A composite energetics study for contrasting south west monsoon years in the recent decade

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RESUMEN

Se hizo un intento para hacer un estudio de energética compuesta para tres tipos contrastantes de la temporada del monzón del suroeste (SWMS, por sus siglas en inglés) en la India: SWMS marginalmente normal (2000 y 2001 cuando la precipitación estacional total fue muy cercana al 90%), SWMS normal (2003, 2005, 2006, 2007 y 2008, cuando la precipitación estacional total fue muy cercana al 100% de su periodo promedio largo), SWMS deficiente (2002, 2004 y 2009, cuando la precipitación estacional total fue menor al 90% de su periodo promedio largo). Para lo anterior, se calculó diariamente, del 1 de mayo al 30 de septiembre, la generación y conversión entre los diferentes términos del promedio decadal para la década 2000-2009 y su anomalía, con base en el promedio decadal, para los diferentes términos energéticos de cada año de esta década, sobre la región limitada entre 65 y 95 ºE 5 y 35 ºN. Estos cálculos se basan en los datos diarios del NCEP de 2.5 º x 2.5º del 1 de mayo al 30 de septiembre de los mencionados diez años. Se construyó el dato compuesto de estas anomalías para los años deficientes del monzón (2002, 2004 y 2009), para los años marginalmente normales (2000 y 2001) y para los años normales (2003, 2005, 2006, 2007 y 2008). En el promedio decadal se observó una caída constante en $C(A_Z, K_Z)$ y $C(A_E, K_E)$ hasta agosto y un incremento constante en $C(A_Z, A_E)$ hasta julio, indicando una supresión de la circulación media del monzón debido a la influencia de los sistemas baroclínicos occidentales de latitud media. El análisis de la anomalía compuesta de los diferentes parámetros energéticos indica que el SWMS deficiente de la década bajo estudio se caracteriza por una circulación media del monzón más débil en comparación con la normal o marginalmente normal en las escalas diaria, mensual y estacional debido a la influencia anómala de los sitemas baroclínicos occidentales de latitud media.

ABSTRACT

An attempt has been made to make a composite energetics study for the three contrasting types south west monsoon season (SWMS) over India, viz. marginally normal SWMS (2000 and 2001 when seasonal total rainfall was very close to 90%), normal SWMS (2003, 2005, 2006, 2007 and 2008 when seasonal total rainfall was very close to 100% of its long period average) and deficient SWMS (2002, 2004 and 2009, when seasonal total rainfall was less than 90% of its long period average). For that, decadal average for the decade 2000-2009 and anomaly, based on above decadal average, for individual year of this decade, of different energy terms, their generation and conversion among different terms have been computed daily during 1 May-30 September in the recent decade (2000-2009) over a limited region between 65º E to 95º E, 5º N to 35 ºN. These computations are based on daily NCEP 2.5º x 2.5º data during 1 May-30 September of the above ten years. The composite of these anomalies have then been constructed for the deficient monsoon years (2002, 2004 and 2009), marginally normal monsoon years (2000 and 2001) and for the normal monsoon years (2003, 2005, 2006, 2007 and 2008). In the decadal average, a steady fall in $C(A_Z, K_Z)$ and $C(A_E, K_E)$ till August and steady rise in $C(A_Z, A_E)$ till July are noticed, indicating a suppressed mean monsoon circulation due to the influence of mid latitude baroclinic westerly systems. Analysis of the composite anomaly of different energetics parameter indicates that the deficient SWM, in the decade under study, are characterized by weaker mean monsoon circulation, as compared to normal or marginally normal SWM, in daily, monthly and seasonal scale, due to anomalous influence of mid latitude baroclinic westerly systems.

Keywords: Energetics, contrasting SW monsoon season.

1. Introduction

The southwest monsoon (SWM) is the backbone of the Indian economy that still thrives on the agriculture sector, which in turn depends heavily on the rainfall vagaries of this season. Despite all the scientific attempts that have been made until now, the monsoon has continued to be a complex system with many unresolved questions, perplexing and baffling at times. Many questions regarding its onset, strengthening, advance and revival from the break conditions have continued to remain unresolved.

The SWM normally sets in over Kerala on 1 June and covers the entire country by 15 July. It generally progresses over India, in a direction from south to north in the peninsular and Central India and from east to west over northern parts of the country. But there are wide variations to this travel time of the monsoon in different years. In the recent decade (2000-2009), there were three years (2002, 2004 and 2009) with deficient all India Summer Monsoon rainfall (ISMR) (seasonal total rainfall less than 90% of its long term average), five years (2003, 2005, 2006, 2007 and 2008) with normal all India SMR (seasonal total rainfall is very close to 100% of its long period average) and two years (2000 and 2001) with all India SMR just marginally normal (seasonal total rainfall very close to 90%) (given in Table I). This is a demonstration of inter-annual variability (IAV) of SWM, which has posed a great challenge to its forecasting. Overall on decadal average basis, the ISMR for the decade 2000-2009 was 6.58% below its long-term normal.

Prediction of the IAV of the ISMR and of the occurrence /nonoccurrence of the extremes (i.e. droughts and excess rainfall seasons) continues to be extremely important, (Gadgil *et al.*, 2007). The inter-annual fluctuations are variously attributed to a wide variety of relationships, from ENSO to Eurasian snow cover and to the Indian Ocean Dipole (IOD). The IAV of the South Asian monsoon has been the subject of extensive research. During the last decade a number of studies have appeared in the literature regarding the inter-annual and intra-seasonal variability of the lower-tropospheric monsoon circulation. Webster *et al*. (1998), using the composite mean monthly outgoing longwave radiation (OLR) and circulation fields, found that at the time of the summer monsoon both the low-level westerlies and the upper level easterlies are considerably stronger during strong monsoon years than during weak years. Their study suggests that the anomalies signify external influences from a broader scale into the monsoon system.

Table I. Monthly and seasonal rainfall during the Southwest Monsoon season over India during the recent decade 2000-2009.

	Monthly and seasonal rainfall departure in %					
Year	Jun	Jul	Aug	Sep	Jun-Sep	Category
2000	14.9	–7.7	–12.7	–21.9	–7.8	Marginally normal
2001	35.6	–4.8	–19.5	–35.8	–7.8	Marginally normal
2002	9.4	–54.2	–1.7	–12.9	–19.2	Deficient
2003	9.8	6.5	–4.5	–1.5	2.3	Normal
2004	–0.8	–19.9	–4.3	–30.0	–13.8	Deficient
2005	–9.5	14.7	–28.4	20.3	–1.3	Normal
2006	–12.7	–2.0	7.3	2.3	–0.4	Normal
2007	18.5	–2.4	–1.8	18.4	5.7	Normal
2008	24.3	–16.5	1.4	–5.5	–1.7	Normal
2009	–47.2	–4.3	–26.5	–20.2	–21.8	Deficient
Decadal average	4.23	–9.06	–9.07	–8.68	–6.58	

Annamalai *et al*. (1999) studied the behavior of the Asian summer monsoon using the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA) and the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis. In terms of IAV, inconsistencies were noticed in the definition of weak and strong monsoon years based on typical monsoon indices such as All-India Rainfall (AIR) anomalies and the large-scale wind shear based dynamical monsoon index (DMI). They identified two dominant modes of IAV that together explain nearly 50% of the variance. Individually, they have many features in common with the composite flow patterns associated with weak and strong monsoons, when defined in terms of regional AIR anomalies and the large-scale DMI.

Krishnamurthy and Shukla (2000) used a gridded daily rainfall dataset prepared from observations at 3700 stations to analyze the intra-seasonal and inter-annual variability of the summer monsoon rainfall over India. They found that the major drought years are characterized by large-scale negative rainfall anomalies covering nearly all of India and persisting for the entire monsoon season. Their study suggests that a simple conceptual model to explain the IAV of the Indian monsoon rainfall should consist of a linear combination of a large-scale persistent seasonal mean component and a statistical average of intra-seasonal variations.

Sperber *et al*. (2000) investigated the relationship between sub-seasonal and IAV of the Asian summer monsoon through analysis of the dominant modes of variability in the 40-year NCEP/NCAR Reanalysis, with complementary satellite and surface-based precipitation data. In this study they performed the statistical test for the hypothesis that the characteristics of monsoon sub-seasonal variability (i.e. weather regimes) are modulated on inter-annual time-scales in a systematic and, therefore, in a predictable manner. This study had identified an inter-annual mode of monsoon variability which is closely related to the observed seasonal mean AIR. A counterpart of this mode has also been identified at sub-seasonal time-scales which projects strongly on to the daily AIR, confirming that a common mode of monsoon variability exists on sub-seasonal and inter-annual time-scales.

Goswami and Ajaya Mohan (2001) investigated how and to what extent the intra-seasonal oscillations (ISO) influence the seasonal mean and its IAV of the Indian summer monsoon.

They found that both ISO and IAV are governed by a common mode of spatial variability. They found similarity between the spatial pattern of standard deviation of intra-seasonal and IAV of low-level vorticity and between the spatial pattern of the dominant mode of ISO variability of the low-level winds and that of the IAV of the seasonal mean winds. The similarity between the spatial patterns of the two modes of variability indicates that higher frequency of occurrence of active (break) conditions would result in ‘‘stronger’’ (‘‘weaker’’) than normal seasonal mean. The study indicates that the strong (weak) monsoon years are associated with higher probability of occurrence of active (break) conditions.

Dynamical understanding of IAV is very much essential. Energetics is one of the very useful and interesting tools for diagnosing many atmospheric phenomena dynamically. Several studies have been carried out to analyze the contrasting circulation features and energetics of normal and deficient monsoon seasons. Joseph (1975) found that large scale failures of SWMR over India during 1965, 1966, 1968, 1972 and 1974 occurred in the triennial oscillation of the upper tropospheric wind in the equatorial region of Asia and Africa. Kanamitsu and Krishnamurti (1978) attempted to assimilate some properties of the circulation regimes during a normal rainfall year and a drought year over the global tropical belt during the northern summer months. Differences in the barotropic energetics were found to be one component among the various contrasts. In particular, they found that during the normal monsoon year, the long waves were a major energy source for all other waves as well as to the zonal flows, whereas during drought year the zonal mean flows were the major energy source for long waves as well as for short waves. Ramesh *et al*. (1996) studied the intra-seasonal characteristics of the two contrasting Asian summer monsoon in the years of 1987 and 1988. They found that the excess rainfall season (1988) is characterized by much stronger tropical easterly jet (TEJ) associated with the upper tropospheric easterlies and the East African low level jet (Somali Jet) associated with lower tropospheric westerlies. Further, the energetics of the TEJ showed that the monsoon of 1988 had comparatively stronger zones of kinetic energy flux divergence (convergence) at its entrance (exit) regions. These zones of kinetic energy flux divergence are largely maintained by the adiabatic processes over the strong kinetic energy flux divergence zones over the Bay of Bengal and east central Arabian Sea as compared to that of 1987.

There are a number of studies on the energetics aspects on onset, progress and maintenance of mean monsoonal circulation. Rao and Rajamani (1972) studied the heat source and sinks and generation of available potential energy of the atmosphere over the Indian region during SWMS. Their computation showed a net generation of available potential energy (APE) over the region of study. Keshavamurty and Awade (1974) showed that during strong monsoon condition the reverse Hadley circulation is stronger but the Walker circulation becomes weaker, resulting into positive conversion $C(A_z, K_z)$ and negative $C(A_E, K_E)$. Krishnamurti and Ramanathan (1982) have shown that a sharp rise in the rotational kinetic energy is an interesting aspect of onset of Indian summer monsoon (ISM). Awade and Bawiskar (1982) have shown that bad monsoon activity is associated with large divergence of heat in the sub-tropics and large convergence of heat in the extra-tropics. Awade *et al*. (1985) have shown that in good monsoon years there is large divergence of momentum in the sub-tropics, while there is large convergence of momentum in mid-latitudes. They argued that this situation leads to a stronger westerlies in mid-latitudes and stronger easterlies in the tropics. Krishnamurti (1985) has shown that divergent kinetic energy must be transferred to rotational kinetic energy, and available potential energy must be transferred to divergent kinetic energy via rising motion over the warm region/sinking motion over the cold region. He has also shown that available potential energy is maintained via heating of warmer air and cooling of colder air.

Rajamani (1985) studied the transformation of APE into kinetic energy. This study shows that differential heating between the Asian landmass and the Indian Ocean causes the generation of zonal APE (A_z), a part of which is converted into zonal kinetic energy (K_z). The study also indicates that diabatic heating generates standing eddy APE (A_E), which is again converted into standing eddy kinetic energy. Krishnamurti and Surgi (1987) have shown that around the period of the onset of monsoon rains over India, there is a sharp rise in the conversion zonal available potential energy to zonal kinetic energy. Yanai *et al.* (1992) showed that the reversal of north-south temperature gradient in the layer between 700 and 200 hPa triggers the onset of the South Asian monsoon.

Krishnamurti *et al.* (1998) studied the energetics of the South Asian monsoon and examined its maintenance using the FSU Global spectral model at T170 resolution. This study indicates that differential heating leads to the growth of APE, which is then passed-on to the divergent motions and then finally divergent kinetic energy (*K.E*) is converted to rotational (*K.E*), which of course critically depends on the orientation of the isopleths of the streamfunction (ψ) and the velocity potential (χ). Results of the study by Wu and Zhang (1998) are in conformity with that of Yanai *et al.* (1992). These studies indicate that during the onset of the South Asian monsoon there is a sudden increase in the zonal APE. Raju *et al*. (2002) studied contrasting features of surplus and deficient monsoon seasons based on mean circulation characteristics and large scale energetic. They found significantly large quantity of diabatic heating, adiabatic generation of (*K.E*) and horizontal convergence of heat and moisture during surplus monsoon compared with the deficient state. Rao (2006) studied the (*K.E*) budget using daily averaged (0000 and 1200 UTC) reanalysis data for the forty year (1960-1999) period (NCEP/NCAR). He studied these aspects during the evolution and established phases of monsoon and showed that in the lower troposphere (*K.E*) is balanced by adiabatic generation and frictional dissipation and in the upper troposphere the same is being done by adiabatic generation and flux divergence. The adiabatic generation of (*K.E*) within boundary layer is mostly due to meridional component. The study also indicates that the adiabatic generation of (*K.E*) is driven by the zonal component during the evolution phase and by the meridional component during the established phase. Rao and Mohanty (2007) have shown that the onset of the Indian southwest monsoon over the Bay of Bengal is discernible by a gradual increase in the adiabatic generation of (*K.E*), while over the Arabian Sea it is first noticeable by a steep and abrupt increase of such generation.

Dutta *et al.* (2009), using NCEP daily composite mean data, studied the energetics aspects of hiatus in the advance of the SWM. They found that the hiatus is associated with a fall in the conversion $C(A_Z, K_Z)$ which in turn is apparently due to anomalous cooling of northern latitude caused by frequent passage of mid-latitude westerly systems. Dutta *et al.* (2011) made a dynamical comparison of the two recent drought years 2002 and 2009 from an energetics point of view. Their study reveals that in 2009 the mean monsoon circulation itself was weaker due to anomalous cooling of northern latitudes caused by larger influence of mid latitude westerlies.

The decade 2000-2009 has witnessed three deficient SWM years, two marginally normal SWM years (marginally normal towards negative side) and two normal SWM years. In the past also we had decades which witnessed three deficient years, details of which are given in Table II. It can be seen in the table that, using the drought area index (DAI) (Bhalme and Mooley, 1980), the decade 1911-1920 was the worst decade and 2000-2009 is the second worst. Although 1911-1920 was the worst decade it still witnessed one excess year. From the table it is also clear that each of the past

Table II. Details of the seasonal rainfall during the Southwest Monsoon for previous decades.

Decade	Years of deficient rainfall	Number of years with excess rainfall	Drought Area Index (%)
1901-1910	1901, 1904, 1905	1	31.3
1911-1920	1911, 1918, 1920	1	42.6
1961-1970	1965, 1966, 1968	1	30.3
1971-1980	1972, 1974, 1979	2	34.3
1981-1990	1982, 1985, 1986, 1987	2	36
2000-2009	2002, 2004, 2009	0	40

decades has witnessed at least one year with excess SWM rainfall. But the decade 2000-2009 is a special one, with no year with excess SWM rainfall.

The objective of the present study is to make a composite energetics study for the contrasting SWM seasons in the recent decade 2000-2009, characterized by below normal rainfall of the monsoon season over India. This would allow us to understand the role played by atmospheric energetics in the performance of the monsoon on a decadal basis.

2. Data

The data comprise daily averaged (0000, 0600, 1200 and 1800 UTC) reanalysis of meteorological parameters (temperature, u-component, v-component, vertical velocity (omega)) for the months of May, June, July, August and September during 2000-2009. The data over the domain (5º N to 35º N, 65º E to 95º E) is extracted from the global reanalysis of NCEP. Data used for the study is at the standard isobaric levels viz. 1000, 925, 850, 700, 500, 300, 200, 100 hPa. The reanalysis data produced by NCEP have a horizontal resolution of 2.5º on a regular latitude/longitude grid.

3. Methodology

First, from the temperature data, at each grid point, the heating rate $\frac{\dot{Q}}{C_p}$ has been computed using the first law of thermodynamics $\frac{\dot{Q}}{C_p} = \frac{dT}{dt} - \frac{\alpha}{C_p}\omega$. In the computation of $\frac{dT}{dt}$, the tendency has been neglected. Then, following Krishnamurti and Bounoua (2000), 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:

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

Area average: $$\overline{S} = \frac{1}{\sin\varphi_n - \sin\varphi_s} \int_{\varphi_s}^{\varphi_n} \left[S\right] \cos\varphi d\varphi \quad (2)$$

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

Departure from zonal average: $S' = S - [S]$ (4)

Departure of zonal average from area average: $S^* = [S] - \overline{S}$ (5)

Then using (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, following Krishnamurti and Bounoua (2000), 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 $C(A_Z, K_E)$ 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.

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

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

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

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

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

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

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

and

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

The above computations were made daily from 1 May to 30 September for all the ten years from 2000 to 2009. The decadal average, for the decade 2000-2009, of the above energetics parameters have been computed, from which daily anomalies were computed for all 10 years. Then composite anomalies of daily values of these parameters have been constructed, separately, for normal monsoon years (2003, 2005, 2006, 2007 and 2008), marginally normal monsoon years (2000 and 2001) and for deficient monsoon years (2002, 2004 and 2009). From these daily composite values, monthly total and seasonal total have also been computed.

4. Results and discussions

4.1 Analysis of decadal averaged energetics

Decadal average of the monthly and seasonal total of $G(A_Z)$, $G(A_E)$, $C(A_Z, K_Z)$, $C(A_E, K_E)$, $C(A_Z, A_E)$ are shown in figures 1 through 5. Figure 1 indicates that there was generation of A_z in all months and in the season as a whole. Dissipation of A_E in all months and in the season as a whole, except in June, can also be noticed from Figure 2.

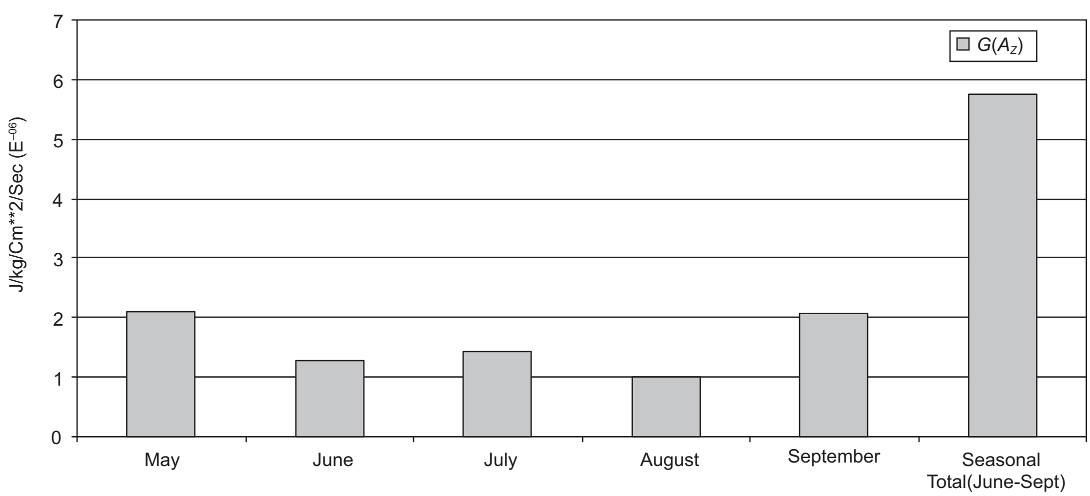

Fig. 1. Monthly and seasonal total $G(A_Z)$: decadal average (2000-2009).

Figure 3 shows that, in the decadal average, $C(A_Z, K_Z)$ was positive in all the months except in August. So, in the decadal mean also, the mean monsoon circulation was very weak/reversed in August. This is in conformity with the fact that in August, decadal average rainfall is least (–9.07 %), seen in Table I.

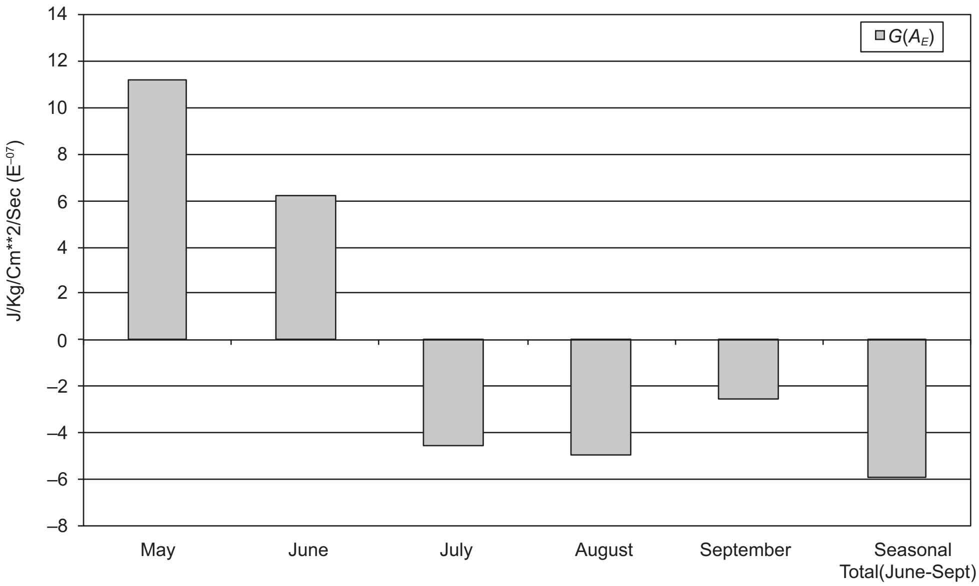

Fig. 2. Monthly and seasonal total $G(A_E)$: decadal average (2000-2009).

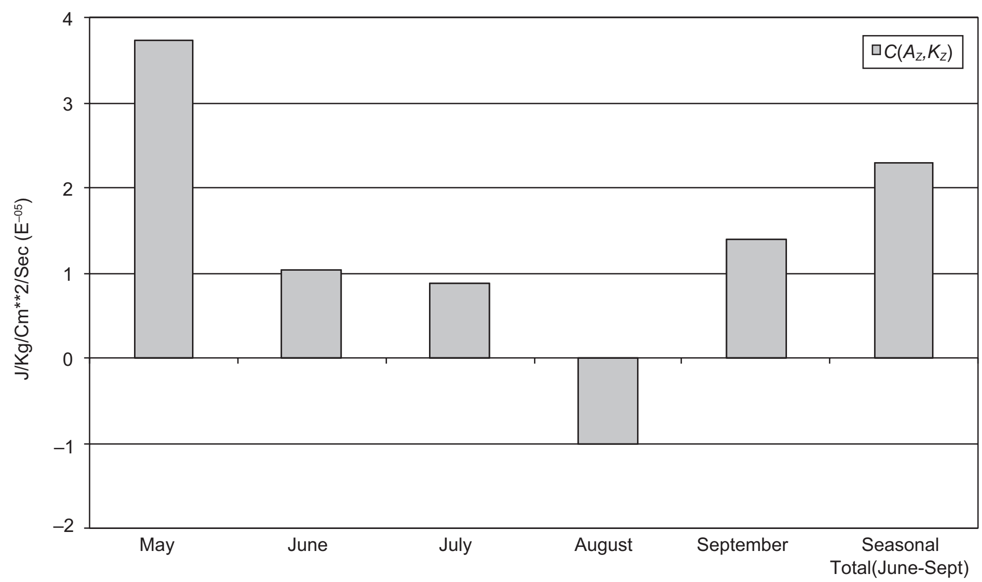

Fig. 3. Monthly and seasonal total $C(A_Z, K_Z)$: decadal average (2000-2009).

Figure 4 indicates that, throughout the season, instead of A_E being converted to K_E, K_E was converted to A_E. It is also well known (Holton, 2004) that K_E is converted to A_E when the contour trough in mid latitude westerly lags behind the thermal trough. In such case the westerly trough gets intensified instead of being moved eastward. Thus, it appears that in the decadal scale, mid latitude westerly systems have affected the mean monsoon circulation maximum in July and August.

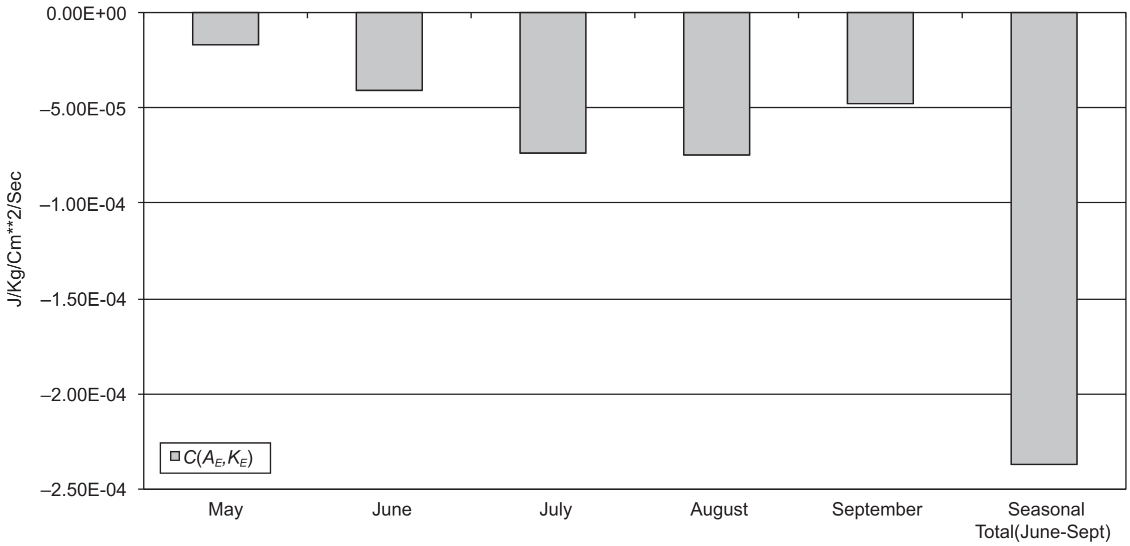

Fig. 4. Monthly and seasonal total $C(A_E, K_E)$: decadal average (2000-2009).

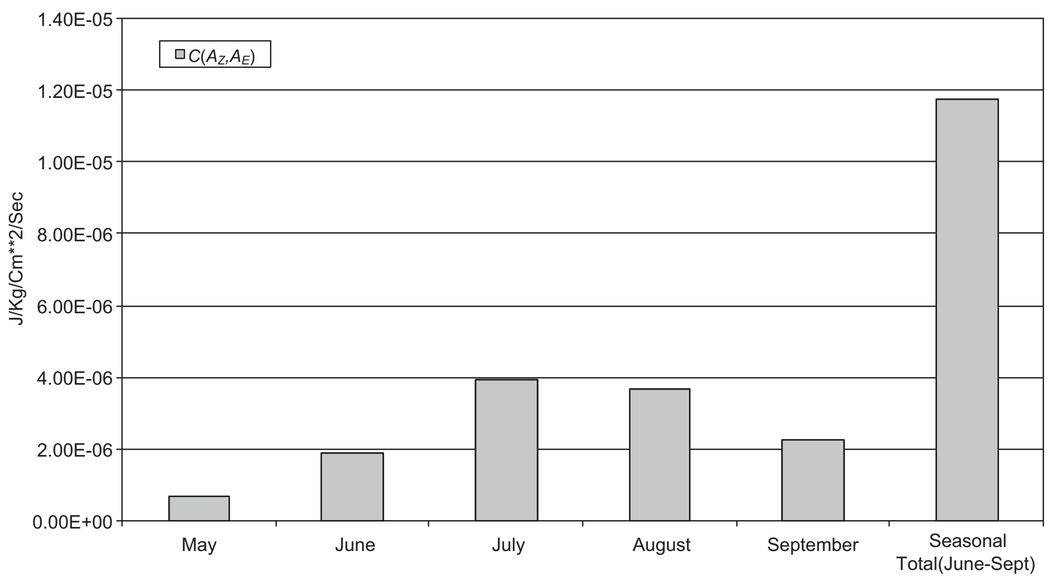

Fig. 5. Monthly and seasonal total $C(A_Z, A_E)$: decadal average (2000-2009).

Figure 5 shows that C (A_Z, A_E), which indirectly indicates the influence of mid latitude westerlies on the mean monsoon circulation, was positive in all months, with maximum in July and August. This result is also in conformity with the fact that the decadal average rainfall in July and August were minimum. It can also be seen from these figures that after May, $C(A_Z, K_Z)$ has been reduced to about one third of its value, where as $C(A_Z, A_E)$ has steadily increased from May to July. So, in this decade, the mid latitude westerly circulation has weakened the mean monsoon circulation by extracting A_Z at a much greater rate.

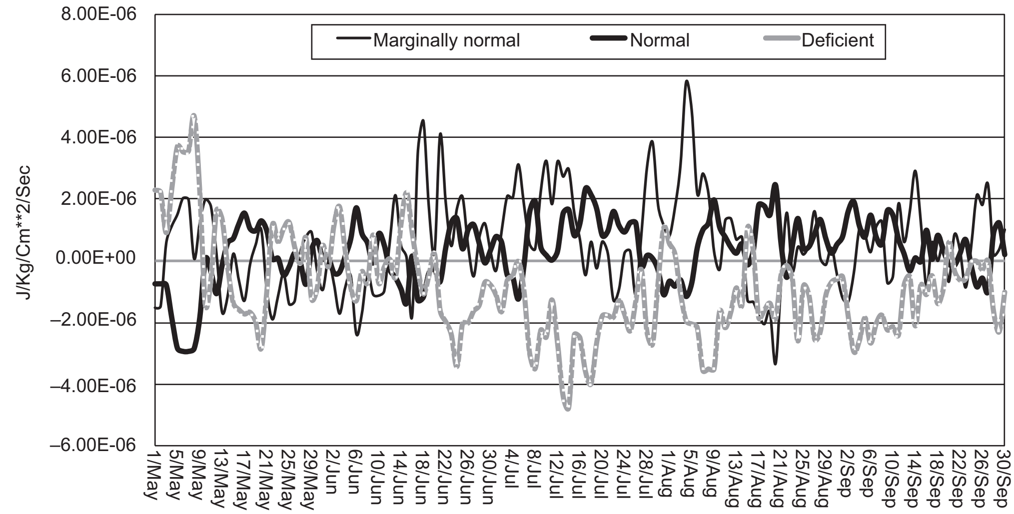

Fig. 6. Daily composite anomaly of $C(A_Z, K_Z)$.

4.2 Analysis of composite anomaly

4.2.1 Composite anomaly of $C(A_Z, K_Z)$

Daily composite anomaly of $C(A_Z, K_Z)$ for normal SWM, marginally normal SWM and deficient SWM are shown in Figure 6. It can be seen that in the deficient years there are a number of longer spells (10 days or more) during the monsoon season with negative $C(A_Z, K_Z)$, where as in other two types of SWM we find comparatively very short spells (2-4 days) with $C(A_Z, K_Z)$ negative. As it is known from Krisnamurti (1985) and Krishnamurti *et al*. (1998), that the mean monsoon circulation is maintained by converting A_Z into K_Z, thus a negative $C(A_Z, K_Z)$ in the composite anomaly signifies

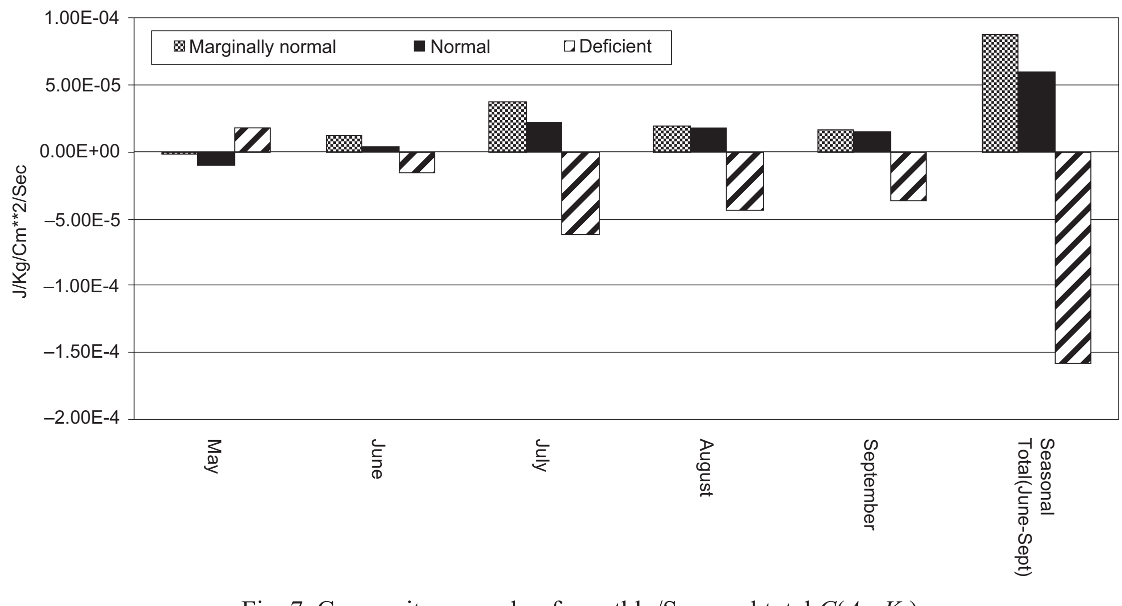

Fig. 7. Composite anomaly of monthly/Seasonal total $C(A_Z, K_Z)$.

that, in the deficient years of the decade under study, the mean monsoon circulation was weaker than normal, at a daily scale. As seen in Figure 7, where monthly and seasonal total composite anomaly of $C(A_Z, K_Z)$ for three types of SWM are shown, then following the above argument, it can be easily noted that the mean monsoon circulation was weaker than normal in the deficient SWM, in monthly as well as in seasonal scale.

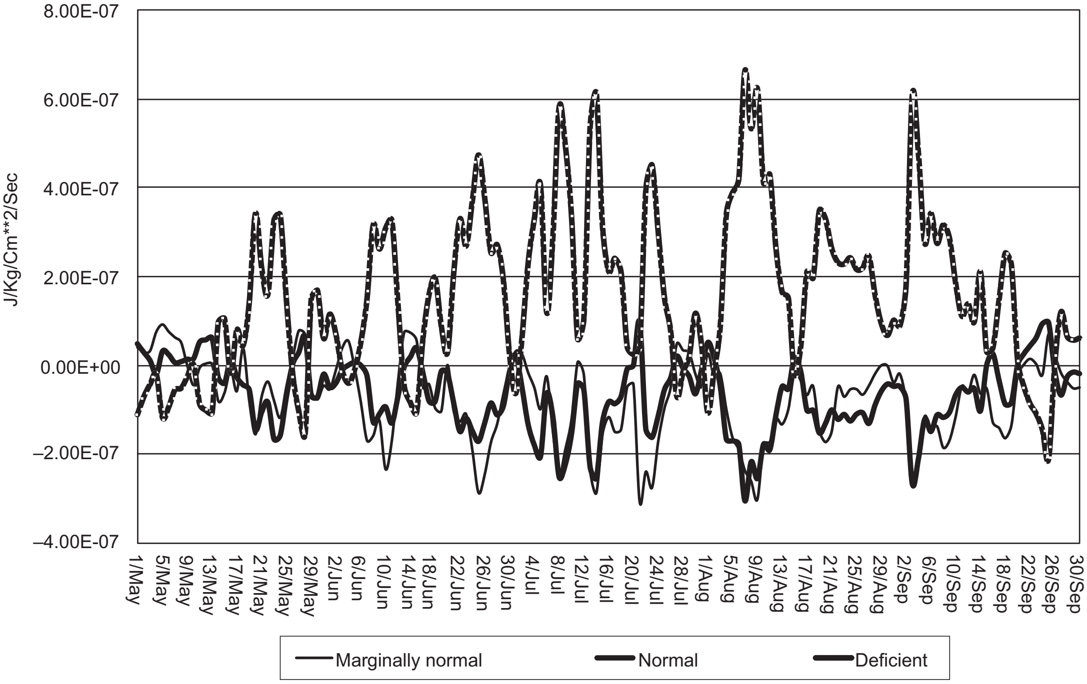

Fig. 8. Daily composite anomaly of $C(A_Z, A_E)$.

4.2.2 Composite anomaly of $C\ (A_Z, A_E)$

The daily composite anomaly of $C\ (A_Z, A_E)$ for three types of SWM is shown in Figure 8. Very easily one can find that $C\ (A_Z, A_E)$ was negative almost throughout the season in the case of normal or marginally normal SWM and was positive for deficient SWM.

It is well known that baroclinic waves in the mid-latitude zonal westerly flow grow by extracting A_Z (Holton, 2004). Thus, a positive $C(A_Z, A_E)$ in the composite anomaly signifies an enhanced influence of mid-latitude baroclinic westerly systems on the mean monsoon circulation. So, in the deficient years, the mean monsoon circulation was affected by enhanced activities of the mid-latitude westerly systems, at a daily scale, than in normal or marginally normal SWM. One can also draw a similar conclusion (Fig. 9) for monthly and seasonal scales.

4.2.3 Composite anomaly of $C(A_E,K_E)$

Figures 10 and 11 show, respectively, the daily and monthly/seasonal total composite anomaly of $C(A_E, K_E)$ for the three types of SWM mentioned in our earlier discussion. Figure 9 shows that for normal or marginally normal SWM, the conversion $C(A_E, K_E)$ was positive almost daily, except during some shorter spells when it had comparatively smaller negative values during

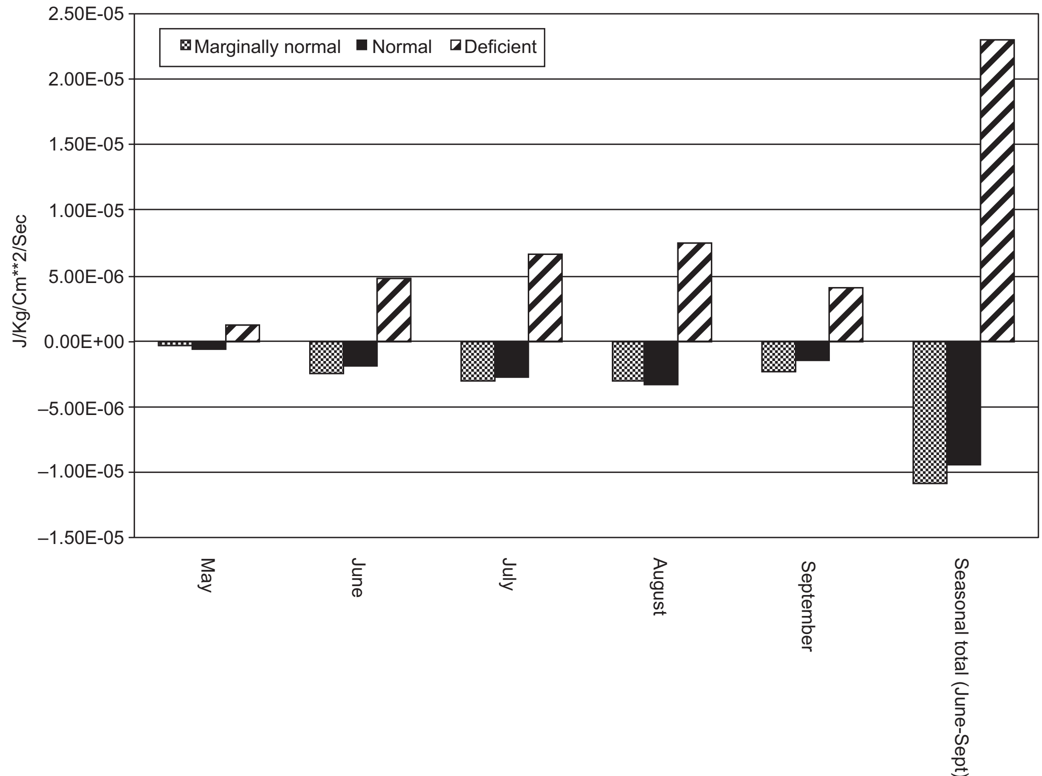

Fig. 9. Composite anomaly of monthly/Seasonal total $C(A_Z, A_E)$.

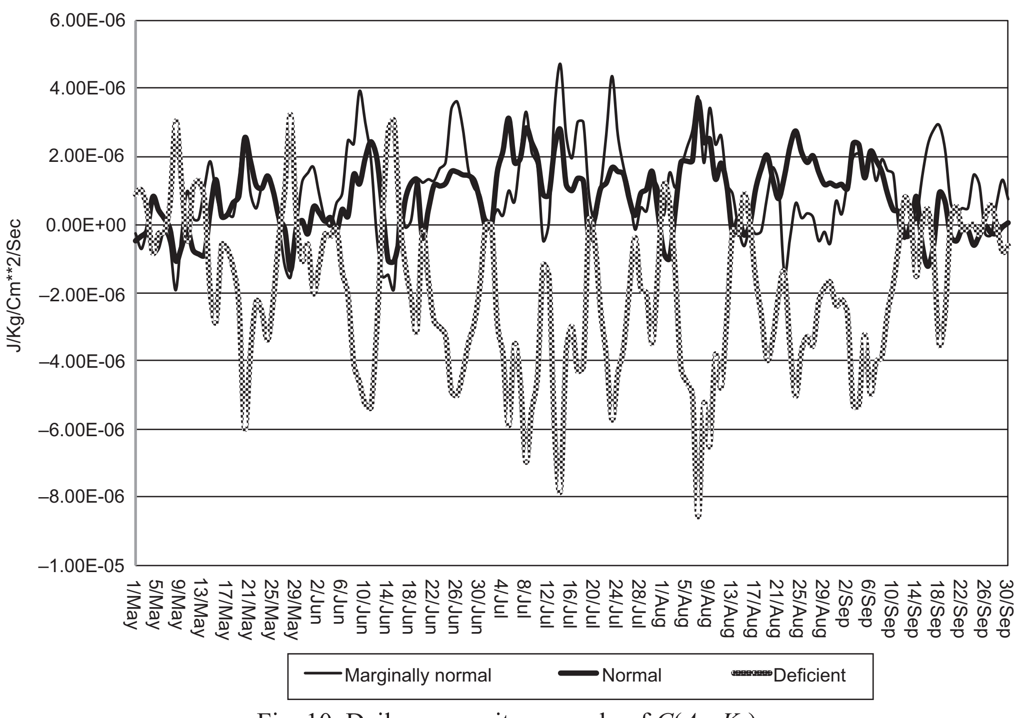

Fig. 10. Daily composite anomaly of $C(A_E, K_E)$.

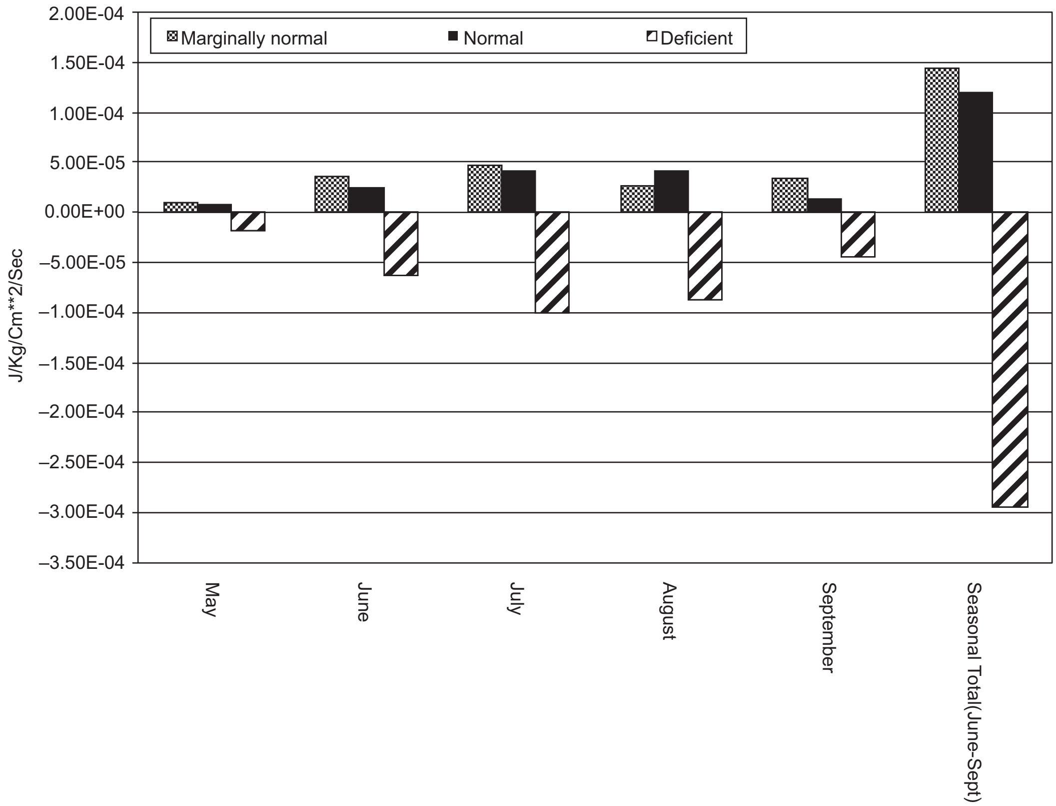

Fig. 11. Composite anomally of monthly/Seasonal total $C(A_E, K_E)$.

the SWM season. But for deficient years, we find a number of very long spells when $C(A_E, K_E)$ was negative. Similar arguments for monthly as well as for seasonal scales also hold, as seen in Figure 11.

5. Summary and conclusions

From the analysis of decadal energetics made in the previous section, we have seen that in the monthly total, the conversion $C(A_Z, K_Z)$ was negative in August, $C(A_Z, A_E)$ was positive in all months with maximum positive in July and August and $C(A_Z, K_E)$ was negative in all months with maximum negative in July and August. From the expression of $C(A_Z, K_Z)$ it appears that it is positive if there is net rising motion of relatively warmer air and net sinking motion of relatively colder air. During the summer, northern latitudes are warmer and southern latitudes are colder. Then rising motion over the warmer north and net sinking motion over the colder south sets up a solenoidal circulation, maintaining the mean monsoon circulation. A positive $C(A_Z, K_Z)$ indicates a direct monsoon circulation, so if $C(A_Z, K_Z)$ is negative then the monsoon circulation is either reversed or weakened. On average, the mean monsoon circulation was weaker in August in the decade under study. This analysis is in conformity with Krishnamurti *et al*. (1998) who showed that during strong monsoon conditions the zonal available potential energy must be converted to divergent kinetic energy by the above-mentioned solenoidal circulation.

From the expression of $C(A_Z, A_E)$ it appears that a positive value of $C(A_Z, A_E)$ requires $\frac{\partial T^*}{\partial y}$ and $\overline{v'T'}$ to be of opposite signs. Again, it is known that for growing baroclinic waves, in mid-latitude zonal westerlies, $\overline{v'T'}$ is positive. They may be of opposite signs if the normal north-south temperature gradient in the region of study is reversed in the presence of growing mid-latitude baroclinic waves or if there is a decaying baroclinic wave in the presence of the normal north-south temperature gradient. This conversion term may be thought to quantify the influence of mid-latitude westerlies on the monsoon circulation. Hence, it appears that on average during July and August in this decade, the influence of mid latitude westerlies on the mean monsoon circulation was larger. Negative value of $C(A_E, K_E)$ during the months of SWM along with large negative values during July and August of the decade, indicates that in this decade the Walker circulation was weaker than normal during the SWM months, being weakest in July and August. In the above discussions already we have seen the possibility of the presence of mid-latitude westerly systems (high positive $C(A_Z, A_E)$). In such case, a large negative value of $C(A_E, K_E)$ signifies rising motion over the cold part and sinking motion over the warm part, leading to the intensification of mid-latitude westerly systems. So, it appears that in this decade, on average during July and August, atmospheric condition lead to the intensification of mid-latitude westerly systems, which in turn might have affected the mean monsoon circulation.

In our discussion of the energetics analysis of the composite anomaly made in the previous section, we have seen that as compared to normal or marginally normal SWM, during the deficient SWM at the daily scale there were a number of long spells when $C(A_Z, K_Z)$ was negative and in the monthly scale it was negative in every month from June to September. Seasonal total was also negative for the deficient SWM. Hence, for normal or marginally normal SWM, the mean monsoon circulation was stronger than normal and it was weaker than normal for deficient SWM. From the expression of $C(A_Z, K_Z)$, it appears that the above may be attributed to an enhanced south to north temperature gradient in normal or marginally normal SWM and to a reduced south to north temperature gradient in the deficient SWM. We have also seen that for the deficient years, composite anomaly of $C(A_Z, A_E)$ was positive on almost daily scale resulting into positive monthly total for every month as well as positive seasonal total. The opposite is the case for normal or marginally normal SWM.

It is known that for both the monsoon circulation and mid-latitude baroclinic westerly systems, the energy reservoir is zonal available potential energy (A_Z). The monsoon circulation becomes stronger if the zonal available potential energy is converted to zonal kinetic energy (K_Z) at a greater rate than the rate at which it is converted to eddy available potential energy (A_E). Hence it appears that for normal or marginally normal SWM, the monsoon circulation dominates over the mid-latitude westerly circulation and for deficient SWM, the former one is dominated by the latter one.

We have also seen that as compared to normal or marginally normal SWM, for the deficient SWM, at the daily scale there were a number of long spells when $C(A_E, K_E)$ was negative and at the monthly scale it was negative in every month from June to September. Seasonal total was also negative for deficient SWM. It is known that, once a baroclinic wave in the mid-latitude zonal westerly flow is generated then it gets kinetic energy by the conversion from A_E to K_E. Thus a positive $C(A_E, K_E)$ signifies conducive condition for movement of westerly systems. Hence, during deficient years, mid latitude westerly systems were stagnant or slower than normal, which causes more cold northerly advection to the warmer northern latitudes causing a reduction in $C(A_Z, K_Z)$ and thus reducing the mean monsoon circulation. For the normal or marginally normal SWM although there were mid-latitude westerly systems present, a positive $C(A_E, K_E)$ in the composite anomaly signifies comparatively faster movement.

From the above study the following conclusions can be made:

1. In the decadal scale, mid latitude westerly systems appears to have affected the mean monsoon circulation maximum in July and August. This is reflected from maximum positive value in the monthly total decadal averaged $C(A_Z, A_E)$ and also from maximum negative value in the monthly total decadal averaged $C(A_E, K_E)$ in July and August.
2. The mean monsoon circulation in deficient monsoon years was weaker than that in normal or marginally normal monsoon year, which is reflected by large negative seasonal total (June-Sept.) as well as monthly total in the composite anomaly of conversion from zonal available potential energy to zonal kinetic energy $C(A_Z, K_Z)$ in deficient monsoon years, whereas in the case of normal/marginally normal monsoon years such conversion was positive.
3. In the daily distribution there were long spells in deficient monsoon years when the composite anomaly of $C(A_Z, K_Z)$ was negative, indicating weaker mean monsoon circulation at the daily scale. In normal/marginally normal monsoon years, although there were spells with negative $C(A_Z, K_Z)$, these spells were comparatively much shorter.
4. The influence of mid-latitude baroclinic westerly systems on the mean monsoon circulation was larger during deficient SWM than during normal/marginally normal SWM, at daily, monthly and seasonal scales. This is reflected from positive (negative) values in the composite anomaly of $C(A_Z, A_E)$ for deficient (normal/marginally normal) SWM, at daily, monthly and seasonal scales.
5. As compared to normal or marginally normal SWM, in the deficient SWM, the mid-latitude westerly systems appear to be more sluggish in movement which might have caused their intensification. This feature is derived from negative (positive) values in the composite anomaly of $C(A_E, K_E)$ for deficient (normal/marginally normal) SWM, at daily, monthly and seasonal scales.

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