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Energetics of super cyclone 'GONU' and very severe cyclonic storm 'SIDR'

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सार – इस शोध पत्र में वर्ष 2007 के दौरान उत्तरी हिंद महासागर में बने दो उष्णकटिबंधीय चक्रवातों नामतः महाचक्रवाती तूफान (जी. ओ. एन. यू.) और अति प्रचंड चक्रवाती तूफान (एस. आई. डी. आर.) के ऊर्जात्मक पहलुओं पर विचार विमर्श किया गया है। भंवर प्राप्य विभव ऊर्जा (A_E), क्षेत्रीय प्राप्य विभव ऊर्जा (A_Z), क्षेत्रीय गतिक ऊर्जा (K_Z), भंवर गतिक ऊर्जा (K_E) तथा उनके उत्पादन और अंतः रूपांतरण नामतः $G(A_E)$, $G(A_z)$, $C(A_E\ K_E)$, $C(A_Z\ K_Z)$, $C(K_Z\ K_E)$, और $C(A_Z\ A_E)$, जैसी विभिन्न ऊर्जात्मक संदर्भों में इनका विश्लेषण किया गया। 'GONU' के लिए 5° उ. से 25° उ., 55° पू. से 75° पू. तथा 'SIDR' के लिए 5° उ. से 25° उ., 77° पू. से 97° पू. के क्षेत्र में इनकी तीव्रताओं की अवधियों के दौरान दिन प्रतिदिन के आधार पर इनका आकलन किया किया गया। उपर्युक्त आकलनों के अलावा प्रतिदन (sigma) के क्षेत्रीय औसत मान, उर्ध्वाधर औसत आर्द्र स्थैतिज ऊर्जा (MSE) का भी आकलन किया गया। इन प्राचलों के दैनिक क्रम विकास का मानचित्रण करके इनकी व्याख्या की गई हैं। इन दो तीव्र भ्रमिलों की ऊर्जात्मकता के कुछ प्रमुख अभिलक्षणों कों प्रस्तुत किया गया है जो पूर्णतः अलग जलवायविक वातावरण में बने हैं। 'GONU' के विषय में यह देखा गया है कि अपने जीवन चक्र के दौरान बैरोट्रापिक और बैरोक्लीनिक दोनों ऊर्जा प्रतिलोमन बने हैं, इनकी तीव्रता के क्रम को $A_E\ K_E$ में संवर्धन और उर्ध्वाधर रूप से समाकलित आर्द्र स्थैतिज ऊर्जा द्वारा अभिलक्षित किया गया है। A_E में संवर्धन को A_E की उत्पत्ति के साथ जोड़ा जा सकता है जैसे पुनः चक्रवात क्षेत्र के असममित वर्षा के साथ संबंद्ध सांद्रता के असममित गुप्त ऊष्मा के साथ जोड़ा जा सकता है। K_E के संवर्धन को K_E में दोनों बैराट्रापिक और बैरोक्लीनिक प्रतिलोमन में संवर्धन के साथ जोड़ा जा सकता है। हालांकि 'GONU' के लिए किए गए अधिकांश प्रेक्षण 'SIDR' के साथ भी मेल खाते हुए पाए गए है, 'SIDR' की तीव्रता में प्रतिरूपी वर्धित मध्य अंक्षाश बैरोक्लीनिक तरंग जैसी समानताएँ देखी गई हैं। इस मामले में, A_E के संवर्धन को भी सकारात्मक $C(A_Z\ A_E)$, के साथ जोड़ा जा सकता है जो मुख्यतः मध्य अक्षांश बैरोक्लीनिक पश्चिमी तरंग के साथ परस्पर क्रिया से उत्पन्न होते हैं। ऊर्जात्मक विश्लेषण से यह भी पता चलता है कि 'GONU' ने मौसमी माध्य याम्योतरी परिसंचरण के संवर्धन में सहयोग दिया है इसके विपरित 'SIDR' ने मौसमी माध्य याम्योतरी परिसंचरण में संवर्धन को रोका है।

ABSTRACT. This paper discusses the energetics aspects of two tropical cyclones formed over the north Indian Ocean during 2007, *viz*., the Super Cyclonic Storm (GONU) and the Very Severe Cyclonic Storm (SIDR). From the analysis of various energetics terms such as 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 generation and inter-conversions *i.e*., $G(A_E)$, $G(A_Z)$, $C(A_E, K_E)$, $C(A_Z, K_Z)$, $C(K_Z, K_E)$ and $C(A_Z, A_E)$ have been computed on day to day basis during the periods of their intensifications over the domain 5° N to 25° N, 55° E to 75° E in respect of 'GONU' and 5° N to 25° N, 77° E to 97° E for 'SIDR'. Besides the above, the area averaged value of σ (Sigma), the vertically averaged Moist Static Energy (MSE), has also been computed on each day. Day-to-day evolution of these parameters is mapped and described. Some of the distinguishing features in the energetic of these two intense vortices which formed in entirely different climatological settings have been brought out. It is noticed that in the case of 'GONU', though both barotropic and baroclinic energy conversions have taken place during the life cycle, the intensification phase is characterized by an enhancement in A_E, K_E and vertically integrated Moist Static Energy. Enhancement in A_E can be attributed to the generation of A_E, which may again be attributed to the asymmetric latent heat of condensation associated with the asymmetric rainfall in the cyclone field. Enhancement in K_E may be attributed to the enhancement in both barotropic and baroclinic conversion into K_E. Though most of these observations made for 'GONU' are found to be attributable to 'SIDR' as well, the intensification of 'SIDR' appears to have more similarity to that of a typical growing mid-latitude baroclinic wave. In this case, the enhancement in A_E, could also be attributed to positive $C(A_Z, A_E)$, which is mainly due to interaction with mid-latitude baroclinic westerly wave. The energetics analysis also indicates that GONU had helped in the enhancement of seasonal mean meridional circulation where as the SIDR had inhibited the enhancement of seasonal mean meridional circulation.

Key words – Energetics, GONU, SIDR.

1. Introduction

Tropical cyclones are one of the most devastating weather phenomena, causing great loss to life and damage to property. In order to have a better prognosis of the track and intensity of these systems, it is essential to understand the energy conversions taking place within the system environment which in turn might lead to its intensification or weakening.

The energetics aspects of tropical cyclones with regard to their genesis, intensification and movement, have been a subject of extensive study by various research workers. The first reasonably accurate description of the energy cycle of cyclonic storms is found in the study of Riehl (1950). Kleinschmidt (1951) pointed out that heat removed from the sea by the storm is the basic energy source of tropical cyclones. Riehl (1954) described hurricanes as heat engines and showed that for the air ascending in the eye-wall to be appreciably warmer than that of the distant environment, a condition for conversion of potential energy to kinetic energy, the inflowing air has to acquire enthalpy from the underlying surface. Frank (1977) argued that 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. He also argued that tropical cyclones act as strong sources of Kinetic Energy (K.E) which can play important roles in the energetics of the general circulation. Sechrist & Dutton (1970) showed that a cyclonic storm initially acquired K.E in the lowest layers southwest of the center and later, the largest K.E increases occurred south of the center at intermediate levels. By the time the system reached maturity, the largest increases were taking place at higher levels northeast of the storm while K.E decreases occurred below.

Estimates of kinetic energy in the field of extra tropical and tropical cyclones have been obtained, among others, by Vincent & Chang (1975) and Kornegay & Vincent (1976). Krishnamurti (1979) has shown that the movement and the intensity of the cyclones in the tropics depend mostly on Sea Surface Temperature (SST). George & Mishra (1993) had examined the temporal variations of the zonal and eddy kinetic and available potential energy in association with the formation, growth and maintenance of a monsoon onset vortex. Their study indicated that barotropic eddy energy transfer dominates over baroclinic eddy energy transfer. Mahbub Alam *et al.*, (2003) have shown that the role of energy fluxes is to govern the atmospheric circulation as well as the physical processes for formation of the Tropical cyclones. Study of K.E in the field of mid tropospheric cyclonic circulations (previously known as MTCs) has also been done by Bhagat (2005).

Hsu *et al*., (2009) studied the interaction between the seasonal mean circulation and the transient eddies over the Western North Pacific (WNP) during El Ninõ-Southern Oscillation (ENSO) warm and cold years by deducing the three dimensional Eddy Kinetic Energy (EKE) and Eddy Available Potential Energy (EAPE) budget equations for total eddy, highfrequency (< 10 days) and low frequency (20-70 days) components. Composites of the energy results indicate that low level anomalous cyclonic circulation, westerly jet and ascending motion associated with the eastward extension of warm SST during warm ENSO years are favorable for eddy barotropic energy conversion (CK) and eddy baroclinic energy conversion (CE). The enhancement of CK and CE might provide KE for the growth of high and low frequency transient eddies including Tropical Storms (TSs) from the Philippine Sea to the date line over the tropical WNP during warm ENSO years. In contrast, high - and low-frequency eddies convert EKE 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 EAPE to EKE due to the eddy baroclinic energy conversion is mainly supplemented by the generation of EAPE associated with eddy diabatic heating. However, the energy conversion from Mean Available Potential Energy (MAPE) to EAPE is also important due to the eddy vertical heat transport which is neglected in the two-dimensional EAPE 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. Maloney & Hartmann (2001) showed that when the 850 hPa wind anomalies associated with the Madden-Julian Oscillation (MJO) are westerlies, small-scale, slow-moving eddies grow through barotropic EKE conversion from the mean flow. They also showed that these growing eddies, together with strong surface convergence, 850 hPa cyclonic shear and high mean SSTs, create a favourable environment for tropical cyclone formation. Periods of strong MJO easterlies over the Pacific are characterized by lesser EKE and negligible eddy growth by barotropic conversion.

Over the Indian Seas, major tropical cyclone periods are the pre and post monsoon seasons. This study focuses on the energetic aspects of two intense cyclonic storms formed over the Indian Seas during 2007, *viz*., the Super Cyclonic Storm 'GONU' which formed over the Arabian Sea and the Very Severe Cyclonic Storm 'SIDR' which formed over the Bay of Bengal. From the historic records of India Meteorological Department on cyclones and depressions since 1877, it is evident that 'GONU' was the first ever cyclonic storm which attained the intensity of a Super Cyclonic Storm over the Arabian Sea. Its life cycle was during 1-7 June 2007. Though this system formed in the cyclonic shear zone at the leading edge of the monsoon current, it caused a hiatus in the further advance of southwest monsoon along the west coast, subsequent to its intensification. In 2007 the onset of Southwest monsoon over Kerala was on 28th May as against its normal date of 1st June. But arrival of Southwest monsoon over Mumbai was on 18th June showing a delay of 8 days (normal onset date is 10th June). The Very Severe Cyclonic Storm 'SIDR' formed over the Bay of Bengal in the post monsoon season of 2007. Its life cycle was during 11-15 November 2007. Preliminary analysis and synoptic charts showed that this formation had been aided by the mid-latitude westerly field. Thus it is noticeable that the environmental and dynamical factors leading to the growth of these two tropical disturbances could be different.

It appears that till date hardly there is any study on the energetics aspects of the above two storms. Objective of the present study is to understand and compare the dynamics of these two storms from the energetics point of view.

2. Data

For this study, temperature (*T*), three components of wind (*u*, *v*, ω), geopotential height (*z*), relative humidity (rh) at different levels from 1000 hPa to 100hPa at 1° × 1° grid over the region from 5° N to 25° N and from 50° E to 70° E for 'GONU' and over the region from 5° N to 25° N and from 77° E to 97° E for 'SIDR' during their respective life - cycle have been used. These data are downloaded from the NCEP website https://dss.ucar.edu/datazone/dsszone/ds083.2.

3. Methodology

From the temperature data, at each grid point, heating rate $\frac{\dot{Q}}{C_p}$ has been computed using first law of thermodynamics $\frac{\dot{Q}}{C_p} = \frac{dT}{dt} - \frac{\alpha}{C_p}\omega$. In the computation of $\frac{dT}{dt}$, tendency has not been taken care of. Then, following Krishnamurti and Bounoua (2000), 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 as below:

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

$$\text{Area average : } \overline{S} = \frac{1}{\sin\varphi_n - \sin\varphi_s} \int_{\varphi_s}^{\varphi_n} S \cos\varphi \, d\varphi \tag{2}$$

$$\text{Departure from area average : } S'' = S - \overline{S} \tag{3}$$

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

Departure of zonal average from area average : $S^* = [S] - \overline{S}$ (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 as below:

$$(A_z) = \int_{100}^{P_s} \frac{\overline{T^{*2}}}{2\sigma} \, dp \tag{6}$$

$$(A_E) = \int_{100}^{P_s} \frac{\overline{T'^2}}{2\sigma} \, dp \tag{7}$$

where, σ is the static stability parameter of the atmosphere.

$$K_Z = \frac{1}{2g} \int_{100}^{P_s} \overline{\left([u]^2 + [v]^2\right)} \, dp \tag{8}$$

$$K_E = \frac{1}{2g} \int_{100}^{P_s} \overline{\left(u'^2 + v'^2\right)} \, dp \tag{9}$$

$$[C(A_z, A_E)] = -\int_{100}^{P_s} \left[\overline{\frac{1}{\sigma} v'T' \frac{\partial T^*}{a\partial \phi}} + \overline{\frac{1}{\sigma} \omega' T' \frac{\partial T^*}{\partial p}} \right] dp \tag{10}$$

$$[C(K_z, K_E)] = \frac{1}{g} \left\{ \begin{array}{l} \int_{100}^{P_s} \left[\overline{\cos\varphi\, u'v' \frac{\partial}{a\partial\varphi} \left[\frac{[u]}{\cos\varphi} \right]} \right] dp \\ + \int_{100}^{P_s} \left[\overline{v'^2 \frac{\partial [v]}{a\partial\varphi}} \right] dp + \int_{100}^{P_s} \overline{\frac{\tan\varphi}{a} u'^2 [v]}\, dp \\ + \int_{100}^{P_s} \left[\overline{\omega' u' \frac{\partial [u]}{\partial p}} \right] dp + \int_{100}^{P_s} \left[\overline{\omega' v' \frac{\partial [v]}{\partial p}} \right] dp \end{array} \right\} \tag{11}$$

$$[C(A_E, K_E)] = -\frac{1}{g} \int_{100}^{P_s} \frac{R}{p} \overline{\omega' T'}\, dp \tag{12}$$

$$C(A_Z, K_Z) = -\frac{1}{g} \int_{100}^{P_s} \frac{R}{p} \overline{\omega^* T^*}\, dp \tag{13}$$

$$G(A_z) = \frac{R_d}{C_p} \oint \frac{(\theta)^* (Q)^*}{p\left(-\frac{\partial \bar{\theta}}{\partial p} \right)} dm \tag{14}$$

and

$$G(A_E) = \frac{R_d}{C_p} \oint \frac{\theta' Q'}{p\left(-\frac{\partial \bar{\theta}}{\partial p} \right)} dm \tag{15}$$

Moist Static Energy (MSE_i) given by $MSE_i = C_p T_i + g z_i + L q_i$, has been computed at each grid point and at each level from 1000 hPa to 100 hPa. Then the pressure weighted vertical average of MSE has been computed at each grid point. And then the area average of the above (σ) have been computed. The above mentioned computed parameters have been compared on day-to-day basis.

4. Results & discussion

The results obtained for the two storms are discussed separately in the following sections.

4.1. *Super cyclonic storm 'GONU'*

4.1.1. *Synoptic history*

Initially the super cyclonic storm 'GONU' was seen as a low pressure area over East Central Arabian Sea on 1st June, 2007. It intensified into a cyclonic storm on 2nd June and started moving in a westerly direction. The cyclonic storm intensified into a severe cyclonic storm and then to a very severe cyclonic storm on 3rd & 4th June. 'GONU' intensified very rapidly from 3rd June to the early hours on 4th June reaching Category 5 intensity (with 140 knot wind speed). The system intensified into a super cyclonic storm at 1500 UTC of 4th June. This was also associated with rapid northerly movement. On 5th June, the super cyclone weakened into very severe cyclonic storm. Subsequently it crossed the coast of Oman on 6th morning. Thereafter it emerged into the gulf of Oman and was moving in a northwesterly direction. It weakened into a severe cyclonic storm on 7th at 2100 UTC and later weakened further into a cyclonic storm at 0300 UTC and crossed the Makran coast. Thus intensification of this cyclonic vortex into Cyclonic Storm and subsequently into Severe Cyclonic Storm, Very Severe Cyclonic Storm and ultimately into a Super Cyclonic Storm took place during 2-4 June, 2007 and thereafter it started weakening from 5th June, 2007. The track of the system is given in Fig. 1(a).

4.1.2. *Energetics profile*

Day-to-day variation in the area averaged 'σ' has been shown in Fig. 2(a). It is seen that during intensification stage, σ increased steadily from 1st to 5th June, 2007 and subsequently it decreased steadily during its weakening stage till 7th June. Enhancement in σ may be attributed to an enhancement in enthalpy and latent heat. Figs. 2(b&c) suggest that maximum intensification was also associated with an enhancement in A_E and K_E. Enhancement in A_E can be attributed to generation A_E, which may again be attributed to asymmetric latent heat of condensation field associated with asymmetric rainfall in the cyclone field and enhancement in K_E may be attributed to the enhancement in both the barotropic and baroclinic conversion into K_E. 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.

Energy flow diagrams for 'GONU' during 1-6 June, 2007 are given in Fig. 3. These diagrams indicate

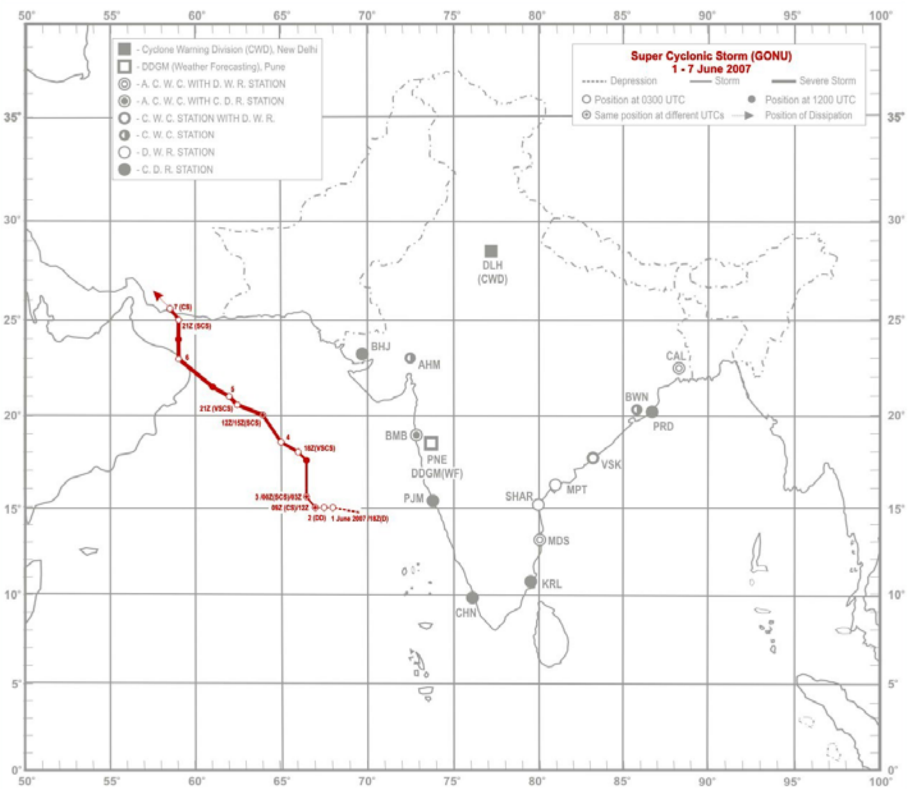


Fig. 1(a). Track of GONU

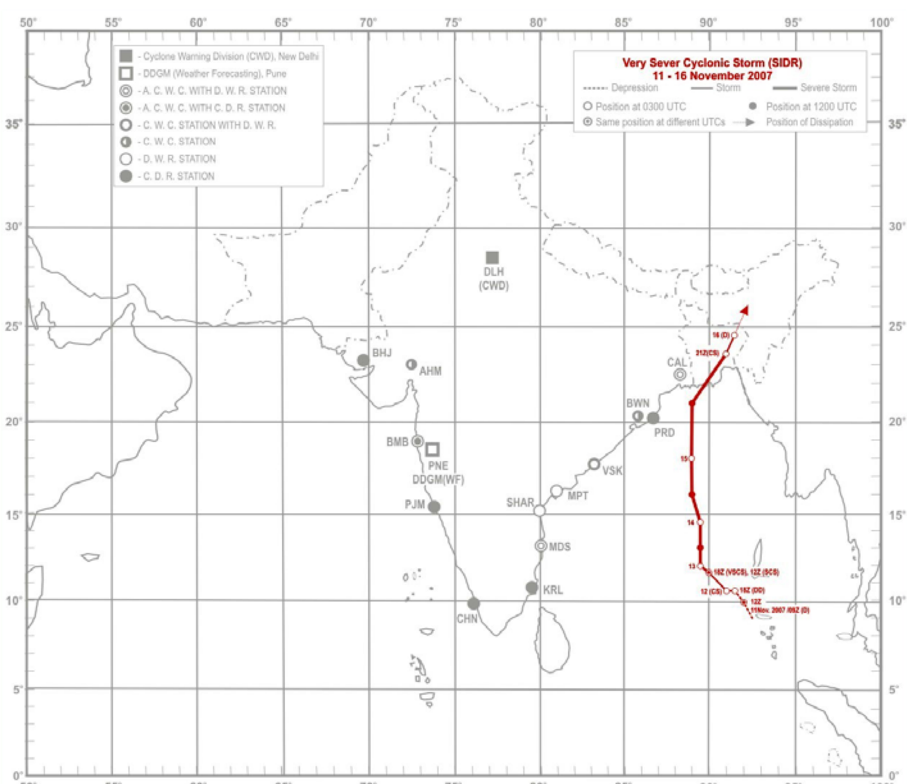
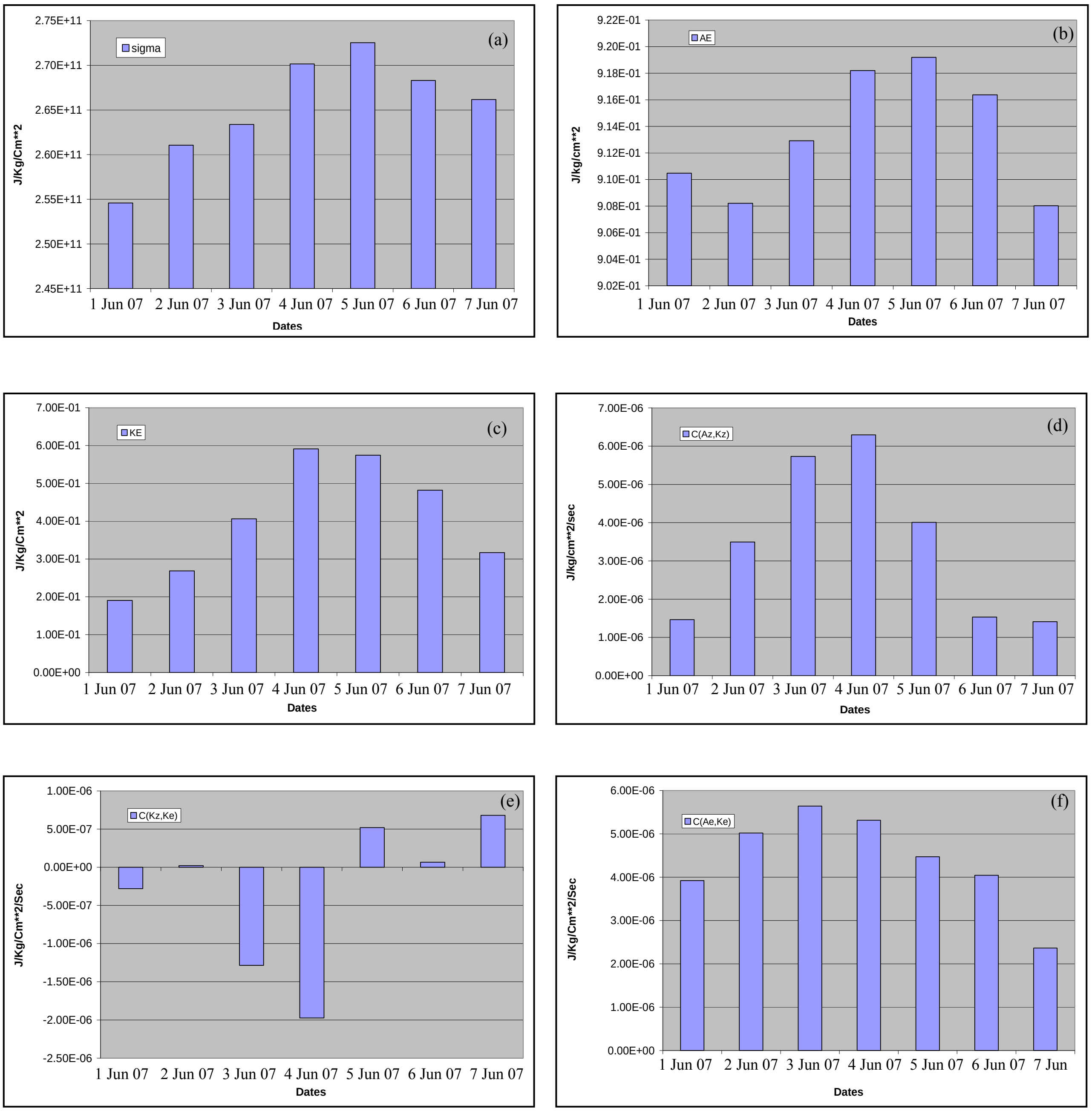


Fig. 1(b). Track of SIDR



Figs. 2(a-f). Daily variation of (a) sigma, (b) A_E, (c) K_E, (d) Time evolution of C(A_Z, K_Z) for GONU, (e) Daily variation of $C(K_Z, K_E)$ and (f) Time evolution of $C(A_E, K_E)$ of energy parameters in case of super cyclone 'GONU' over Arabian Sea

conversion to K_E from both A_E and K_Z. These suggest the presence of both barotropic and baroclinic energy conversion processes, during the intensification. From these figures it also appears that the barotropic energy conversions ($K_Z \leftrightarrow K_E$) are of the order of 10^{-8}–10^{-6} Jcm^{-2}s^{-1}, whereas the baroclinic energy conversions ($A_Z \leftrightarrow K_Z$ & $A_E \leftrightarrow K_E$) are of the order of 10^{-6}Jcm^{-2} s^{-1}. Thus on most days barotropic energy conversion is being dominated by baroclinic energy conversion. So during the genesis and initial period of intensification and northwestward moving phase, the main energy reservoir was the A_Z, which was due to net heating of relatively warmer northern latitudinal belt & the energy flow was $A_Z \rightarrow A_E \rightarrow K_E$ and $A_Z \rightarrow K_Z$. In the mature stage of intensification the main energy reservoir was A_E and the energy flow was $A_E \rightarrow K_E \rightarrow K_Z$ and $A_E \rightarrow A_Z$. During

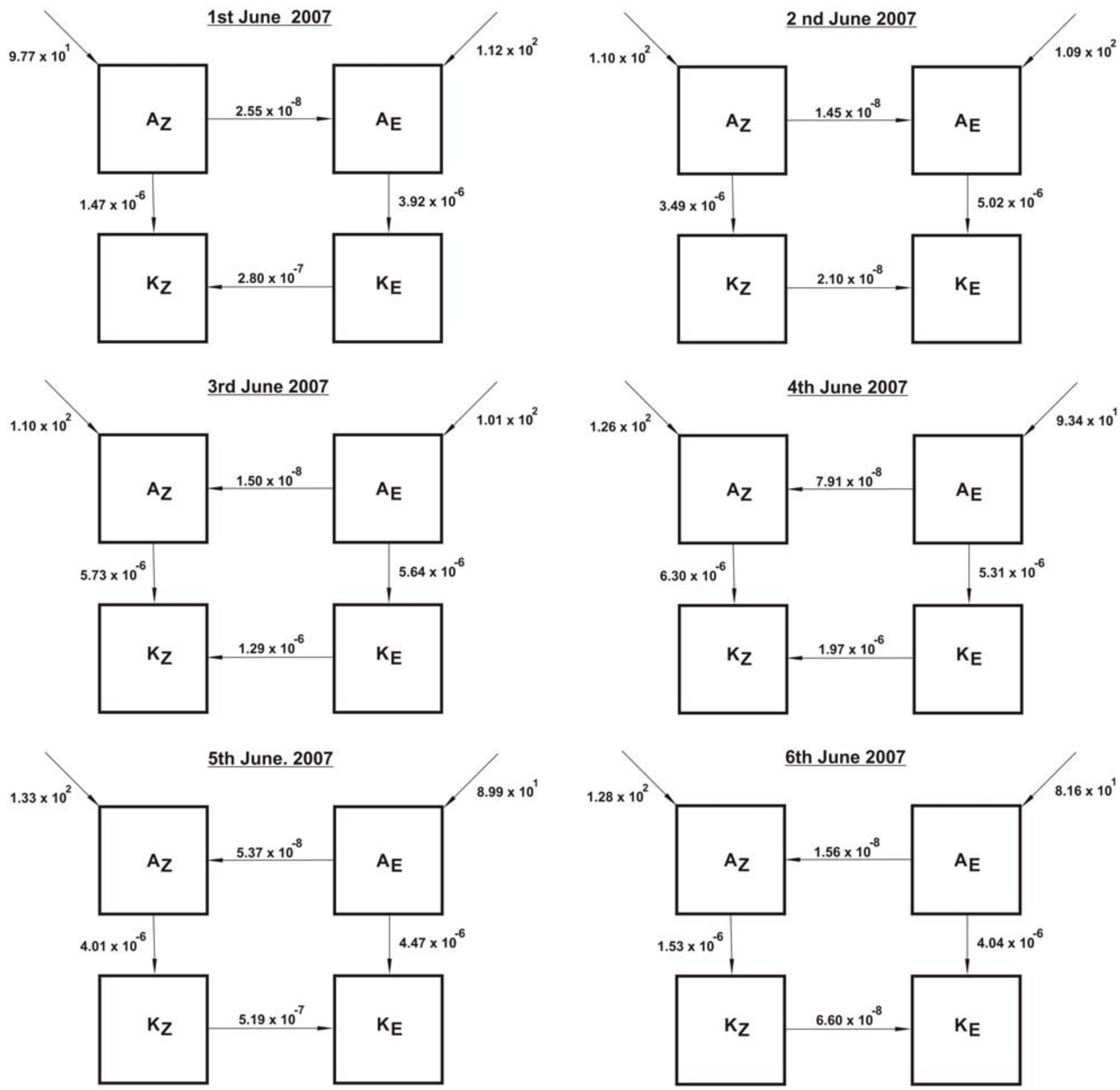
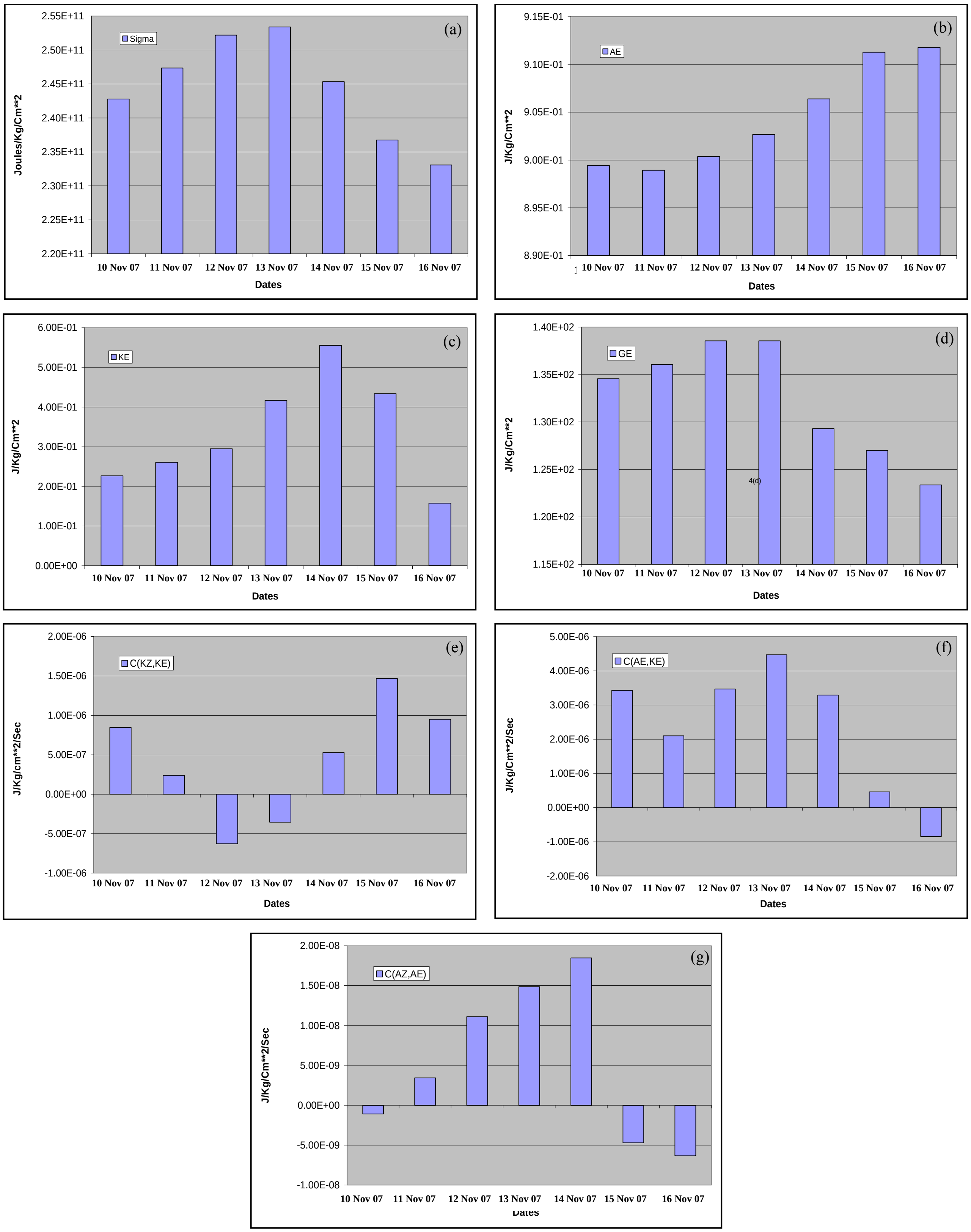


Fig. 3. Energy flow diagram for 'GONU' during 1-6 June, 2007

the weakening phase, the energy flow was $A_Z \rightarrow K_Z \rightarrow K_E$, $A_E \rightarrow K_E$ and $A_E \rightarrow A_Z$.

Another interesting point to note here is 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, which is due to rising motion over warm latitudinal zone and sinking motion over cold latitudinal zone. Thus mean meridional circulation during the summer monsoon season is observed to be strengthened over this particular longitudinal belt at the time of intensification of 'GONU'. It can also be seen that although the conversion of zonal available potential energy to eddy available potential energy [$C(A_Z, A_E)$] remained positive on 1st & 2nd June, it started decreasing in magnitude from 2nd June and remained negative for the remaining days, with large fluctuations in magnitude upto 6th June. Positive values in $C(A_Z, A_E)$ indicates the influence of the mid latitude baroclinic circulation [Dutta *et al.*, (2011)]. Thus the result



Figs. 4(a-g). Daily variation of (a) Sigma, (b) A_E, (c) K_E, (d) G_E, (e) $C(K_Z, K_E)$, (f) $C(A_E, K_E)$ and (g) $C(A_Z, A_E)$

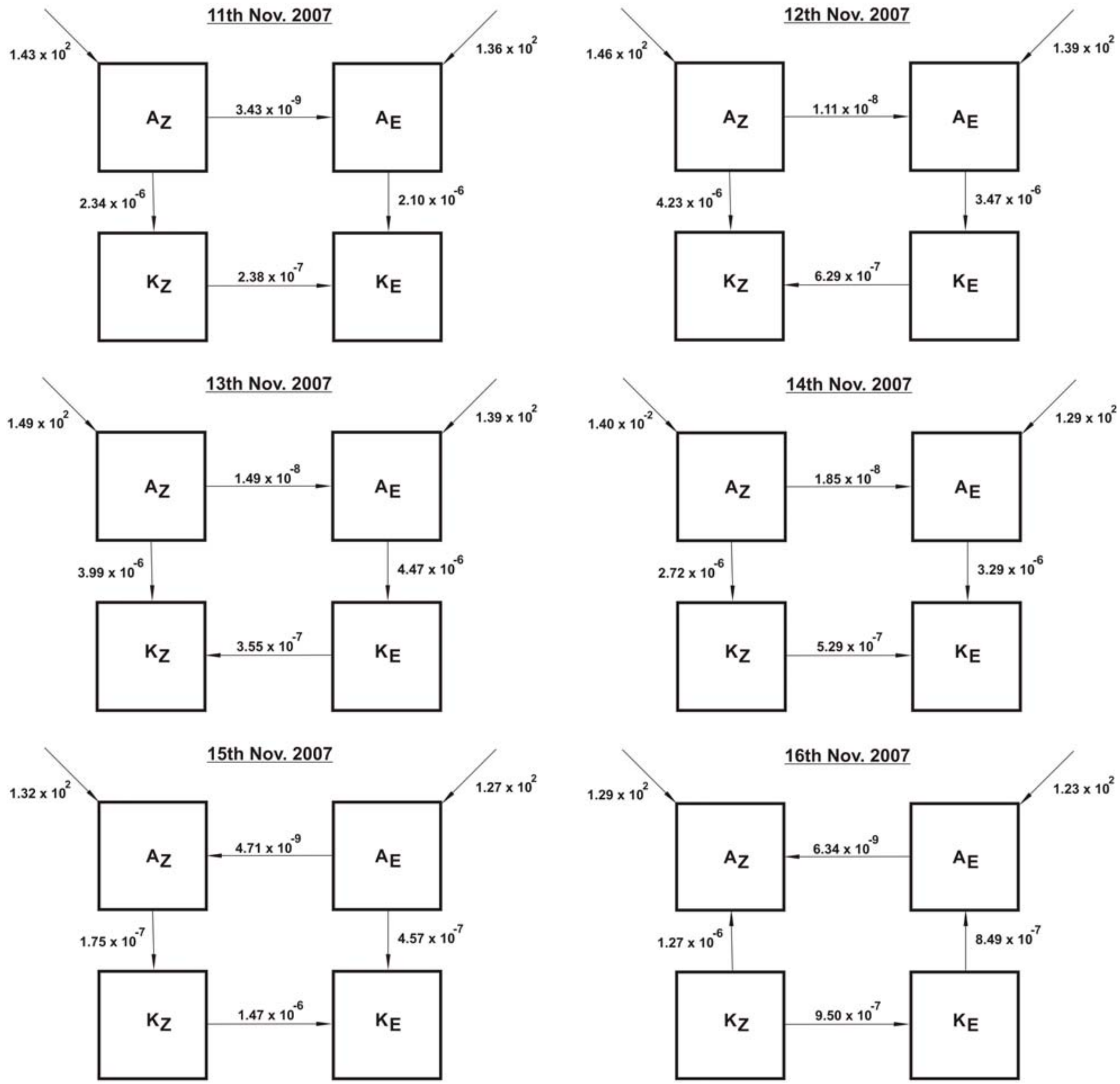


Fig. 5. Energy flow diagram for 'SIDR' during 11-16 November, 2007

suggests that hardly there was any significant influence of the mid latitude baroclinic circulation on the intensification or movement of 'GONU'.

4.2. *Very Severe Cyclonic Storm 'SIDR'*

4.2.1. *Synoptic history*

An upper air cyclonic circulation lay over southeast Bay of Bengal and adjoining south Andaman Sea during 8-10 November, 2007. Initially moderate upper-level wind shear inhibited organisation of the system, while strong diffluence aloft aided in developing convection. During this period, easterly wave was also active and vertical wind shear decreased significantly as the circulation became better defined. Under the influence of these factors, a low pressure area formed at 0300 UTC of 11th November over southeast Bay of Bengal and neighbourhood. It concentrated into a depression and subsequently into a deep depression on the same day.

Moving in a northwesterly direction, it intensified into cyclonic storm 'SIDR' and lay centred at 0300 UTC of 12th November, about 220 km southwest of Port Blair. It further intensified into severe cyclonic storm at 1200 UTC and very severe cyclonic storm at 1800 UTC, while moving in a north-northwesterly direction. It continued to move in north-northwesterly direction till 0000 UTC of 13th. It then moved in a northerly direction and lay centred at 0300 UTC of 15th November near Lat. 18.0° N & Long. 89.0° E, about 530 km south of Kolkata. The system then moved rapidly and lay centred at 1200 UTC of 15th November near Lat. 21.0° N and Long. 89.0° E, about 200 km south-southeast of Kolkata. It then started to move north-northeastwards and crossed west Bangladesh coast around 1700 UTC near longitude 89.8° E and lay centred at 1800 UTC near Lat. 22.5° N & Long 90.5° E, about 100 km south of Dhaka, Bangladesh. It weakened rapidly into a cyclonic storm, while moving northeastwards. It further weakened into a depression and lay centred at 0300 UTC of 16th November, about 50 km north of Agartala. It lay as well marked low pressure area over northeastern states at 1200 UTC of 16th November and became unimportant at 1500 UTC of the same day. The track followed by this system is shown in Fig. 1(b).

4.2.2. *Energetics profile*

Time evolutions of different energetic parameters are shown in Figs. 4(a-g). Similar to the previous case, here also σ increases steadily till 13th November during the intensification phase of 'SIDR', which again may be attributed to an enhancement in enthalpy and latent heat. These figures also suggest that, similar to earlier case in the case of 'SIDR' also maximum intensification was associated with an enhancement in A_E and K_E. Enhancement in A_E can be attributed to generation A_E, which may again be attributed to asymmetric latent heat of condensation field associated with asymmetric rainfall in the cyclone field and enhancement in K_E may be attributed to the enhancement in both the barotropic and baroclinic conversion into K_E. Baroclinic eddy energy conversion is due to the upward movement of relatively warmer air inside the clouds and downward movement of relatively colder air outside. Unlike the previous case, in this case the intensification was also associated with a steady increase in $C(A_Z,A_E)$ and a steady decrease in $C(A_Z, K_Z)$.

Energy flow diagram for 'SIDR' for the period 11-16 November, 2007 is shown in Fig. 5. These diagrams indicate conversion to K_E from both A_E and K_Z. These suggest the presence of both barotropic and baroclinic energy conversion processes, during intensification. From these figures it also appear that on most days barotropic energy conversion is being dominated by baroclinic energy conversion.

Another interesting point to note that during 12-14 November, *i.e.*, during initial phase of intensification, a steady decrease in $C(A_Z, K_Z)$ was observed. From its expression, it is clear that $C(A_Z, K_Z)$ represents the strength of mean meridional circulation, which is due to rising motion over warm latitudinal zone and sinking motion over cold latitudinal zone. Thus mean meridional circulation, *i.e.*, Hadley circulation during the northern post monsoon season, is observed to be weakened during the intensification of 'SIDR'. It can also be seen that during the intensification of 'SIDR' the conversion of zonal available potential energy to eddy available potential energy $C(A_Z, A_E)$ has increased steadily up to 14th November. Thus, the mid latitude baroclinic circulation might have influenced significantly on the intensification as well as movement of 'SIDR' [Dutta *et al*., (2011)].

4.3. *Energetics comparison between* "*SIDR and GONU*"

From the foregoing discussion the following comparison Table can be made.

Super cyclone 'GONU' in Arabian Sea	*V S C S 'SIDR' in Bay of Bengal*
Similarities	
Baroclinic energy conversion was dominating over Barotropic energy conversion.	Baroclinic energy conversion was dominating over Barotropic energy conversion.
The maximum intensification was associated with an enhancement in A_E, K_E, and vertically integrated MSE.	The maximum intensification was associated with an enhancement in A_E, K_E and vertically integrated MSE.
Enhancement in A_E can be attributed to generation A_E, which may again be attributed to asymmetric latent heat of condensation field associated with asymmetric rainfall in the cyclone field.	Enhancement in A_E can be attributed to generation A_E, which may again be attributed to asymmetric latent heat of condensation field associated with asymmetric rainfall in the cyclone field and also to positive C (A_Z, A_E) which is mainly due to interaction with midlatitude baroclinic westerly wave.
Enhancement in K_E may be attributed to the enhancement in both the barotropic and baroclinic conversion into K_E.	Enhancement in K_E may be attributed to both barotropic and baroclinic conversion into K_E, although the later one dominated the former one.

Dissimilarities	
Energetics during intensification phase appears to be similar to that of southwest monson circulation.	Energetics during intensification phase appears to be similar to that of a typical growing mid-latitude baroclinic wave.
During intensification of GONU, seasonal mean meridional circulation appeared to have enhanced	During intensification of SIDR, seasonal mean meridional circulation appeared to have reduced.

5. Conclusions

The Super Cyclonic Storm ‘GONU’ formed in the cyclonic shear zone of the low level jet over the Arabian Sea during the onset phase of southwest monsoon. The Very Severe Cyclonic Storm ‘SIDR’ formed in an active easterly wave trough aided by the upper level diffluence provided by the baroclinic wave in mid-latitude upper tropospheric westerly mean flow.

Based on the computation of various energy characteristics of the above two intense vortices the following may be concluded:

(*i*) For both the systems, baroclinic energy conversion was observed to be dominating over the barotropic energy conversion.

(*ii*) For both the systems, intensification observed to be associated with steady increase in A_E, K_E and σ (vertically integrated MSE).

(*iii*) For both the systems enhancement in K_E may be attributed to the enhancement in both the barotropic and baroclinic conversion into K_E.

(*iv*) For both the systems enhancement in σ, may be attributed to enhanced enthalpy, enhanced updraft and moisture content.

(*v*) Baroclinic energy conversion remained to be the significant contributor in the development of ‘SIDR’ implying the role played by the mid-latitude wave in the upper tropospheric westerlies.

(*vi*) During the intensification of ‘GONU’, mean meridional circulation got strengthened whereas same appeared to be weakened during the intensification of ‘SIDR’.

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