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Barotropic energetics analysis of tropical cyclone Khai Muk

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सार – इस शोध पत्र में 11–14 नवम्बर 2008 के दौरान बंगाल की खाड़ी में बनने और उसके आगे बढ़ने वाले उष्णकटिबंधीय चक्रवात कैमुक की गतिकीय स्थितियों के विशलेषण पर विचार–विमर्श किया गया जो निचले स्तर पर परिवर्तित वायुदाब–उष्णकटिबंध (बेरोट्रापिक) उर्जा पर केन्द्रित था। इस दौरान यह पाया गया कि पश्चिमी प्रशांत महासागर से उपोष्णीय पूर्वी हवायें मध्य बंगाल की खाड़ी के उत्तर तक बढ़ी और ऊपर उद्धृत अवधि में भूमध्यरेखीय पश्चिमी हवायें (पछवाँ) आई.टी.सी.जेड़. के दक्षिण तक बढ़ी जिसके कारण क्षैतिजय अपरूपण प्रवाह अत्याधिक मात्रा में बना। इससे चक्रवाती अपरूपण भ्रमिलता उत्पन्न हुई और विक्षोभ बना, जो बाद में उष्णकटिबंधीय चक्रवात कैमुक में विकसित हो गया। निचले क्षोभमंड़ल में मूलभूत क्षेत्रीय प्रवाह वायुदाबउष्णकटिबंध रूप से अस्थिर था जिसे निरपेक्ष भ्रमिलता के याम्योतरी वितरण के लक्षण के परिवर्तन द्वारा बताया गया है जिससे बवंडर के बनने में गतिकीय ऊर्जा मिली। इस दौरान निरपेक्ष भ्रमिलता के माध्य क्षेत्रीय प्रवाह और याम्योतरी प्रवणता के बीच सकारात्मक सहसंबंध था जिससे वायुदाबउष्णकटिबंध द्वारा बवंडर माध्य प्रवाह की अन्तरक्रियाओं के द्वारा बवंड़र की गतिकीय ऊर्जा में वृद्धि हुई। ऊर्जस्वी विश्लेषण से पता चला है कि बवंड़र वाली गतिकीय ऊर्जा के सकारात्मक परिवर्तन के उच्च दर के क्षेत्र परिवर्ती वायुदाब उष्णकटिबंध के सकारात्मक क्षेत्रों से मेल खाते हैं और परिवर्ती उष्णकटिबंध के परिमाण भ्रमिल उत्पत्ति वाले क्षेत्र के आस–पास बवंड़र वाली गतिकीय ऊर्जा के परिवर्तन के स्थानीय समय के साथ मेल खाते हैं। मूलभूत क्षेत्रीय प्रवाह के याम्योतरी अपरूपण द्वारा परिवर्तित वायुदाब उष्णकटिबंध ऊर्जा उष्णकटिबंधीय चक्रवात कैमुक के बनने और उसके आगे बढ़ने वाले एक महत्वपूर्ण ऊर्जा स्त्रोत था।

ABSTRACT. Analysis of dynamical conditions in respect of formation and growth of tropical cyclone Khai Muk over the Bay of Bengal during 11-14 November 2008 is discussed with focus on barotropic energy conversion at lower level. It is observed that the extension of subtropical easterlies from the Western Pacific in to central Bay of Bengal to the north and equatorial westerlies to the south of ITCZ during the above period constituted a large scale horizontal shear flow. This led to generation of cyclonic shear vorticity and initiation of disturbance which later developed in to tropical cyclone Khai Muk. The basic zonal flow in the lower troposphere was barotropically unstable as depicted by change of sign of meridional distribution of absolute vorticity which provided the kinetic energy for the growth of eddy. There existed positive correlation between mean zonal flow and the meridional gradient of absolute vorticity which favoured increase of eddy kinetic energy through barotropic eddy-mean flow interactions. Energetic analysis indicated that areas of high rate of positive change of eddy kinetic energy coincided with positive areas of barotropic conversion and the magnitude of barotropic conversion matched with local rate of change of eddy kinetic energy around the area of vortex generation. Barotropic energy conversion by meridional shear of basic zonal flow was an important energy source for the formation and initial growth of tropical cyclone Khai Muk.

Key words – Tropical cyclone, Absolute vorticity, Energetics, Eddy kinetic energy, Barotropic instability, Barotropic conversion, Khai Muk.

1. Introduction

Climatologically, the northeast monsoon season of October-December is the chief cyclone season for the North Indian Ocean (NIO) basin. The necessary favourable conditions for tropical cyclogenesis such as warm sea surface temperatures coupled with a deep oceanic mixed layer, cyclonic low-level relative and planetary vorticities, weak to moderate vertical wind shear and high mid-level relative humidity are met with during this season. Yet, multitude of cloud clusters do not develop into tropical cyclones which suggests that broad climatological conditions are not sufficient for formation and growth of tropical cyclones. A local enhancement of regions already favourable for cyclogenesis by increasing ambient relative vorticity, enhancing ascent and humidity, modifying vertical shear or any combination of all three by transient modes contribute significantly to Tropical Cyclone (TC) formation and further development. A number of studies reported the importance of barotropic instability of large scale zonal flow in the vortex development process [*e.g.*, Krishnamurthi *et al.* (1981), Mishra *et al.* (1985), Ferreira and Schubert (1997), Ross and Krishnamurthi (2008)]. Subrahmanyam *et al.* (1981) showed, using a two layer model that the preferred divergent barotropic wave was in good agreement with observed wavelength of the summer monsoon depression formed over the Bay of Bengal (BOB). George and Mishra (1993) studied the formation of a monsoon onset vortex over Arabian Sea and showed that the energy conversion from zonal kinetic energy to eddy kinetic energy dominates over the baroclinic conversion from eddy available potential energy to eddy kinetic energy. George *et al.* (1999) analysed a complete energy cycle of a severe cyclonic storm formed over eastern Arabian sea and showed that both baroclinic and barotropic energy conversions are responsible for maintenance of the system, however dominance of one over the other is noticed at different stages of the system at different heights.

The above studies generally dealt with supply of kinetic energy to the formation and development of vortex from instability of westerly flow. The location of the Inter Tropical Convergence Zone (ITCZ) over the Indian longitudes is one of the main factors controlling the tropical cyclogenesis over the NIO. The climatological position of ITCZ over BOB during the month of November is along 9° N (7° N) at surface (850 hPa). At times, strong easterlies from Western North Pacific extend in to BOB and strengthen the easterlies north of the ITCZ. These strengthened easterlies together with westerlies on the southern side of ITCZ play an important role for the generation of barotropic instability through the horizontal shear that in turn lead to the formation and growth of a vortex. During the Bay of Bengal Tropical cyclone Experiment (BOBTEX), a low pressure system formed over BOB, intensified into TC Khai Muk and crossed south coastal Andhra Pradesh coast as Deep depression during the period of 11-16th November, 2008. In the present study, the barotropic energy conversions arising from horizontal shear of the lower tropospheric subtropical easterlies incombination with equatorial westerlies in association with ITCZ in the formation and development of the TC Khai Muk is examined.

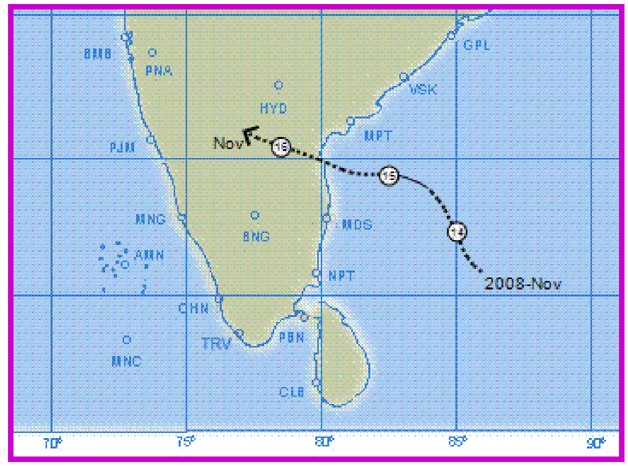


Fig. 1. Track of the TC Khai-muk (13-16 November 2008) (*Source* : www.rmcchennaieatlas.tn.nic.in)

2. Data and analysis

The eddy kinetic energy equation used for the analysis, based on Norquist *et al.* (1977), is as follows:

$$\frac{\partial K_E}{\partial t} = C(A_E, K_E) + C(K_Z, K_E) + BK_E - D_E \qquad (1)$$

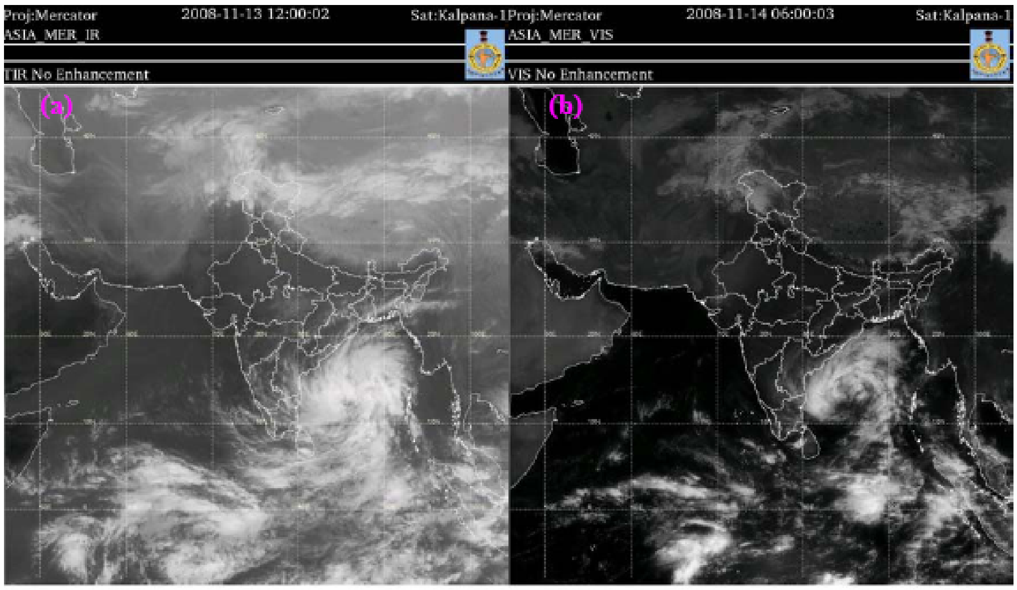
Where C (A_E, K_E) refers to baroclinic conversion of zonal available potential energy (A_E) to eddy kinetic energy (K_E) and C (K_Z, K_E) corresponds to barotropic conversion of zonal kinetic energy (K_Z) to K_E. BK_E and D_E represent the boundary fluxes and the frictional dissipation of eddy kinetic energy.

The barotropic energy conversion [C (K_Z, K_E)] for mean flow – eddy interaction in pressure co-ordinates contains the following four terms (Ross and Krishnamurti, 2008).

$$-u'v'\frac{\partial[u]}{\partial y}, -v'^2\frac{\partial[v]}{\partial y}, -u'\omega'\frac{\partial[u]}{\partial p}, -v'\omega'\frac{\partial[v]}{\partial p} \qquad (2)$$

Where [u] & [v] refer to the zonal average of zonal and meridional winds, u' and v' refer to departure of zonal and meridional winds from the respective zonal means.

For the present study we considered the domain 70° E – 100° E: Equator – 25° N of the NIO region. The longitudinal belt of 70°E – 100°E is considered for determining the zonal average. The data used is 1° × 1° 6-hourly NCEP Final Analysis (FNL) datasets for the period 11-16 November 2008. The daily rate of change of eddy kinetic energy ($\partial K_E/\partial$t) is determined



Figs. 2(a&b). Satellite imageries during (a)13th/1200 UTC and (b) 14th/0600 UTC

from $\left(u'^2 + v'^2\right)/2$. As we focus on barotropic conversions only, conversion of eddy available energy to eddy kinetic energy, boundary energy fluxes and dissipation of eddy kinetic energy by friction present in the R.H.S. of Eqn. 1 are not considered.

3. Results and discussions

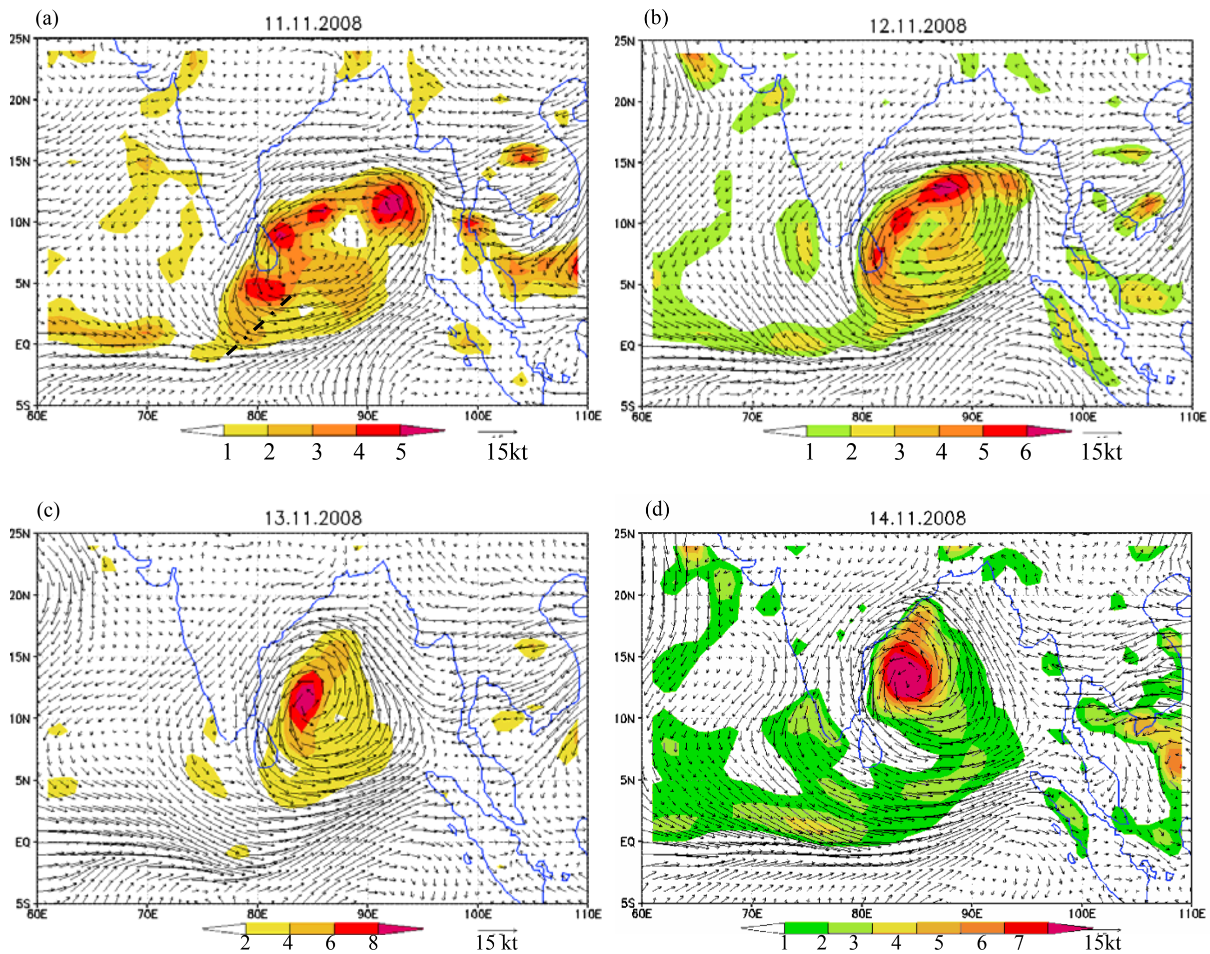
3.1. *Synoptic features*

The genesis of the TC Khai Muk could be traced from a low pressure area over southeast BOB and adjoining areas on 12th. It intensified into a depression on 13th/1200 UTC over the southwest and adjoining southeast BOB. Warm SST (29-30° C), low to moderate vertical wind shear (10-20 knots), presence of moisture up to the mid tropospheric levels favoured the intensification (IMD, 2009). It further intensified into a cyclonic storm (TC Khai Muk) under the influence of low vertical wind shear (5-10 knots) on 14th/1200 UTC. Fig.1 presents the track of the TC Khai Muk. The satellite images of the system during the formation and initial intensification stages (Fig. 2) show feeder bands associated with system extending from the equatorial ITCZ.

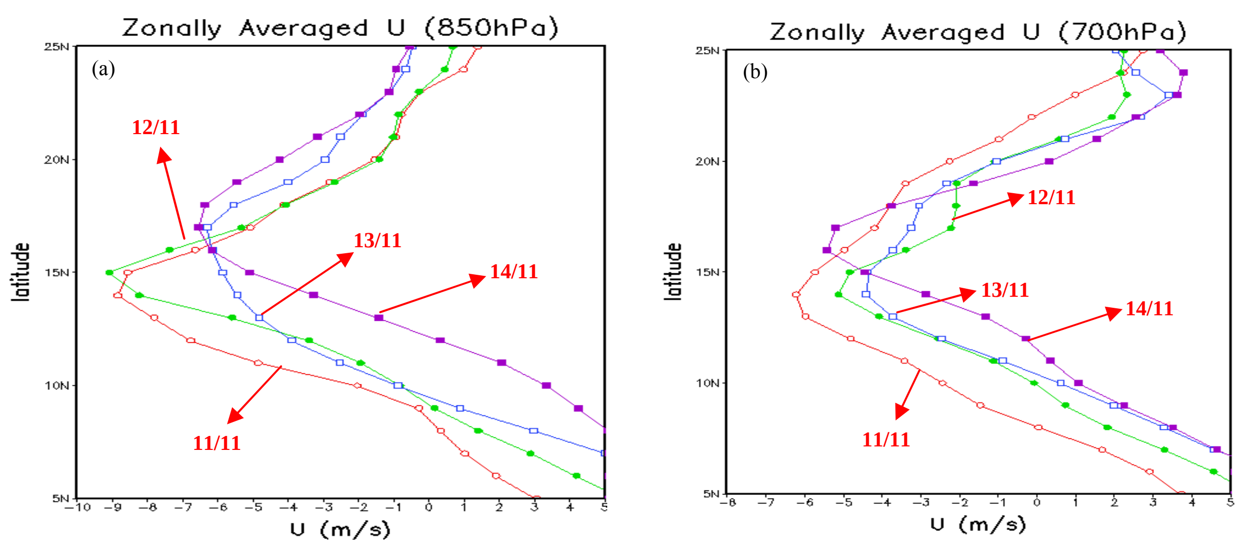
The flow pattern and spatial distribution of relative vorticity at 850 hPa during 11th - 14th November are shown in Figs. 3(a-d). On 11th November, a broad circulation oriented in NE - SW direction with vorticity maxima spanning west of the system is located over southern Bay of Bengal. It may be noted that east to westward extension of strong easterlies along 12-13° N from Western North Pacific to Bay of Bengal. These strong subtropical easterlies and equatorial westerlies constituted large scale shear flow that resulted in creation of cyclonic vorticity. On 12th November 2008, the circulation contracted with merging of vorticity maxima on the western side of the system. Associated with this circulation, a NW to SE oriented trough could be noticed south of Sri Lanka with westerlies to south and easterlies to the north. This trough leads to conversion of basic state kinetic energy in to eddy kinetic energy through poleward transport of westerly momentum. On 13th November 2008, a positive vorticity centre developed near 12° N/85° E with strengthening of circulation resulting in formation of depression over west central BOB. However, at the same time the easterly feed from western Pacific weakened. On 14th November, the vorticity maxima centre expanded and system intensified further into cyclonic storm and moved northwestwards. It weakened into a deep depression on 15th/0600 UTC in association with a vertical wind shear of about 15-20 knots. It crossed coast north of Kavali in south coastal Andhra Pradesh, at about 2200-2300 UTC of 15th and weakened gradually thereafter.

3.2. *Barotropic Instability*

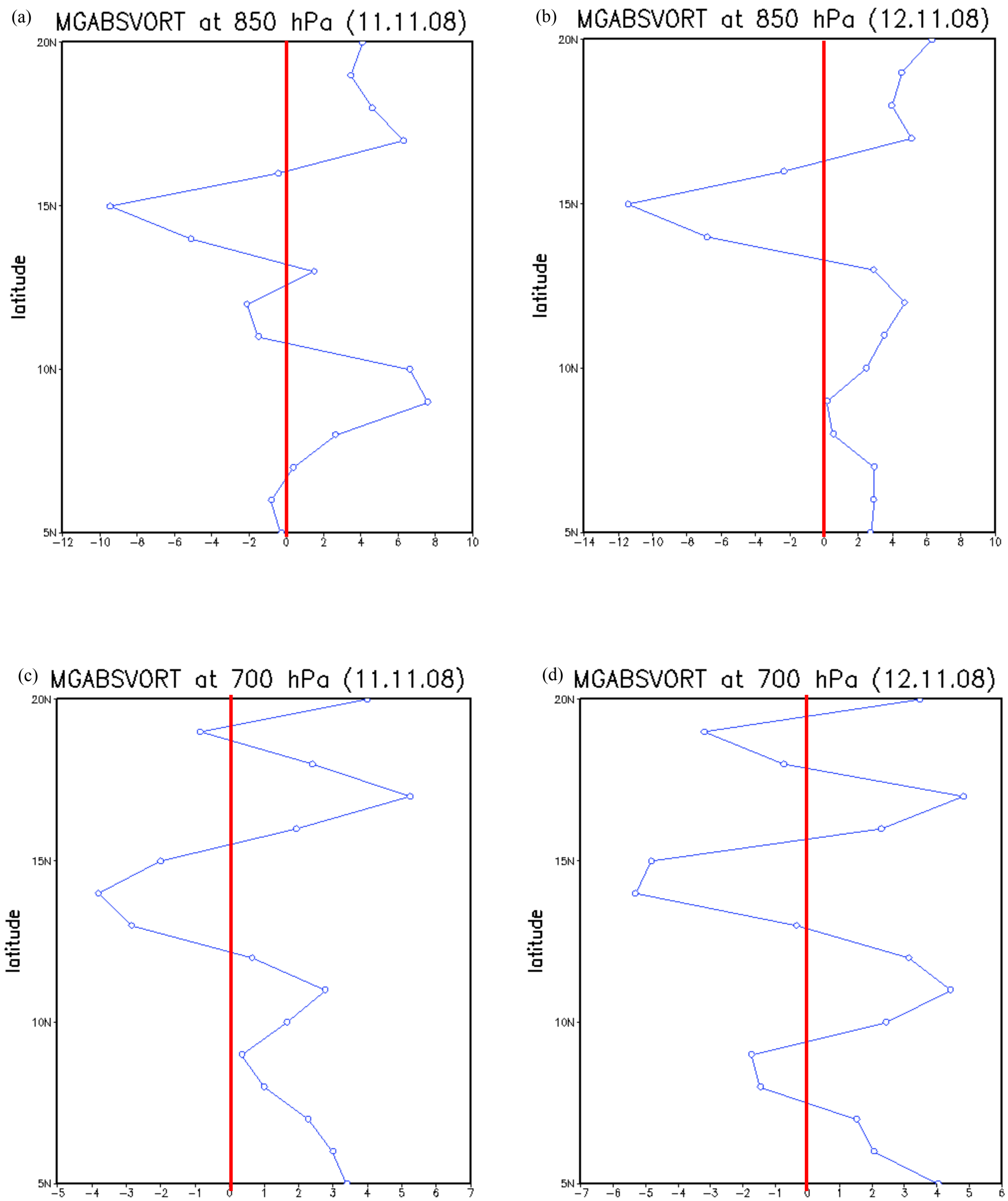
The meridional profile of daily zonal mean winds (U) at 850 hPa and 700 hPa during 11th - 14th November, 2008 are shown in Figs. 4(a&b). It is noted that, at both 850 hPa and 700 hPa levels, peak easterly wind occurred



Figs. 3(a-d). Mean flow pattern and relative vorticity (in units of $\times 10^{-5}$ s^{-1}; positive values are shaded and negative values are suppressed) at 850 hPa during 11th, 12th, 13th and 14th November 2008

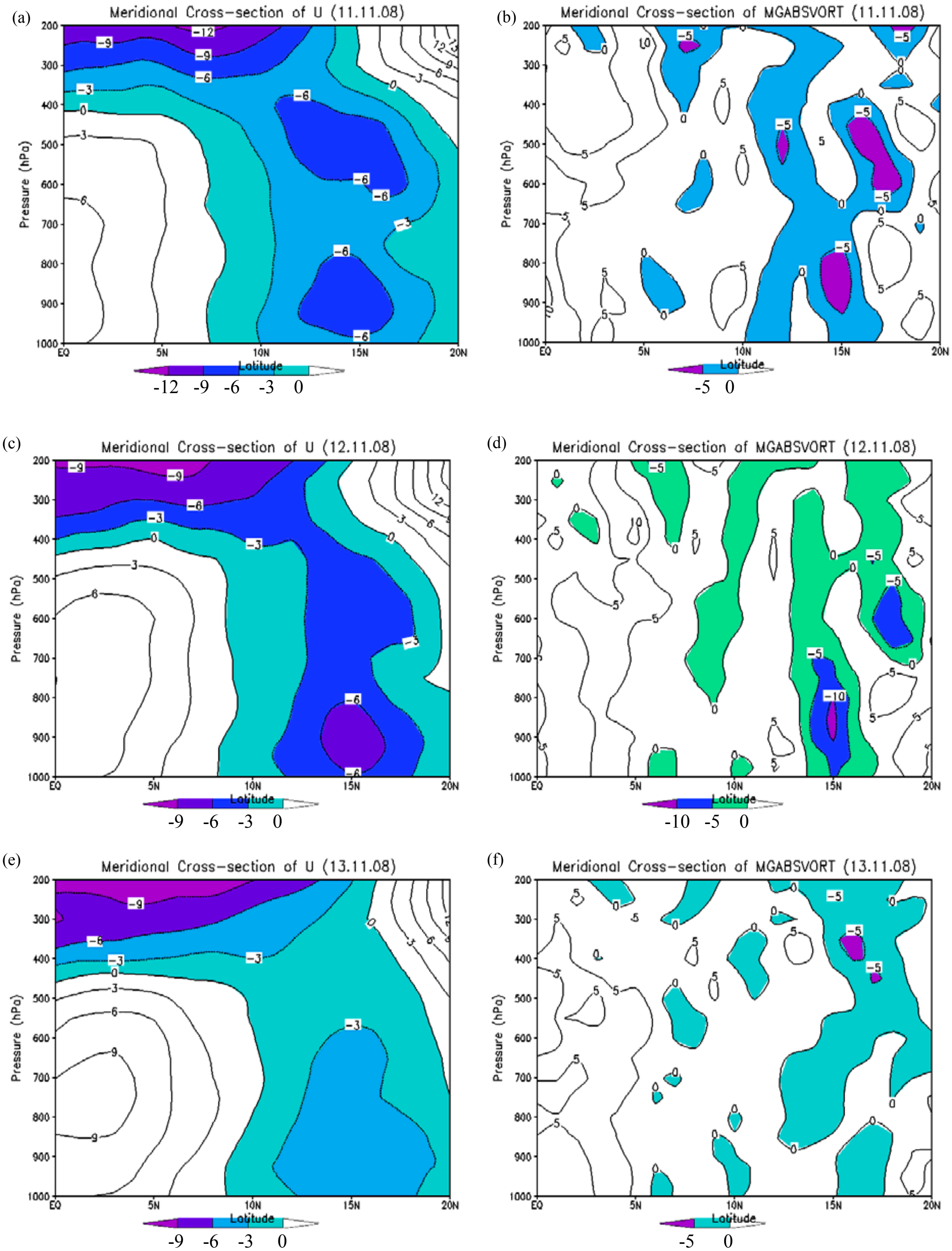


Figs. 4(a&b). Meridional profile of mean zonal wind (U) averaged over 70-100°E during 11th, 12th, 13th and 14th November 2008 at (a) 850 hPa and (b) 700 hPa



Figs. 5(a-d). Meridional profile of meridional gradient of absolute vorticity ($\times 10^{-11} s^{-1} m^{-1}$) (a&b) at 850 hPa and (c&d) at 700 hPa during 11th, 12th November 2008

around 14°N on 11th November, which decreased in magnitude and shifted to around 17° N on 14th November indicating role of kinetic energy of mean easterly zonal flow in the development of the vortex. The barotropic instability of zonal flow with horizontal shear can be examined based on meridional gradient of absolute



Figs. 6(a-f). Latitude – Pressure profile of (a, c & e) zonal mean wind (U in ms^{-1}) and (b, d & f) meridional gradient of absolute vorticity (MGABSVORT in units of $\times 10^{-11}$ $s^{-1}m^{-1}$) averaged over 70-100° E during 11th, 12th and 13th November 2008. Negative values are shaded

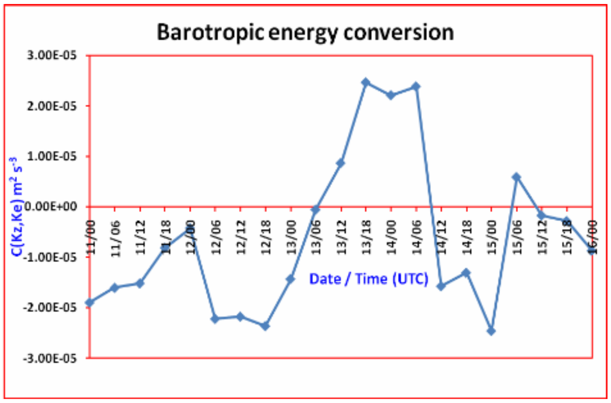


Fig. 7. Barotropic energy conversion from zonal to eddy kinetic energy C(K_Z,K_E) averaged over the region 70-100° E and Equator-25°N during the period 11th-16th/0000 UTC

vorticity (MGABSVORT). The zonally averaged MGABSVORT is given by

$$[M] = -\frac{\partial^2}{\partial y^2}[u] + \beta \qquad (3)$$

Where u = zonal wind;

β = meridional gradient of Coriolis parameter.

The profiles of MGABSVORT at 850 hPa [Figs. 5(a&b)] and 700 hPa [(Fig. 5(c&d)]on 11th and 12th November 2008 show occurrence of negative gradient between 10° N and 15° N and positive gradients at north and south and thus MGABSVORT had both signs in the meridional plane on an isobaric surface in the lower troposphere. This indicates zonal flow satisfied necessary condition for barotropic instability (Kuo, 1949).

Under the positive correlation between the mean zonal flow and meridional gradient of absolute vorticity, growth of disturbances takes place from energy supply of unstable zonal flow (Eliassen, 1983). The latitude - Pressure plot of mean zonal wind component and meridional gradient of absolute vorticity during 11th-13th November is shown in Figs. 6(a-f). It is noted that from Fig.6, that on 11th November 2008, the zero line of zonal flow existed near 7° N in the lower and middle troposphere separating easterlies to the north and westerlies to the south. The strength of easterlies decreased day by day indication transfer of energy from zonal flow to eddy. It is noted that negative gradient of absolute vorticity coincided with easterlies between 10° N – 15° N while positive gradient corresponded to westerlies that existed south of 7° N. Compared to 12th November, the easterlies and meridional gradient of absolute vorticity weakened considerably on 13th November. Thus the dynamically unstable zonal flow helped in the growth of TC Khai Muk through barotropic energy conversion which is discussed further in the following section.

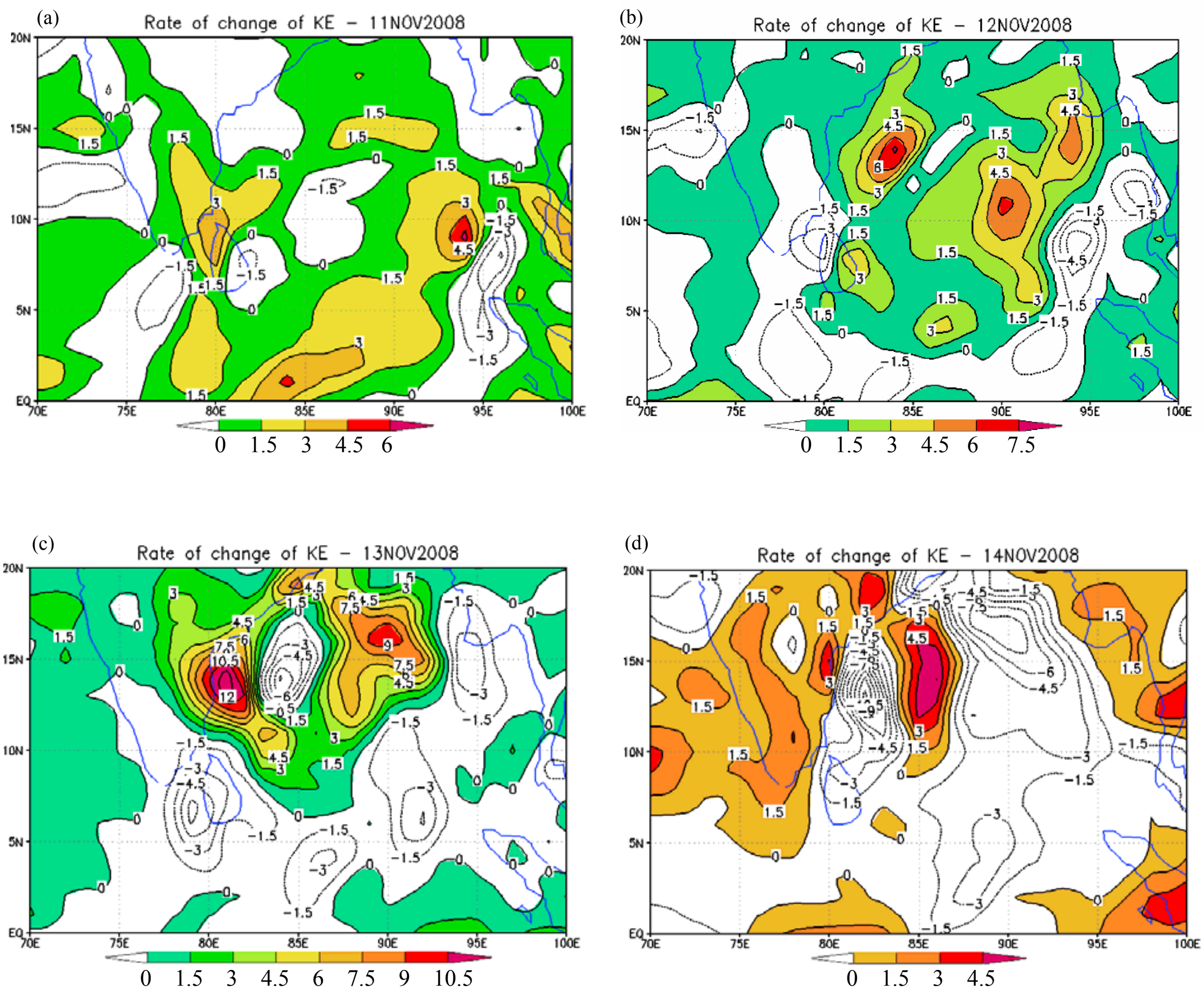
3.3. *Barotropic energy conversion*

Local barotropic energy conversion between the mean flow and transient eddies at low levels could intensify the 3-10 day transient eddies associated with tropical cyclogenesis (Lau and Lau, 1992). The relative importance of the eddy momentum transport associated with eddy barotropic energy conversion in the development of TC Khai Muk is examined here.

From energy point of view, the intensification and westward extension of easterlies to the north of ITCZ over BOB established a favorable environment with increased cyclonic shear for eddy barotropic conversion at low levels. The divergence of eddy flux of westerly (easterly) momentum in the region of strong westerlies (easterlies) contributes significantly to the growth of disturbance kinetic energy (Krishnamurthy *et al.*, 1981). Plot of barotropic energy exchange C (K_Z, K_E)] as a function of time during 11th - 15th, November 2008 is shown in Fig.7. It is noted that positive barotropic exchange from zonal to eddy kinetic energy occurred during genesis and intensification of TC Khai Muk (13/0600-14/0600 UTC) and there was negative barotropic exchange during rapid weakening of the system from cyclone stage (14/1200 UTC) back to depression stage (15/0600 UTC).

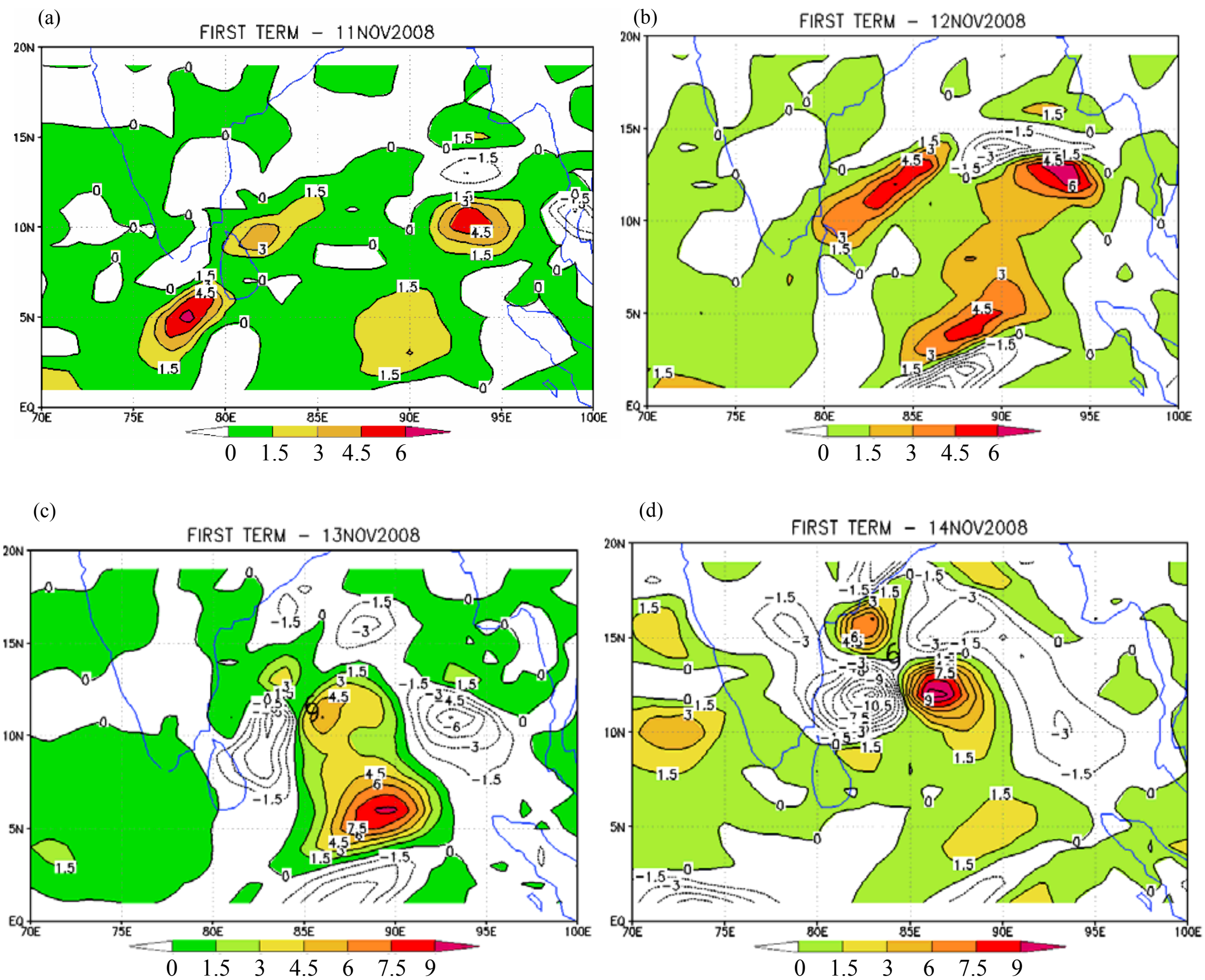
Next, the spatial correspondence between the local eddy kinetic energy tendency and the barotropic energy conversions are examined. All the four terms of barotropic conversion given in Eqn. 2 were computed and it was observed that the first term was one order more than the other terms (not shown). Hence, the first term alone is considered to represent barotropic conversion in further analysis. The dominance of the first term has also been reported in some of the earlier studies [Ross and Krishnamurti (2008) and Pang-Chi & Chih-Hua (2009)]. The daily mean eddy kinetic energy tendency during the period 11-14 November 2008 are shown Figs. 8(a-d) and the first term of barotropic conversion during the same period are shown in Figs. 9(a-d).

On 11th and 12th November, 2008 there were positive eddy kinetic energy tendency as well as barotropic energy conversion of the order of 4.5 to 6 ($\times 10^{-4}$ $m^2 s^{-3}$) in the longitudinal belt of 90-95° E at about 10° N. On 13thwhen the system intensified into a depression, there was substantial increase in eddy kinetic energy tendency to the order of 9×10^{-4} $m^2 s^{-3}$ which coincided with the positive barotropic conversion over the area east of the vortex. On



Figs. 8(a-d). Rate of change of eddy kinetic energy (K_E) at 850 hPa during 11th, 12th, 13th and 14th November 2008. Positive values are shaded. (Units: $\times 10^{-4}$ (m^2s^{-3}) (Refer text for symbols and notations)

14th, the system intensified further into a cyclonic storm for a brief period and started to weaken and correspondingly there was a reduction of eddy kinetic energy tendency to the order of 4.5×10^{-4} m^2s^{-3}. However, on the same day, the magnitude of the positive contours of barotropic conversion increased substantially to 9×10^{-4} m^2s^{-3}. Decrease in the rate of eddy kinetic energy despite large increase in barotropic conversion on 14th implies the influence of other factors in reducing the local eddy kinetic energy tendency (especially when a TC attains a finite strength). Diabatic processes may play a role in further intensification after the initial vortex formation (Mao and Wu, 2011). Moreover, the spatial distribution during 14th November shows the denser negative contours of the larger magnitude compared to the positive contours in eddy kinetic energy tendency as well as in barotropic conversion term indicating the reduction in kinetic energy due to the negative barotropic energy conversion i.e. from eddy to zonal kinetic energy that may ultimately cause for the decrease in intensity of cyclone to depression stage. During the formative stages, in general, areas of high rate of positive change of eddy kinetic energy coincides with positive areas of barotropic conversion and the magnitude of barotropic conversion matches with local rate of change of eddy kinetic energy around the area of vortex generation. This implies that an interaction between the eddy and the basic zonal flow with barotropic energy conversionis an important energy source.



Figs. 9(a-d). Barotropic energy conversion at 850 hPa from the first term, $-u'v'\frac{\partial[u]}{\partial y}$, during 11th, 12th, 13th and 14th November 2008. Positive values are shaded. (Units: $\times10^{-4}$ (m^2s^{-3})) (Refer text for symbols and notations)

The increase of eddy kinetic energy through barotropic process leads to the expectation of weakening of easterly and westerly mean flow as the kinetic energy of these zonal flows are converted in to eddy kinetic energy. However, as shown in Fig.3, the near equatorial westerly flow strengthened between 11th and 14th, November 2008. This may be due to enhancement of cross equatorial pressure gradient that replenished the loss of kinetic energy of zonal westerly flow. It may be noted that apart from the barotropic energy conversion, diabatic process related to convection associated with latent heat and hence baroclinic energy conversion might also have played a significant role during intensification and mature stage of the TC Khai Muk.

4. Summary

The analysis of dynamical conditions during genesis and growth of TC Khai Muk with focus on barotropic energy conversion at lower level show that:

(*i*) Genesis of the system was due to synoptic scale shear associated with ITCZ. The easterlies on the northern side of ITCZ strengthened with flow from the Western Pacific in to Bay of Bengal. These strengthened easterlies together with westerlies on the southern side of ITCZ generated strong horizontal shear that eventually lead to the formation and growth of a vortex through barotropic instability as the basic shear flow was barotropically unstable as depicted by change of sign of meridional gradient of absolute vorticity.

(*ii*) There existed positive correlation between mean zonal flow and the meridional gradient of absolute vorticity which favoured increase of eddy kinetic energy through barotropic eddy-mean flow interactions.

(*iii*) Barotropic conversion term is dominant with its magnitude comparable to the local rate of increase of eddy kinetic energy during the vortex formation and is an important energy source for the initial growth of the TC Khai Muk.

(*iv*) There was positive barotropic exchange from zonal to eddy kinetic energy during genesis and intensification and negative exchange during rapid weakening of the system.

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