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ARTICLE

Climatology of Energetics of Cyclones over Indian Seas

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ABSTRACT

An attempt has been made to bring out a climatology of the energetics associated with the tropical cyclones formed over North Indian Seas, viz., the Arabian Sea (AS) and the Bay of Bengal (BOB). Study period is from 1991 to 2013. During this period a total 88 cyclones that developed over the Indian Seas have been considered. These intense systems are categorized on the basis of their formation region and season of formation. It is seen that during the study period, the frequency of formation of cyclones over BOB is twice that over AS which is consistent with the climatology of the regions. Further, it is noticed that over both the regions, they are more frequently formed in the post monsoon period compared to pre monsoon. The trend analysis of the frequency of cyclones forming over both basins, season wise shows that the overall trend for both basins is of just decreasing type. However, for Arabian Sea; the decreasing trend is more apparent in the post monsoon season, whereas in the case of the Bay of Bengal the decreasing trend is more evident in the pre-monsoon season. Various energy terms, their generation and conversion terms have been computed using NCEP/NCAR reanalysis data. Day to day quantitative analysis of these parameters is studied critically during various stages of the cyclones. The composites of these categorized systems are formed and studied. The formative, intensification and dissipation stages showed variations in their energy terms.

1. Introduction

Understanding of how tropical cyclone activity has varied in the past and will vary in the future is a topic of great interest to meteorologists, policymakers and the general public. Some have expressed concern about the possibility that anthropogenic climate change due to increases in "greenhouse" gases may alter the frequency, intensity and areal occurrence of tropical cyclones. A review of the inter-annual variations of tropical cyclones, their causes and seasonal predictability has been covered by Landsea (2000) [18]. As per the ESCAP-WMO Panel on Tropical Cyclone (2013)[5]; in the North Indian Ocean (over the Bay of Bengal (BOB) and Arabian Sea (AS)), the average number of tropical cyclones formed in a year are just around 5 which accounts for only 6% of the total global average. However, the loss of life, damage to the property and human suffering

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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. The understanding of the trend in the frequency and intensity of tropical cyclones is very important and quite relevant for being both the source of precipitation and cause of damage to life and property.

A lot of work has been carried out by various researchers on these intense systems formed over the Indian seas. Karl & Ludovic (2010) [8], studied the climatology of the intense tropical cyclones over the past three decades from 1990-2008 indicated that there is no increasing trend in the intensity of cyclones since 1980. They also indicated that the reliable data set is too short to highlight multi-decadal variations. Akter and Tsuboki (2014) [1] studied the cyclone frequency distribution over the BOB during 1990-2009 and found that the distribution is bimodal, with a primary post monsoon peak and a secondary pre monsoon peak. They also concluded that the maximum occurrence rate was 0.8 cyclones/year in November. Further, they stated that in the BOB, the trough position and the accompanying low vertical shear are only a precondition for cyclone occurrence. Jamal (2015) [19], while studying the tropical cyclones over the North Indian Seas during 1998-2014 introduced a measure of annual tropical cyclone activity including the effects of frequency, wind speed, and duration. However the investigation of a sample of 92 tropical cyclones showed no signs of the trend within the period of the study with respect to the cyclone activity measure used.

Many investigators found analysis of energetics to be a very useful and interesting tools for diagnosing many atmospheric phenomena dynamically. There are a number of studies on the energetics aspects of onset, progress and maintenance of mean monsoonal circulation viz. Keshavamurty and Awade (1970) [10], Rao & Rajamani (1972) [22] , Krishnamurti & Ramanathan (1982) [11], Krishnamurti (1985) [12], Krishnamurti & Surgi (1987) [13], Yanai et al. (1992) [25], Raju et al. (2002) [21], Rao (2006) [23], Rao and Mohanty (2007) [24] etc. Dutta et al. (2011) [3], Dutta et al. (2012) [4], Krishnamurti et al. (2013) [15], Dutta et al. (2014) [2] etc. The present study focuses on what have been the long-term variations in tropical cyclone activity over the North Indian seas and what may be responsible for such variability with respect to the cyclone energetics. The two basins of the Indian Ocean - the AS and the BOB have been examined in detail. Understanding tropical cyclone variability on inter-annual to inter-decadal timescales has been hampered by the relatively short period over which accurate records are available. Changes in the tropical cyclone databases due to observational platform improvements (and sometime degradations) can often be mistaken as true variations in tropical cyclone activity. Although the Atlantic basin and Northwest Pacific basin have had extensive aircraft surveillance giving valid records going back to at least the late 1940s [Neumann et al. (1993) [20]] and 1950s [JTWC (1974)[6]] . The routine aircraft reconnaissance has not been available for the North Indian Ocean basin and reliable estimates of tropical cyclones only exist in the satellite era beginning in the mid-1960s (Landsea;1993 [16]). Thus, with the instrumental record so limited, it is difficult to make extensive analyses of trends and of the physical mechanisms responsible for the tropical cyclone variability on a global basis. Because of this limitation, most studies on long-term changes in tropical cyclone activity have focused upon the Atlantic and Northwest Pacific. However, even with these limitations, some conclusions can be drawn about past variations in the Indian Ocean basin.

Taking into account of the studies and outcomes of the research carried out by different scientists, an attempt has been made here to study the energy conversion terms of cyclones developed in the Indian Ocean during the recent decade of 1991–2013. Some of the distinguishing features and similarities have been brought out and compared.

2. Data and Methodology

For this study, 6-hourly mean data of temperature field and wind (u, v) and vertical wind (w) reanalyzed data produced by NCEP at grid point (2.5° x 2.5°) have been used. These have been utilized to compute the different energy generation and conversion terms. The period of the study chosen is 1991 to 2013. The energetic terms have been computed on a six-hourly basis beginning from two days before the initial formative stage till the two days post dissipation stages of cyclones over the spatial domain of 2.5°N to 40°N Lat, 40°E to 110°E Lon. The pressure levels considered are from 1000 hPa to 100 hPa i.e. 1000, 850, 700, 600, 500, 400, 300, 250, 150, 100 hPa.

Using these data, following Krishnamurti and Bounua (2000) [14], we have computed zonal & eddy available potential energy [], zonal & eddy kinetic energy , generation of zonal and eddy available potential energy , conversion from eddy available potential energy to eddy kinetic energy , conversion from zonal available potential energy to zonal kinetic energy and conversion from zonal available potential energy to eddy available potential energy . Detail mathematical expression of these energetics parameters are given in table 1.

Frequency of cyclones over AS and BOB for pre mon-

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soon and post monsoon have been plotted in the form of a line graph for the period 1991 to 2013. A linear trend is also computed and analyzed for these frequency plots. Bar Graphs of each of the computed energetic terms, generation as well as conversion terms for each cyclone have been plotted for the pre monsoon and post monsoon seasons of both, AS and BOB. Day to day quantitative analysis of these parameters has been studied critically during various stages of the cyclones. Daily mean values of above mentioned energy conversion terms have been calculated by taking the average of the computed 6-hourly energetics data. Then the composites for the above obtained data have been plotted for pre monsoon and post monsoon of the Arabian Sea and Bay of Bengal for the period 1991 to 2013.

The above mentioned composites have been compared, both season wise and basin wise.

Table 1. Detail mathematical expression of energetics parameters

	Mathematical expression of different terms
A_Z	$\int_{100}^{P_s} \frac{\overline{T^{*2}}}{2\sigma} dp$
A_E	$\int_{100}^{P_s} \frac{\overline{T'^2}}{2\sigma} dp$
K_Z	$\frac{1}{2g}\int_{100}^{P_s} \overline{([u]^2+[v]^2)}dp$
K_E	$\frac{1}{2g}\int_{100}^{P_s} \overline{(u'^2+v'^2)}dp$
$G(A_Z)$	$\frac{R_d}{C_p}\oint \frac{[\theta]^*[\dot{Q}]^*}{p\left(-\frac{\partial\bar{\theta}}{\partial p}\right)}dm$
$G(A_E)$	$\frac{R_d}{C_p}\oint \frac{\theta'\dot{Q}'}{p\left(-\frac{\partial\bar{\theta}}{\partial p}\right)}dm$
$C(A_E,K_E)$	$-\frac{1}{g}\int_{100}^{P_s}\frac{R}{p}\overline{\omega'T'}dp$
$C(A_Z,K_Z)$	$-\frac{1}{g}\int_{100}^{P_s}\frac{R}{p}\overline{\omega^*T^*}dp$
$C(K_Z,K_E)$	$\left\{\begin{array}{l}\int_{100}^{P_s}\left[\cos\frac{\varphi\overline{u'v'}\partial}{a\partial\varphi}\left[\frac{[u]}{\cos\varphi}\right]\right]dp \\ +\int_{100}^{P_s}\left[\overline{v'^2}\frac{\partial[v]}{a\partial\varphi}\right]dp+\int_{100}^{P_s}\left[\frac{\tan\varphi}{a}\overline{u'^2}[v]\right]dp \\ +\int_{100}^{P_s}\left[\frac{\overline{\omega'u'}\partial[u]}{\partial p}\right]dp+\int_{100}^{P_s}\left[\frac{\overline{\omega'v'}\partial[v]}{\partial p}\right]dp\end{array}\right\}$
$C(A_Z,A_E)$	$-\int_{100}^{P_s}\left[\frac{1}{\sigma}\overline{v'T'}\frac{\partial T^*}{a\,\partial\emptyset}+\frac{1}{\sigma}\overline{\omega'T'}\frac{\partial T^*}{\partial p}\right]dp$

3. Results and Discussion

The results obtained for frequency/trend analysis and composite analysis are discussed separately in the following sections.

3.1 Frequency/Trend Analysis

The annual tropical cyclone frequency distribution over Indian seas, during 1991-2013 is shown in Fig. 1. It is clearly seen from the figure that distribution is bimodal and consistent with previous reports (Akter and Tsuboki, 2014 [1] and references therein). The primary peak is in November whereas the secondary peak is in May. Frequency and Trend analysis for the cyclones developed from 1991 to 2013 during pre monsoon and post monsoon and in both basins are shown in Fig. 2 (a-d) respectively.

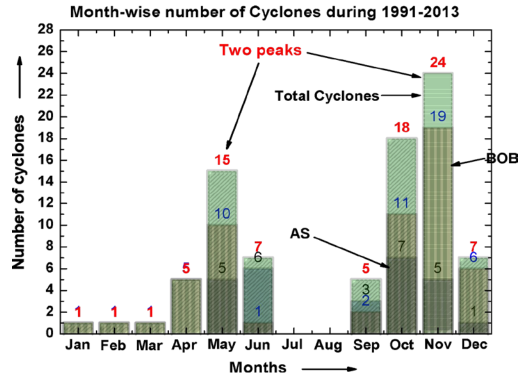

Figure 1. Annual tropical cyclone occurrence frequency over AS and BOB

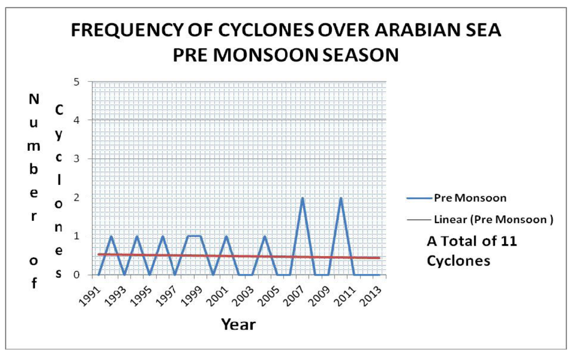

Figure 2 (a). Frequency of cyclones over Arabian Sea – pre monsoon

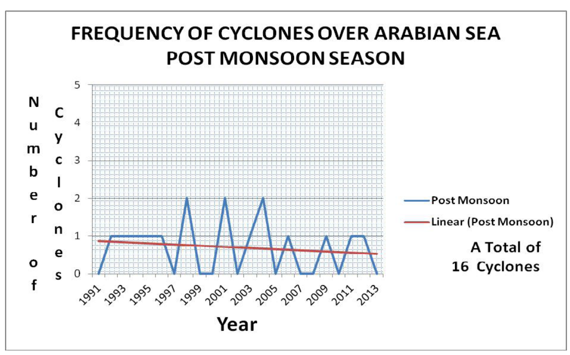

Figure 2 (b). Frequency of cyclones over Arabian Sea – post monsoon

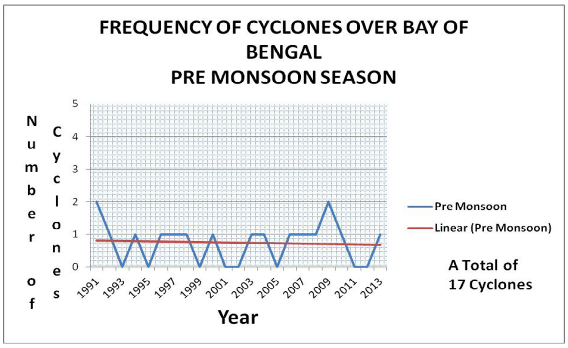

Figure 2 (c). Frequency of cyclones over Bay of Bengal–pre monsoon

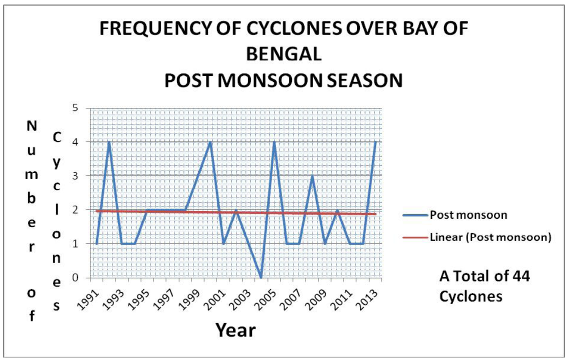

Figure 2 (d). Frequency of cyclones over Bay of Bengal–post monsoon

3.1.1 Frequency Analysis

It is observed that a total of 61 cyclones developed in the BOB during the period from 1991 – 2013 while 27 developed in the AS. Also the frequency of events was much higher for the post monsoon season rather than the pre monsoon season. The frequency of cyclones over AS is observed to range from 0 to 2 cyclones in a year during the period from 1991 to 2013 for both seasons. On the other hand, for the BOB number of cyclones developed in a year for the same period range from 0 to 2 for the pre monsoon season and 0 to 4 for the post monsoon season. This shows that the maximum frequency of formation of cyclones over BOB is twice that over AS. Further, it is noticed that over BOB they are more frequently formed in the post monsoon season compared to pre monsoon season.

3.1.2 Trend Analysis

The general trend for both basins is found to be of just decreasing type for both seasons. However, for AS; the decreasing trend is more apparent in the post monsoon season, whereas in the case of BOB the decreasing trend is more evident in the pre monsoon season.

3.2 Composite Analysis

3.2.1 Composite Analysis of C (Ae, Ke)

Daily Composite Analyses of C (Ae, Ke) for pre and post monsoon over both basins viz. AS and BOB are shown in Fig. 3 (a,b) and Fig. 4 (a,b) respectively. It can be seen that during the formative and mature stage, most cyclones are showing generation of Ae with C(Ae,Ke) negative. Generation of Ke from Ae with C(Ae,Ke) positive is occurring only in the dissipating stage. Ke is converted to Ae when the contour trough lags behind the thermal trough. In this case the trough gets intensified instead of moving, Holton (2004) [9]. Thus the negative C(Ae,Ke) in the composite signifies that in the formative and mature stage of cyclones under study, Ae was generated at the cost of Ke on a daily scale in both seasons, which resulted in its intensification. The positive C(Ae,Ke) in the composite is seen in the dissipating stage indicating that the cyclone gained movement in this stage.

However, in the Bay of Bengal some cyclones are showing C (Ae,Ke) as positive all throughout their lifecycle, Fig. 3 (b) and Fig. 4 (b). This indicates that although Ae is generated at the cost of Ke in most cyclones over both basins; there are certain cyclones that developed in the Bay of Bengal, which did not follow this pattern and there was a continuous generation of Ke at the cost of Ae. This denotes that they gained movement from the formative stage itself and continued gaining movement till the end of their lifecycle.

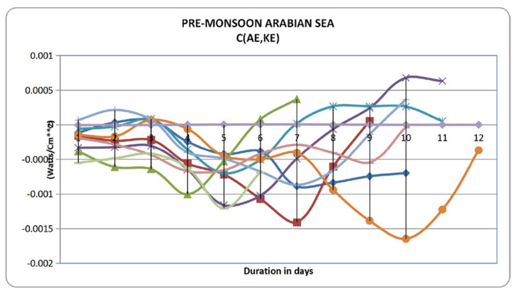

Figure 3 (a). Daily mean composite of C(Ae,Ke) – pre monsoon: Arabian Sea

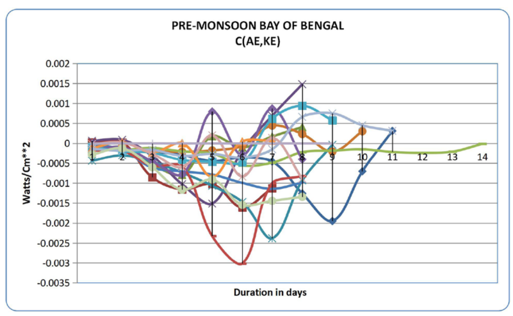

Figure 3 (b). Daily mean composite of C(Ae,Ke) – pre monsoon: Bay of Bengal

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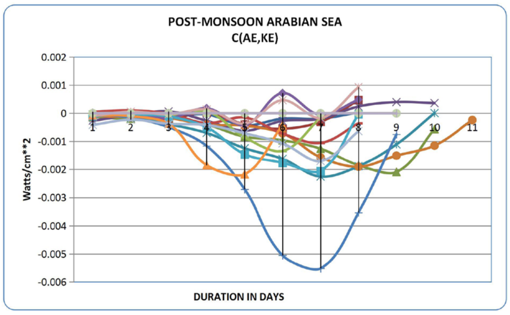

Figure 4 (a). Daily mean composite of C(Ae,Ke) - post monsoon: Arabian Sea

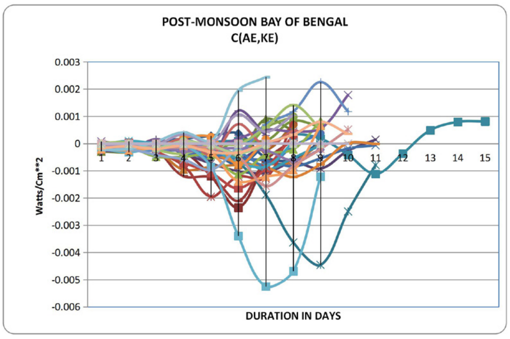

Figure 4 (b). Daily mean composite of C(Ae,Ke) - post monsoon: Bay of Bengal

3.2.2 Composite Analysis of C (Az,Kz)

Daily Composite Analyses of C (Az,Kz) for pre and post monsoon over both the basins viz. AS and BOB are shown in Fig. 5 (a,b) and 6 (a,b) respectively. It can be seen that in the pre monsoon season during the formative stage and dissipating stage, most cyclones are showing generation of Kz with C (Az,Kz) positive. Generation of Az from Kz with C (Az,Kz) negative is occurring in the mature stage. This pattern of energy conversion is similar for both the basins. This indicates that at the time of cyclone intensification over both basins; during pre monsoon, weakened mean meridional circulation prevails. From its expression, it is clear that C (Az,Kz), [equation (13)] represents the strength of mean meridional circulation, which is due to rising motion over the warm latitudinal zone and sinking motion over the cold latitudinal zone. Thus the negative C (Az,Kz) in the mature stage in both seasons indicates the weakened effect of mean meridional circulation, i.e, Hadley circulation and development of Az at the expense of Kz. The decrease in Kz could be attributed to friction. However, some cyclones in the post monsoon season show generation of Kz at the expense of Az all throughout their life cycle with C (Az,Kz) positive. This signifies the strong mean meridional circulation and subsequent strong mean flow at the time of the lifecycle of these cyclones.

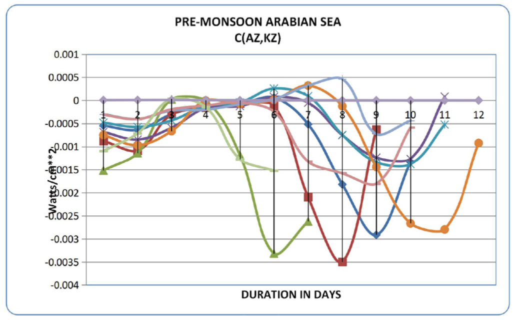

Figure 5 (a). Daily mean composite of C(Az,Kz) – pre monsoon: Arabian Sea

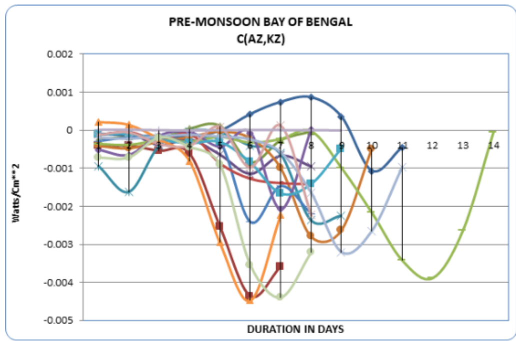

Figure 5 (b). Daily mean composite of C(Az,Kz) – pre monsoon: Bay of Bengal

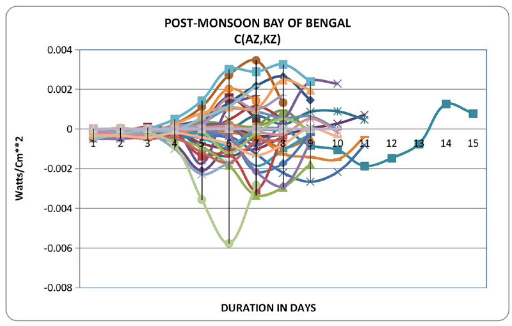

Figure 6 (a). Daily mean composite of C(Az,Kz) – post monsoon: Bay of Bengal

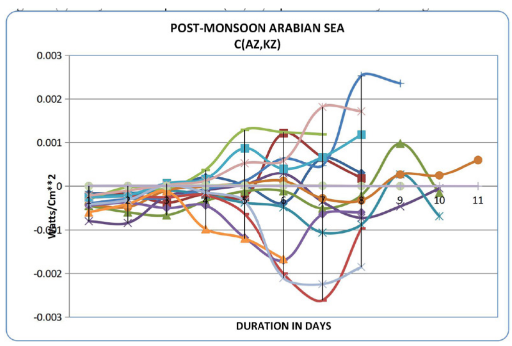

Figure 6 (b). Daily mean composite of C(Az,Kz) – post monsoon: Arabian Sea

3.2.3 Composite Analysis of C(Kz,Ke)

Daily Composite Analyses of C (Kz, Ke) for pre and post monsoon over both basins viz. AS and BOB, are shown in fig. 7 (a,b) and 8 (a,b) respectivly. It can be seen that during the formative and mature stage, most cyclones are showing generation of Ke with C (Kz,Ke) positive. Generation of Kz from Ke with C (Kz,Ke) negative is occurring only in the dissipating stage. However, in the post monsoon some cyclones are showing C (Kz,Ke) as negative with the generation of Kz from Ke in mature stage and generation of Ke at the expense of Kz in the dissipating stage. This indicates that over both basins generation of maximum wind speed at the expense of Kz during pre monsoon and post monsoon was during formative and mature stages. Although there were some cyclones (over both basins) that developed in the post monsoon, which showed a departure from this pattern and maximum wind speed was generated at the cost of Kz only during the dissipating stage. Enhancement of Ke at the expense of Kz during formative and mature stage indicates that the systems are gaining maximum wind speed at the expense of zonal mean flow. It can also be seen that during the mature stage C (Az,Kz) was negative with steady decrease in Kz. Thus the weakened mean meridional circulation might have influenced significantly on the gain of maximum wind speed for the cyclones. Further, the term C (Ae,Ke) was also negative at the same time, Figs. 3 (a,b) and 4 (a,b). This indicates cyclones were gaining Ke solely at the expense of Kz. However, during the dissipating stage, composites indicate the generation of Kz from Ke with C(Kz,Ke) term as negative. At the same time positive C(Az,Kz) was also observed, indicating an increase in mean zonal flow at the expense of both Az and Ke, Figs. 5 (a,b) and 6 (a,b).

However, some cyclones in the post monsoon showed an opposite pattern with the generation of Kz at the expense of Ke during the formative and mature stage with C(Kz,Ke) term negative and generation of Ke from Kz during the dissipating stage with C(Kz,Ke) term positive. The production of Kz at the expense of Az was also seen in some cyclones at the same time with C(Az,Kz) positive all throughout. So for these cyclones gain in mean zonal flow was again at the expense of Az and Ke. Further, during dissipation these cyclones gained maximum wind speeds (Ke) at the expense of the increased mean zonal flow (Kz).

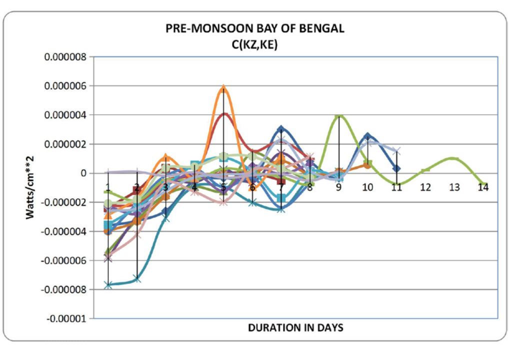

Figure 7 (a). Daily mean composite of C(Kz,Ke) – pre monsoon: Bay of Bengal

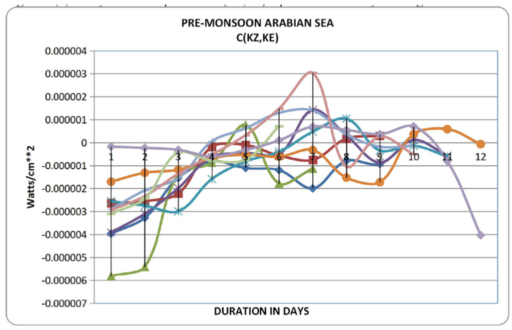

Figure 7 (b). Daily mean composite of C(Kz,Ke) – pre monsoon: Arabian Sea

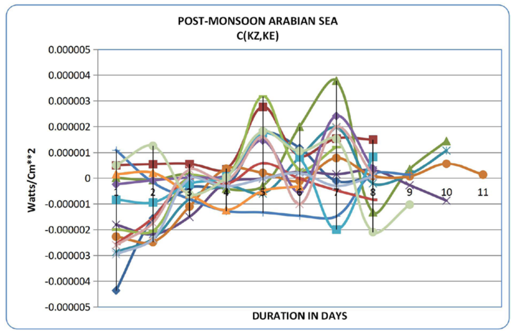

Figure 8 (a). Daily mean composite of C(Kz,Ke) – post monsoon: Arabian Sea

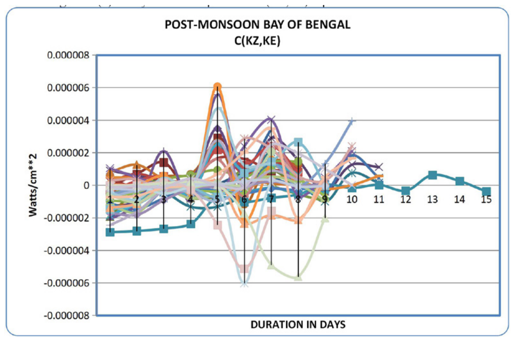

Figure 8 (b). Daily mean composite of C(Kz,Ke) – post monsoon: Bay of Bengal

3.2.4 Composite Analysis of C(Az,Ae)

Daily Composite Analyses of C (Az,Ae) for pre and post monsoon over both the baisns viz. AS and BOB are shown in Fig. 9 (a,b) and 10 (a,b) respectively. Although no distinct pattern can be seen from the figures, the evolution of C(Az,Ae) for a particular cyclone can be studied. The time evolution of C(Az,Ae) for cyclonic storm 'Yemyin' which developed over the Arabian Sea in the Pre monsoon season with lifecycle 25 – 26 June 2007 and severe cyclonic storm 'Alia' which developed over Bay of Bengal in the with lifecycle 23 – 26 May 2009 is shown in Fig 11 (a,b). The time evolution of C(Az,Ae) for cyclonic storm which developed over Arabian Sea in post monsoon season with lifecycle 11

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– 17 Oct 1998 and very severe cyclonic storm which developed over Bay of Bengal with lifecycle 23 – 28 Dec 2000 is shown in Fig 12 (a, b). The figures indicate the generation of Ae from Az with C(Az,Ae) positive and generation of Az from Ae with C(Az,Ae) negative is occurring only in the dissipating stage. Generation of Ae from Az with C(Az,Ae) positive indicates the influence of mid latitude baroclinic circulation. [Dutta et. al, (2011) [3]]. Thus the daily mean composite suggests that the mid latitude baroclinic circulation might have influenced significantly on the development and intensification of the selected cyclones. It can be observed that at the same time there was generation of Ae from Ke as well with C (Ae,Ke) negative. However, negative C (Az,Ae) during dissipation indicates that there was hardly any influence of mid latitude baroclinic circulation.

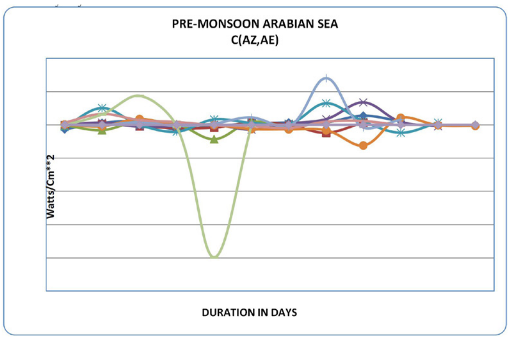

Figure 9 (a). Daily mean composite of C(Az,Ae) – pre monsoon: Arabian Sea

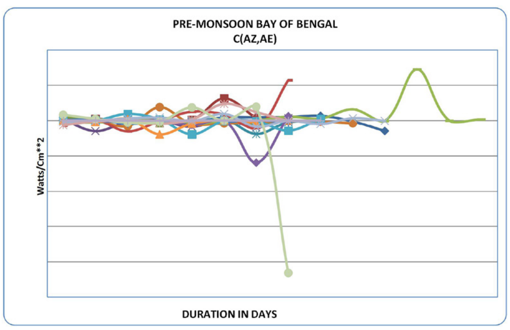

Figure 9 (b). Daily mean composite of C(Az,Ae) – pre monsoon: Bay of Bengal

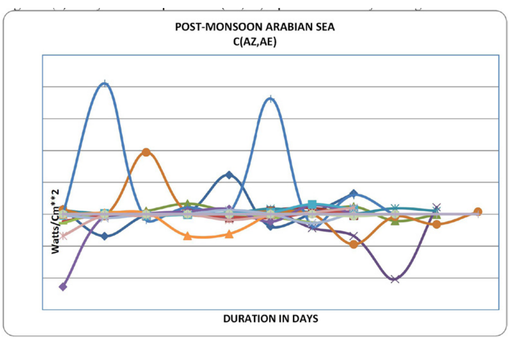

Figure 10 (a). Daily mean composite of C(Az,Ae)– post monsoon: Arabian Sea

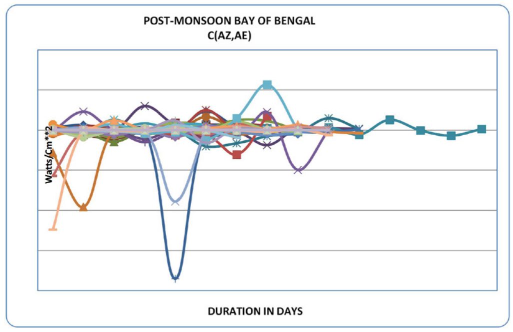

Figure 10 (b). Daily mean composite of C(Az,Ae)– post monsoon: Bay of Bengal

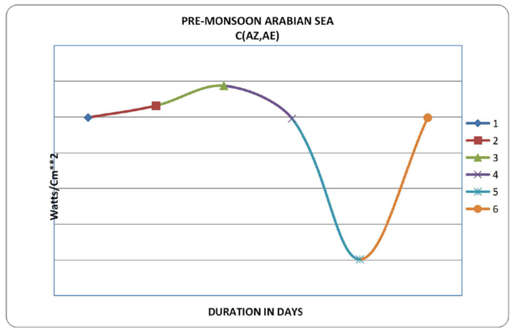

Figure 11 (a). Daily mean of C(Az,Ae) case wise – pre monsoon: Arabian Sea

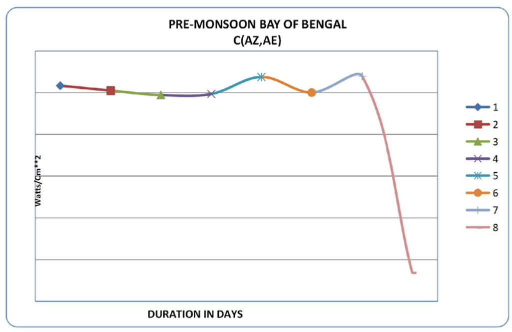

Figure 11 (b). Daily mean of C(Az,Ae) case wise – pre monsoon: Bay of Bengal

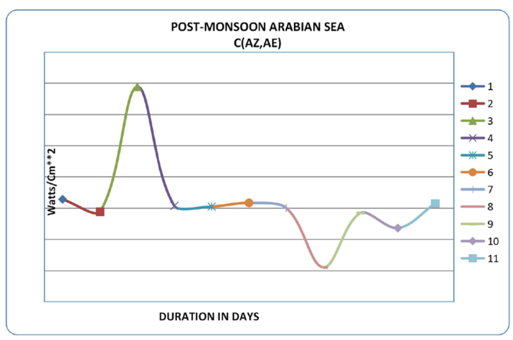

Figure 12 (a). Daily mean of C(Az,Ae) case wise – post monsoon: Arabian Sea

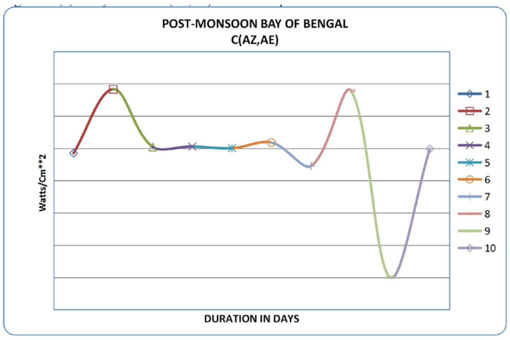

Figure 12 (b). Daily mean of C(Az,Ae) case wise – post monsoon: Bay of Bengal

4. Conclusions

Based on the frequency/ trend analysis of cyclones over the period from 1991 to 2013 following may be concluded:

1) The maximum frequency of formation of cyclones over BOB is twice that over AS. Further, it is noticed that over BOB they are more frequently formed in the post monsoon season compared to pre monsoon season.

2) The overall trend for both basins is of just decreasing type in both seasons. The decreasing trend being more evident in the post monsoon season in case of the AS and in the case of BOB it is more evident in the pre monsoon season.

Based on the computation of various energetic terms and subsequent comparison of the energy conversion terms following may be concluded:

3) In both the seasons, Ae was generated at the cost of Ke on a daily scale in the formative and mature stage of cyclones under study which resulted into their intensification. The same may be attributed to contour trough lagging behind the thermal trough. In the dissipating stage the enhancement of Ke indicates cyclones gained movement in this stage. In both the basins the above pattern was observed, however, certain cyclones over BOB gained movement from the formative stage itself and continued gaining movement till the end of their life-cycle. This is indicative that thermally directed circulation was strong for these cyclones over the entire period.

4) In both the basins, at the time of cyclone intensification; Az is generated at the cost of Kz during pre monsoon. This may be attributed to weakened mean meridional circulation in both basins during the pre monsoon season. However, during post monsoon the continual generation of Kz at the cost of Az of some cyclones may be attributed to strong mean meridional circulation over the systems during that time.

5) In both the basins, the enhancement of Ke and generation of maximum wind speed at the expense of Kz during pre monsoon and post monsoon was during the formative and mature stage. This, along with generation of Ke from Ae for the same period suggests an enhancement of Ke which may be attributed to the enhancement in both the barotropic and baroclinic conversion into Ke. Although there were some cyclones (over both basins) that developed in the post monsoon, which showed a departure from this pattern and had maximum wind speed which was generated at the cost of Kz only during the dissipating stage. It is to be noted that the enhancement in Kz from Az was observed continually over some cyclones in post monsoon. This shows that the energy flow here was Az -> Kz -> Ke.

6) In both the basins, the mid latitude baroclinic circulation might have influenced significantly on the development and intensification of the selected cyclones. However, during dissipation there was hardly any influence of mid latitude baroclinic circulation.

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