous cyclonic activity. Some interesting features of the increased cyclogenesis in 2013 are mentioned below:

(a). 5 intense cyclonic vortices with strength Cyclonic storm (CS) or more, formed over the Bay of Bengal for

the first time after 1987 and no CS over the Arabian Sea against the long period average ratio of 4:1 over Bay of Bengal and Arabian Sea. Out of them, 4 intensified into severe cyclonic storms (SCS) for the first time since 1982.

(b). 03 Very Severe Cyclonic Storm (VSCS) occurred over Northern Indian Ocean (NIO) for the first time since 1999.

(c). Post-monsoon season (Oct.-Dec.) was very active with the formation of 03 VSCS and 01 SCS. 04 such SCS during post-monsoon occurred over Bay of Bengal in the years 1922 & 1966 which is concluded after scrutinising the data of 1891-2012 whereas 03 VSCS occurred in the years 1967, 1971, 1977 & 1981, for which the data base is of 1965-2012.

(d). Though there were 05 cyclones, only one cyclone (PHAILIN) crossed coast as VSCS and other two (VIYARU and HELEN) as CS. Other two cyclones (LEHAR and MADI) crossed the coast as depressions. However, cyclone LEHAR crossed Andaman and Nicobar Islands as a SCS. It was the first SCS that crossed Andaman and Nicobar Islands since November 1989.

(e). While cyclone LEHAR was straight moving, tracks of all other cyclones were re-curving in nature. The PHAILIN re-curved after landfall whereas cyclone VIYARU re-curved north-eastwards over the sea, cyclone HELEN re-curved west-south-westwards just before landfall and cyclone MADI re-curved south-westwards over the sea. Comparing the tracks, the track of MADI was most unique in nature and had a rare analogue with past records.

(f). The total life period of cyclonic disturbances during 2013, was maximum (42.6 days) as compared to previous years (1990-2012).

Visualising these peculiarities of cyclogenesis in 2013, the present study aims to understand the atmospheric dynamics over the region under study, from an energetics perspective, which has caused 2013 an anomalous cyclogenesis over NIO during Cyclone seasons, i.e., during March-May and October-December.

2. Data

For the computations of the energy and their conversion terms, temperature (T), three components of wind (u , v , ω), geopotential height (z), relative humidity (RH) at different levels from 1000hPa to 100hPa at $2.5^\circ \times 2.5^\circ$ grid over the region from 5°N to 25°N and from 55°E to 110°E during their respective life-cycle have been used. Besides, we have also used the monthly mean data of these parameters, for March-May and October-December during the years 2000-2013 at the above mentioned levels over the region from 5°N to 25°N and from 55°E to 110°E . All these data have been downloaded from the NCEP/NCAR

website <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html>. Section 3 describes the methodology of the computation of energy terms.

3. Methodology

From the temperature data, at each grid point, heating rate $\frac{Q}{C_p}$ has been computed using first law of thermodynamics

$$\frac{\dot{Q}}{C_p} = \frac{dT}{dt} - \frac{\alpha}{C_p} \omega. \quad \text{Details about symbols used are given in table 2.}$$

Then, the zonal average, area average, deviation from the area average, deviation from zonal average and finally the departure of the zonal average from area average of an arbitrary field 'S' have been computed^[10] as below:

$$\text{Zonal average: } [S] = \frac{1}{\lambda_e - \lambda_w} \int_{\lambda_w}^{\lambda_e} S d\lambda \quad (1)$$

$$\text{Area average: } \bar{S} = \frac{1}{\sin \varphi_n - \sin \varphi_s} \int_{\varphi_s}^{\varphi_n} S \cos \varphi d\varphi \quad (2)$$

$$\text{Departure from area average: } S' = S - \bar{S} \quad (3)$$

$$\text{Departure from zonal average: } S'' = S - [S] \quad (4)$$

$$\text{Departure of zonal average from area average: } S''' = [S] - \bar{S} \quad (5)$$

Then using eqn. (1) to (5), zonal averages, area averages, departure from zonal and area average and finally zonal eddy components of the above fields, including heating rate, have been computed. Using these averages and zonal eddies, zonal available potential energy (A_z), zonal kinetic energy (K_z), eddy available potential energy (A_E), eddy kinetic energy (K_E), generation of zonal available potential energy [$G(A_z)$], generation of eddy available potential energy [$G(A_E)$], conversion of A_z to A_E [$C(A_z, A_E)$], conversion of A_z to K_z [$C(A_z, K_z)$], conversion of A_E to K_E [$C(A_E, K_E)$] and conversion of K_z to K_E [$C(K_z, K_E)$] have been computed^[4].

Besides above, mean monthly values of area averaged Convective Available Potential Energy (CAPE), height weighted Moist Static Energy (Sigma), mean monthly values of above mentioned ten energetics parameters have also been computed^[3] for the months March-May & October-December during 2000-2013. Using these mean monthly values of these parameters for different years, climatology of them for above months has been prepared, based on the period 2000-2013. This climatology has been used to find out anomaly in the mean monthly value for the months March-May & October-December during 2000-2013.

4. Results and Discussions

Anomalous behaviour of these five cyclonic storms (or of more intensity systems) have been studied critically taking into consideration their observed track, life cycle and movement and most importantly their energetics profile

and are described below one by one.

4.1. Cyclonic Storm - VIYARU (08th – 16th May 2013)

4.1.1 Observed Track

Observed track of the cyclonic storm VIYARU has been given in Fig. 1(a). From the observed track, following salient features can be seen:

(i) The genesis of the disturbance took place in lower latitude, near 5°N. It re-curved north-eastwards after initial north-westward movement.

(ii) It was one of the longest track over NIO in recent period after the very severe cyclonic storm, PHET over the Arabian Sea (31 May-07 June, 2010)

(iii) The cyclonic storm moved very fast (about 40-50 km per hour on the day of landfall, i.e. on 16th May 2013). Such type of fast movement of the cyclonic storm is very rare.

(iv) Due to the faster movement, the adverse weather due to the cyclonic storm was relatively less.

4.1.2 Life Cycle and Movement

Initially it was seen as a low pressure area over southeast Bay of Bengal on 8th May, which became well marked on 10th May, remaining stationary, it concentrated into a Depression at 0900UTC and further concentrated into a Deep Depression at 1200UTC. Moving north-westwards, it intensified into Cyclonic Storm (VIYARU) at about 350 km south-southwest of Car Nicobar at 0300UTC of 11th May. It moved further north-eastwards and lay over west central Bay near about 240km south-southeast of Kolkata. Moving north-north-eastwards, it crossed Bangladesh coast between Chittagong and Feni around 0800UTC of 16th and weakened into a Deep Depression over Mizoram at 1200UTC of 16th. Continuing its north-eastwards movement, it further weakened into a Depression over Manipur at 1800UTC of 16th about 40km west-northwest of Imphal and weakened into a well-marked low pressure area over Nagaland and neighbourhood at 0000 UTC of 17th.

4.1.3 Energetics Profile

Day-to-day variation in the Eddy Available Potential Energy (A_E), Zonal Available Potential Energy (A_Z), Zonal Kinetic Energy (K_Z), Eddy Kinetic Energy (K_E), and their generations and inter conversions i.e. $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$, $C(A_Z, A_E)$ have been shown in Figs. 1(b-k).

The figure suggests that maximum intensification of this system was associated with an enhancement in K_E and K_Z , Fig. 1(b and c). These enhancement in K_E and K_Z may be attributed to the enhancement in baroclinic eddy energy conversion into K_E and K_Z , Fig. 1 (h and i). Baroclinic

eddy energy conversion is due to the upward movement of relatively warmer air inside the clouds and downward movement of relatively colder air in the cloud free area, Sunita Devi et al., (2014).

It can be observed that there is a steady decrease in the conversion of Zonal Available Potential Energy to Zonal Kinetic Energy $C(A_Z, K_Z)$ during intensification, Fig. 1 (i). $C(A_Z, K_Z)$ represents the strength of mean meridional circulation, which is due to rising motion over warm latitudinal zone and sinking motion over cold latitudinal zone. The mean meridional circulation during the pre-monsoon season is observed to be weakened over this particular longitudinal belt at the time of intensification of 'VIYARU'. It can also be seen from Fig. 1(k) that although the conversion of Zonal Available Potential Energy to Eddy Available Potential Energy $C(A_Z, A_E)$, remained negative during development stage it became positive after the intensification. It remained positive throughout its lifetime with fluctuations in the magnitude of conversion terms. Positive values of $C(A_Z, A_E)$ indicates the influence of the mid latitude baroclinic circulation, Dutta et al., (2011). Thus the result suggests that there was significant influence of the mid latitude baroclinic circulation on the movement of 'VIYARU' after intensification.

$G(A_E)$ and $G(A_Z)$ are seen to be decreasing steadily which implies that the intensification process of the system results in steady dissipation of A_E and A_Z . The dissipation of A_E and A_Z continued till the system became unimportant.

From the average energy conversion values it is clear that most of the days during its life time baroclinic energy conversions such as $C(A_E, K_E)$, $C(A_Z, K_Z)$ which are of the order of 10^{-6} $\text{JKg}^{-1}\text{cm}^{-2}\text{s}^{-1}$ dominates over barotropic energy conversions such as $C(K_Z, K_E)$ which is of the order of 10^{-7} - 10^{-8} $\text{JKg}^{-1}\text{cm}^{-2}\text{s}^{-1}$.

4.2 Very Severe Cyclonic Storm (VSCS)- PHAILIN (08th -14th Oct 2013)

4.2.1 Observed track

Observed track of the VSCS PHAILIN is shown in Fig. 2(a). From the observed track, following salient features may be brought out:

(i) VSCS PHAILIN was the most intense land falling cyclone after Odisha Super Cyclone of 29th October 1999.

(ii) At the time of landfall on 12th Oct, maximum sustained surface wind speed in association with the cyclone was about 115 knots (215 kmph) and estimated central pressure was 940 hPa with a pressure drop by 66 hPa at the centre compared to surroundings.

(iii) There was rapid intensification of the system from 10th Oct. morning to 11th October morning leading to an

increase in wind speed from 45 knots to 115 knots.

4.2.2 Life cycle and Movement

The VSCS PHAILIN was initially seen as a low pressure area under the influence of a cyclonic circulation over Tenasserim coast and neighbourhood on 07th Oct, which concentrated into a Depression on 08th Oct. While moving north westwards, it intensified into a Deep Depression over north Andaman Sea about 50kms east of Maya Bandar at 0000UTC of 09th Oct. It moved north-westwards and intensified into a Cyclonic Storm (PHAILIN) at 1200UTC of 09th Oct, which further intensified into a Severe Cyclonic Storm and subsequently into a Very Severe Cyclonic Storm at 0600UTC of 10th Oct subsequently weakened into a low pressure area following path as Severe Cyclonic Storm Cyclonic Storm Deep Depression Depression low pressure on 15th morning.

4.2.3 Energetics Profile

Figs. 2 (b-k) show the day-to-day variation in the A_E , A_Z , K_Z , K_E , and their generations and inter conversions i.e. $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$, $C(A_Z, A_E)$ during the period from 2 days prior to the initiation till the dissipation of the VSCS PHAILIN. Similar to last case, the figures suggest that maximum intensification of this system was also associated with an enhancement in K_E . It can be observed that there is a steady increase in $C(A_Z, K_Z)$ during intensification. $C(A_Z, K_Z)$ represents the strength of mean meridional circulation. Thus it appears that intensification of 'PHAILIN' has resulted into strengthening of the mean meridional circulation during the post-monsoon season over this particular longitudinal belt. It can also be seen that although $C(A_Z, A_E)$ remained positive during development and mature stage further it appeared as negative during weakening. But it showed large fluctuations in magnitude throughout the life cycle. Positive values circulation of $C(A_Z, A_E)$ indicates the influence of the mid latitude baroclinicity. Thus the result suggests that there was significant influence of the mid latitude baroclinic circulation on the intensification and movement of 'PHAILIN'. But while weakening hardly there was any influence of the mid-latitude baroclinic circulation. Similar to the last case, in this case also, it appears intensification process of the system resulted in steady dissipation of A_E and A_Z .

For this system the maximum wind speed appears to be due to the enhanced barotropic and baroclinic kinetic energy conversion, which is demonstrated by enhancement in $C(K_Z, K_E)$ and $C(A_E, K_E)$ during intensification. Similar to last case, in this case also during its life time baroclinic energy conversions appears to dominate over barotropic energy conversions.

4.3 Severe Cyclonic Storm - HELEN (19th- 22nd November 2013)

4.3.1 Observed track

The observed track of the SCS HELEN has been shown in Fig. 3(a). From the observed track, following salient features can be brought out:

(i) It changed its direction of movement from west-northwest and moved west-south-westward 12 hrs before landfall

(ii) It weakened slightly before landfall and rapidly after the landfall and hence caused less rainfall over coastal Andhra Pradesh.

(iii) Under its influence rainfall at most places with isolated heavy to very heavy rainfall occurred over coastal Andhra Pradesh.

4.3.2 Life cycle and Movement

This intense cyclonic vortex was initially formed as a low pressure area over southeast and adjoining central Bay of Bengal on 18th November under the influence of a trough at mean sea level lay over Andaman Sea on 17th November. It rapidly concentrated into a Depression over west-central Bay of Bengal about 500 kms southeast of Vishakhapatnam at 0000UTC of 19th November. It further intensified into a Deep Depression at 1500UTC of 19th. Moving westwards it intensified into Cyclonic Storm (HELEN) with centre at about 310 kms south-south-east of Vishakhapatnam at 0300UTC of 20th. It moved west-northwestwards, intensified into a Severe Cyclonic Storm (HELEN) on 21st November.

Further moving northwestwards, it crossed Andhra Pradesh coast close to south of Machilipatnam between 0800 and 0900UTC of 22nd, and weakened into a Deep Depression on same evening. It became depression on 22nd and subsequently low pressure area on 23rd.

4.3.3 Energetics Profile

Figs. 3 (b-k) show the day-to-day variation in the A_E , A_Z , K_Z , K_E , and their generations and inter conversions i.e. $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$, $C(A_Z, A_E)$ during the period from 2 days prior to the initiation till the dissipation of the SCS HELEN. From the above figures it can be seen that similar to last two cases, in this case also maximum intensification appears to be associated with an enhancement in K_E , which is again due to the enhancement in both barotropic and baroclinic eddy energy conversion into K_E . It can be observed that there is a steady increase in $[C(A_Z, K_Z)]$ during intensification. From its expression, it is clear that $C(A_Z, K_Z)$ represents the strength of mean meridional circulation. Thus the intensification of HELEN has helped in the strengthening of mean meridional circulation during the post-monsoon season over this

particular longitudinal belt.

It can also be seen that although $[C(A_Z, A_E)]$ remained positive during the entire life cycle of this system, which suggests that there was significant influence of the mid-latitude baroclinic circulation on the development, intensification and movement of 'HELEN'. As has been observed in the last two cases, in this case also, dissipation of AE and AZ continued till the system became unimportant. Intensification of this system appears to be associated with an enhancement in the baroclinic eddy kinetic energy conversion, as is revealed from the figure of temporal variation of $C(A_E, K_E)$ during the intensification. In this case also it is clear that most of the days during its life time baroclinic energy conversions dominate over barotropic energy conversions.

4.4 Very Severe Cyclonic Storm – LEHAR (23rd - 29th November 2013)

4.4.1 Observed track

Observed track of VSCS LEHAR is shown in Fig. 4(a). Following broad salient features may be brought out from the above track:

- (i) It was the first severe cyclonic storm to cross Andaman and Nicobar Islands after November, 1989.
- (ii) It had second landfall near Machillipatnam as a depression.
- (iii) It rapidly weakened over the sea from the stage of very severe cyclonic storm to depression in 18 hours.

4.4.2 Life Cycle and Movement

The VSCS LEHAR initiated as a low pressure area over Sumatra coast and neighbourhood on 21st which progressed as well-marked low pressure area- Depression-Deep Depression-Cyclonic Storm- Severe Cyclonic Storm (LEHAR) and subsequently as Very Severe Cyclonic Storm 'LEHAR' at 2100 UTC of 25th. It started weakening after 27th into low pressure area on 30th November.

4.4.3 Energetics Profile

Fig. 4(b-k) depicts the day-to-day variation in the A_E , A_Z , K_Z , K_E and their generations and inter conversions i.e. $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$, $C(A_Z, A_E)$ associated with this system. The figures suggest that maximum intensification of this system was associated with an enhancement in K_E and K_Z . The enhancement in KE may be attributed to the enhancement in baroclinic eddy energy conversion into K_E only. Unlike other systems, peak intensification of this system helped in the strengthening of mean meridional circulation over the specific longitudinal belt, as it can be seen from the figure of temporal variation of $C(A_Z, K_Z)$.

From the figure of temporal variation of $C(A_Z, A_E)$, it appears that this conversion term steadily increased

during intensification, suggesting a significant influence of mid-latitude baroclinic circulation. Similar to the last three cases, in this case also dissipation of A_E and A_Z continued till the system became unimportant. From the average energy conversion values it is clear that most of the days during its life time baroclinic energy conversions such as $C(A_E, K_E)$, $C(A_Z, K_Z)$ which is of the order of $10^{-6} \text{ JKg}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ dominates over barotropic energy conversions such as $C(K_Z, K_E)$ which is of the order of 10^{-7} - $10^{-8} \text{ JKg}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$.

4.5 Very Severe Cyclonic Storm - MADI (6th - 13th December 2013)

4.5.1 Observed Track

Observed track of the VSCS 'MADI' is shown in Fig. 5(a), from which following salient features can be brought out:

- (i) It has a unique track with near northerly movement till 15.7° N and then it re-curved south-westwards to Tamil Nadu coast.
- (ii) It moved very slowly during its northward journey and speed peaked up gradually after the re-curvature to southwest.

4.5.2 Life cycle and movement

In the formative stage it appeared as a low pressure area over southeast Bay of Bengal and neighbourhood on 1st December under the influence of a trough of low at mean sea level. It concentrated into a Depression and into Deep Depression on 6th, into Cyclonic Storm and Severe Cyclonic Storm (MADI) on 7th and became Very Severe Cyclonic Storm (MADI) on 8th December. From 9th onwards it started weakening from Severe Cyclonic storm and became low pressure area on 13th.

4.5.3 Energetics Profile

Day-to-day variation in the A_E , A_Z , K_Z , K_E and their generations and inter conversions i.e. $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$, $C(A_Z, A_E)$ have been computed during the intensification and they have been shown in Figs. 5(b-k). The figure suggests that maximum intensification of this system was associated with an enhancement in K_E and K_Z . The enhancement in KE may be attributed to the sharp enhancement in both barotropic and baroclinic eddy energy conversion into KE. It can be observed that there is a steady decrease in $[C(A_Z, K_Z)]$ during intensification. From its expression, it is clear that $C(A_Z, K_Z)$ represents the strength of mean meridional circulation. Thus the intensification process of 'MADI' appears to have weakened the strength of mean meridional circulation over this particular longitudinal belt. It can also be seen that although $C(A_Z, A_E)$ remained positive during development and mature stage further it appeared as negative while weakening. Thus the result suggests that there was

some influence of the mid latitude baroclinic circulation on the developing stage of 'MADI' but there was hardly any influence during weakening stage.

$G(A_E)$ and $G(A_Z)$ are seen as diminishing steadily which implies that at the expense of A_E and A_Z system intensified. The dissipation of A_E and A_Z continued till the system became unimportant. From the average energy conversion values it is clear that most of the days during its intensification baroclinic energy conversions such as $C(A_E, K_E)$, $C(A_Z, K_Z)$ which are of the order of $10^{-6} \text{ Jkg}^{-1}\text{cm}^{-2}\text{s}^{-1}$ dominates over barotropic energy conversions such as $C(K_Z, K_E)$ which is of the order of 10^{-7} - $10^{-8} \text{ Jkg}^{-1}\text{cm}^{-2}\text{s}^{-1}$. The main energy reservoir for the development of this cyclonic system was Zonal Available Potential Energy which may be due to the warmer latitudinal belts as origin.

5. Discussions about anomalous cyclogenesis during cyclone seasons in 2013

From the information and discussions made in above section, there appears to be an anomalous cyclogenesis over North Indian Ocean in 2013. In the above section we have discussed the energetics of the 5 intense vortices (CS and above) formed over North Indian Ocean in 2013. In this section an attempt has been made to examine the causes for anomalous cyclogenetic behavior of atmosphere in 2013 over Indian longitude from an energetics perspective. For this purpose monthly area averaged Moist Static energy, CAPE, and another ten energetics parameters (as discussed earlier) have been computed over the region bounded by latitude 5°N & 25°N and longitude 55°E & 110°E for the cyclone months, viz., March, April, May, October, November, December for the years 2002-2013. Then Climatology of these parameters for the above months and monthly anomaly of these parameters (based on above mentioned climatology) have been computed and discussed in following subsections.

6. Discussion on Climatology of energetics and convective instability parameters

In this section we shall discuss the climatology of atmospheric energetics and some convective instability parameters, viz., CAPE and Sigma (pressure weighted MSE) based on 2000-2013 period. Climatology of mean monthly values of area averaged CAPE and Sigma for the months March-May and October-December are shown in Figs. 6(a-b). From the figures it can be seen that area averaged CAPE decreases from a value $4202.25 \text{ J/kg/cm}^2$ in March to $1061.17 \text{ J/kg/cm}^2$ in May and then increases to $4355.50 \text{ J/kg/cm}^2$ in Nov, decreasing afterwards to a value 3288 J/kg/cm^2 in December. From the figure it can also be seen that Sigma increases from 401230 J/kg/cm^2 in March to 404208 J/kg/cm^2 in May. It also decreases from 402619 J/kg/cm^2 in October to 401062 J/kg/cm^2 in De-

ember. Thus CAPE is more in March, October and November, whereas Sigma is more in May and October.

Climatology of mean monthly values of the energetics parameters for the months March-May and October-December are shown in Figs. 7 (a-e). Fig. 7(a) suggests that mean monthly values of A_E and A_Z for these months practically remains same with A_E varying between $3.37 \times 10^{-01} \text{ J/kg/cm}^2$ and $3.41 \times 10^{-01} \text{ J/kg/cm}^2$ and A_Z varying between 2.58 J/kg/cm^2 and 2.62 J/kg/cm^2 . Both of them are maximum in December, A_E is minimum in March, April, May and A_Z is minimum in April. From Fig. 7(b), it can be seen that climatological value of mean monthly K_E doesn't vary significantly, with minimum in October with value $4.79 \times 10^{-2} \text{ J/kg/cm}^2$ and maximum in March with value $7.49 \times 10^{-2} \text{ J/kg/cm}^2$. Fig. 7 (b) also shows that climatological value of mean monthly K_Z decreases from the value 1.28 J/kg/cm^2 in March, attains minima with value $2.88 \times 10^{-01} \text{ J/kg/cm}^2$ in May and then increases from a value $3.23 \times 10^{-01} \text{ J/kg/cm}^2$ in October, reaching at the maxima in December with value 1.32 J/kg/cm^2 . From Fig. 7(c), one can find that climatologically there is generation of A_Z in May, October and November, with maximum generation in May and minimum in October, which may be attributed to maximum heating at latitudinal belt with warm anomaly in May and minimum heating at latitudinal belt with warm anomaly in October. Maximum dissipation in March may be attributed to heating over latitudinal belt with cold anomaly. This figure also indicates that climatologically there is generation of A_E in April, May and October with maximum in May and minimum in April, where as there is dissipation in March, November and December, with maximum dissipation in December. One can see the climatological variation of mean monthly barotropic and baroclinic eddy kinetic energy conversions during cyclone periods in India in Fig. 7(d). This figure suggests that climatologically both are positive in May and October with later one dominating over the former one, both are negative in November, December and having opposite sign in March-April. Fig. 7(e) shows the climatological variation of $C(A_Z, K_Z)$ & $C(A_Z, A_E)$ during cyclone months in India. Strength of mean meridional circulation and that of the influence of mid latitude baroclinic circulation can be measured, at least qualitatively, by these two parameters, Dutta et al. (2011). From this figure it can be seen that during cyclone months the later one is very small as compared to the former one. Former one has a maximum negative value $-4.35 \times 10^{-06} \text{ J/kg/cm}^2/\text{sec}$ in March, increases steadily, attaining positive maximum value $3.09 \times 10^{-06} \text{ J/kg/cm}^2/\text{sec}$ in May and then decreases steadily till December with a negative value $-2.11 \times 10^{-06} \text{ J/kg/cm}^2/\text{sec}$. Order of magnitude of later one is $10^{-09} \text{ J/kg/cm}^2/\text{sec}$, with negative in March and December.

7. Discussion on anomalous behaviour of energetics and convective instability parameters

In this section we shall discuss the monthly anomaly of atmospheric energetics parameters and that of some convective instability parameters, viz., CAPE and Sigma (pressure weighted MSE) based on 2000-2013 period.

7.1 Moist Static Energy (MSE).

Monthly anomaly of height weighted MSE, for the individual months during Cyclone seasons (March-May & Oct-Dec) in India, based on the 2000-2013 climatology, are shown in Fig. 6(c). From the figure it is found that in 2013, the value of this parameter was above normal in all months during cyclone season. Thus above normal cyclogenesis during these two years may, at least partly, be attributed to the above normal MSE in the atmosphere. This result is in conformity with the earlier findings of Sunitha Devi et al. (2014).

7.2 Convective Available Potential Energy (CAPE)

Monthly anomaly of CAPE for the months during cyclone seasons have been shown in Figs. 6 (d). From these figures one can see that in 2010, CAPE was below normal in all months during cyclone seasons, except in March whereas in another anomalous cyclogenesis year 2013, it was above normal in all months during cyclone seasons, except in November-December. Thus anomalous cyclogenesis in 2013 may be attributed, at least partly, to the release of convective instability in the atmosphere also.

7.3 Eddy and Zonal Available Potential Energy

Monthly anomaly of these two energetic parameters for different months during cyclone season are given in Figs. 8(a-f). These figures indicate eddy available potential energy and zonal available potential energy was above normal in all months during cyclone seasons in 2013, except in March, when the former was below normal.

7.4 Eddy and Zonal Kinetic Energy

Monthly anomaly of eddy and zonal kinetic energy for different months during cyclone season are given in Figs. 9 (a-f). From these figures it can be seen that, eddy kinetic energy was below normal in these months in 2013, however it was above normal in March, April and November in 2010. But zonal kinetic energy was above normal in March, April, November and December in 2013 and in April and October in 2010.

7.5 Generation of Eddy and Zonal Available Potential Energy

Monthly anomaly of these two energetics parameters are shown in Figs. 10(a-f). These figures indicate that in 2010, both these parameters were above normal during May,

October, November and December. However in 2013, although the later one behaved similarly as in 2010, but the former one was above normal during April, May and October.

8. Barotropic Eddy Kinetic Energy Conversion and Baroclinic Eddy Kinetic Energy Conversion

Baroclinic eddy kinetic energy conversion can be represented by the energetic parameter $C(A_E, K_E)$ and Barotropic eddy kinetic energy conversion may be represented by $C(K_Z, K_E)$, Sunitha Devi et al., (2014). Monthly anomaly of these two parameters are shown in Figs. 11 (a-f). In 2010, the former one was above normal during Oct-Dec and was below normal during March-May. The later one was below normal in almost all months during cyclone season except in May. Baroclinic eddy kinetic energy conversion was above normal in almost in all months during cyclone season in 2013, except in March and Barotropic eddy kinetic energy conversion was above normal in May, November and December. So, in 2013, both the eddy kinetic energy conversions were above normal in Nov-Dec and most of the cyclonic storms and above in 2013 formed During Nov-Dec only, although magnitude of positive anomaly was more for Baroclinic eddy kinetic energy conversion, but in 2010 mainly Baroclinic eddy kinetic energy conversion dominates.

9. Strength of Mean Meridional Circulation and Influence of Mid Latitude Baroclinic Circulation

Strength of mean meridional circulation and that of the influence of mid latitude baroclinic circulation can be measured qualitatively, by two energetic parameters, viz., $C(A_Z, K_Z)$ & $C(A_Z, A_E)$, Dutta et al. (2011). Monthly anomalies of them are shown in Figs. 12(a-f). These figures indicate that $C(A_Z, A_E)$ was almost normal in all the months during cyclone seasons, however $C(A_Z, K_Z)$ was above normal during April, May, November and December in 2013. The results suggest that in 2013 there has been an anomalous strengthening of mean meridional circulation during above 4 months and mid latitude baroclinic circulation didn't have any anomalous influence in any cyclone months.

10. Conclusions

Based on the computations of the various energy characteristics of the cyclones occurred in 2013 the following may be concluded:

a. Maximum intensification of all these systems was associated with an enhancement in Eddy Kinetic Energy which may be attributed to the enhancement in both barotropic and baroclinic eddy kinetic energy conversion.

b. There was significant influence of the mid latitude baroclinic circulation on the movement during development and intensification of PHAILIN, HELEN and MADI whereas it influence the movement after intensification for VIYARU and LEHAR.

c. For all of these systems baroclinic eddy kinetic energy conversions dominates over barotropic eddy kinetic energy conversions.

d. Anomalous cyclogenesis in 2013 may, at least partly, be attributed to an above normal MSE in the atmosphere, above normal eddy available potential energy, baroclinic and barotropic eddy kinetic energy conversion and above normal release of convective instability during cyclone months over the region under study.

e. Climatologically CAPE has been found to be more in March, October and November, whereas for Sigma, it is in May and October.

f. Climatologically, none of A_z , K_E and A_E vary significantly in the months during cyclone season. Climatologically K_z decreases from March, attains minima in May and then increases from October, reaching at the maxima in December. Order of magnitude of A_z is 10^0 J/kg/cm², that of K_z varies from 10^{-01} - 10^0 J/kg/cm² and that of K_E is 10^{-01} J/kg/cm².

g. Climatologically there is generation of A_z in May, October and November, with maximum generation in May and minimum in October and there is generation of A_E in April, May and October with maximum in May.

h. Climatologically both baroclinic and barotropic eddy kinetic energy conversion are positive in May and October with later one dominating over the former one, both are negative in November, December and having opposite sign in March-April.

i. Eddy available potential energy and zonal available potential energy was above normal in all months during cyclone seasons in 2013, except in March, when the former was below normal.

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