

A dynamical comparison between two recent drought southwest monsoon seasons 2002 and 2009 over India

SOMENATH DUTTA, S. G. NARKHEDKAR*, D. R. SIKKA** and SUNITHA DEVI

India Meteorological Department, Pune, India

**Indian Institute of Tropical Meteorology, Pune, India*

***40, Mausam Vihar, Delhi – 110 051, India*

(Received 7 May 2010, Modified 27 August 2010)

e mail : dutta.dr.somenath@gmail.com

सार – इस शोध पत्र में ऊर्जा विज्ञान के परिप्रेक्ष्य में हाल के दो सूखा वर्षों 2002 और 2009 की गतिकीय रूप से तुलना करने का प्रयास किया गया है। ऐसी विभिन्न ऊर्जा की अवधियों के लिए 65° पू. से 95° पू., 5° उ. से 35° उ. के बीच के सीमित क्षेत्र के उक्त दो वर्षों के 01 मई से 30 सितम्बर के दौरान की विभिन्न अवधियों में उनके उत्पन्न होने और उनके रूपान्तरित होने का आकलन किया गया है। ये आकलन 01 मई से 30 सितम्बर के दौरान उक्त दो वर्षों के दैनिक एन.सी.ई.पी. 2.5° X 2.5° आँकड़ों पर आधारित हैं।

इस अध्ययन से पता चला है कि यद्यपि दोनों वर्षों में सूखा पड़ा परन्तु 2002 की तुलना में 2009 में माध्य मॉनसून परिसंचरण दैनिक, मासिक, और मौसमी पैमाने पर काफी कमजोर रहा। दैनिक पैमाने पर माध्य मॉनसून परिसंचरण के कमजोर होने के कारण जून से सितम्बर 2009 के दौरान तुलनात्मक रूप से मॉनसून के दौर लंबे रहे जिसमें क्षेत्रीय उपलब्ध विभव ऊर्जा से क्षेत्रीय गतिज ऊर्जा $[C(A_z, K_z)]$ के रूपान्तरण का मान नकारात्मक रहा। $C(A_z, K_z)$ के मौसमी कुल मान और मासिक कुल मान के बड़े नकारात्मक मानों से मासिक और मौसमी पैमाने पर माध्य मॉनसून परिसंचरण के कमजोर होने का पता चलता है।

इस अध्ययन से यह भी पता चला है कि दोनों वर्षों में उपलब्ध क्षेत्रीय विभव ऊर्जा से उपलब्ध भंवर विभव ऊर्जा $[C(A_z, A_E)]$ के रूपान्तरण के मौसमी कुल मान (जून से सितम्बर) सकारात्मक थे परन्तु 2009 में इसके परिमाण का क्रम $10^{-4} \text{ J/kg/cm}^2/\text{sec}$ था जबकि 2002 में यह $10^{-6} \text{ J/kg/cm}^2/\text{sec}$ था जिससे यह पता चलता है कि मध्य-अक्षांशीय पश्चिमी पवनों का प्रभाव 2009 में काफी अधिक था जिसके कारण 2009 में माध्य मॉनसून परिसंचरण कमजोर रहा।

ABSTRACT. An attempt has been made to compare dynamically the recent two drought years, *viz.*, 2002 and 2009, from energetics aspects. For that different energy terms, their generation and conversion among different terms have been computed during 1st May - 30th September for the above two years over a limited region between 65° E & 95° E, 5° N & 35° N. These computations are based on daily NCEP 2.5° × 2.5° data during 1st May - 30th September of the above two years.

The study shows that although for both the years we had drought, the mean monsoon circulation itself was much weaker in 2009 as compared to 2002, in daily, monthly as well as in the seasonal scale. The weaker mean monsoon circulation, in daily scale, has been demonstrated by comparatively longer spells during June-September 2009 with negative value of conversion of zonal available potential energy to zonal kinetic energy $[C(A_z, K_z)]$. Large negative values of the monthly total as well as seasonal total of $[C(A_z, K_z)]$ indicate weaker mean monsoon circulation in monthly and in the seasonal scale.

The study also shows that in both years, the Seasonal total (June-September) of conversion of zonal available potential energy to eddy available potential energy $[C(A_z, A_E)]$ was positive, but in 2009 its order of magnitude was

10^{-4} J/kg/cm²/sec where as in 2002 it was 10^{-6} J/kg/cm²/sec, indicating that the influence of mid-latitude westerly was much more in 2009, which may have attributed towards weaker mean monsoon circulation in 2009.

Key words – Energetics, South west monsoon, KE, APE, Drought.

1. Introduction

Southwest monsoon is the backbone of 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 be unresolved.

Southwest monsoon (SWM) normally sets in over Kerala on 1st June and covers the entire country by 15th July. Then 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 monsoon in different years. A drought over the country is declared when the all-India monsoon (June to September) rainfall is less than 90% of long period average and at least 20% of the country experiences rainfall deficiency of 25% or more. In the current decade (2000-2009) two all India drought years have been witnessed, *viz.*, 2002 and 2009. After a continuous spell of 14 good monsoons since 1987, the year 2002 became an all-India drought year, the seasonal rainfall (June to September) for the country as a whole being 19% below its long period average. This monsoon had many intriguing aspects. In the rainiest month of July, the country witnessed the lowest rainfall in the history of recorded observations. The year 2009 was the year of worst all-India rainfall deficiency, amounting to 22% of Long Period Average (LPA) in the current decade. This large rainfall deficiency on a wide spatial scale, categorizes the SWM-2009 under all India drought year, preceded by 2002 in the current decade. Such scanty rainfall causes concerns to the farmers and other weather dependent activities. Although the years 2002 and 2009 were drought, they differ in many aspects.

Energetics is one of the very useful and interesting tools for diagnosing many atmospheric phenomena dynamically. There are number of studies on the energetics aspects of onset, progress, maintenance of mean monsoonal circulation. Keshavamurty and Awade (1970) found that maintenance of mean monsoon trough against frictional dissipation is mainly due to the work

done by horizontal pressure gradient. Their study also indicates a loss in standing eddy kinetic energy by rising of relatively colder air and sinking motion of relatively warmer air.

Rao & Rajamani (1972) studied the heat source & sinks and generation of available potential energy of the atmosphere over the Indian region during southwest monsoon season. Their computation showed a net generation of APE over the region of study.

Krishnamurti & Ramanathan (1982) have shown that a sharp rise in the rotational kinetic energy is an interesting aspect of onset of SWM. Awade and Bawiskar (1982) have shown that bad monsoon activity is associated with large divergence of heat at sub-tropics and large convergence of heat at extra tropics. Awade *et al.*, (1985) have shown that in good monsoon years there is large divergence of momentum in subtropics, while there is large convergence of momentum in mid latitude. They argued that this situation leads to a stronger westerly in mid-latitude and stronger easterly at tropics. Krishnamurti (1985) has shown that divergent kinetic energy, must be transferred to rotational kinetic energy, available potential energy must be transferred to divergent kinetic energy *via* rising motion over warm region / sinking motion over cold region. He has also shown that available potential energy is maintained *via* heating of warmer air & cooling of colder air. Rajamani (1985-I) computed the diabatic heating and generation of APE over south Asia for typical monsoon month July 1963. The study has inferred positive generation of both zonal and standing eddy APE. Rajamani (1985-II) made a study on available potential energy (APE) and its transformation into kinetic energy. This study shows that differential heating between Asian landmass and 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 & Surgi (1987) have shown that around the period of the onset of monsoon rains over India, there is a sharp rise in the conversion of zonal available potential energy (A_z) to zonal Kinetic energy (K_z).

Yanai *et al.*, (1992) have shown that reversal of north-south temperature gradient in the layer between 700 and 200 hPa triggers the onset of South Asian monsoon. George and 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 vortex during southwest monsoon. Their study indicated that barotropic eddy energy transfer dominates over baroclinic eddy energy transfer. They have also showed that $C(K_z, K_E) > C(A_E, K_E)$. Biswas *et al.* (1998) have studied the role of the mechanical barrier of the Himalayan massif – Tibetan plateau and the mid tropospheric sub-tropical ridge in the hiatus in the advance of southwest monsoon.

Krishnamurti *et al.* (1998) studied the energetics of south Asian monsoon. Using Florida State University (FSU) Global spectral model at T 170 resolution, they examined the maintenance of the monsoon. This study indicates that differential heating leads to the growth of APE, which is next passed on to the divergent motions and then finally divergent K.E. is converted to rotational K.E, which of course critically depends on the orientation of the isopleths of ψ and 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 South Asian monsoon there is a sudden increase in the zonal available potential energy. 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 K.E. budget using daily averaged (0000 UTC and 1200 UTC) reanalysis data for forty year (1960-1999) period from National centre for environmental prediction/National centre for atmospheric research (NCEP/NCAR). He studied evolution and established phases of monsoon. This study indicates that in lower troposphere K_E is balanced by adiabatic generation and frictional dissipation and in 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 (K_E) is driven by zonal component during evolution phase and by meridional component during established phase.

Raju *et al.* (2005) studied the onset characteristics of the southwest monsoon over India. Their study reveals that the low level kinetic energy, vertically integrated generation of kinetic energy and net tropospheric moisture can be used as potential predictors to predict the onset of southwest monsoon. 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 kinetic energy, while over the Arabian Sea it is first noticeable by a steep and abrupt

increase of generation. Dutta *et al.* (2009), using NCEP daily composite mean data have studied the energetics aspects of hiatus in the advance of SWM. They found that hiatus is associated with fall in $C(A_z, K_z)$ which in turn is apparently due to anomalous cooling of northern latitude caused by frequent passage of mid-latitude westerly systems.

The present study aims at dynamical comparison of the two recent drought years 2002 and 2009 from energetics point of view.

2. Data

Daily NCEP/NCAR air temperature (T), Zonal wind (u), meridional wind (v) and vertical wind (ω) reanalysis data have been used for the period 1st May - 30th September of the years 2002 and 2009 over the region from 5° N to 35° N and 65° N to 95° N.

3. Methodology

First, from the temperature data, at each grid point, heating $\frac{\dot{Q}}{C_p}$ rate 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), 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:

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

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

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

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

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

Then using Eqns. (1)-(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 [$C(A_E, K_E)$] and conversion of K_z to K_E [$C(K_z, K_E)$] have been computed using following formulae:

$$(A_z) = \int_{100}^{P_s} \frac{\overline{T'^2}}{2\sigma} dp \quad (6)$$

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

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

$$K_z = \frac{1}{2g} \int_{100}^{P_s} \overline{([u]^2 + [v]^2)} dp \quad (8)$$

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

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

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

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

$$[C(A_z, K_z)] = - \frac{1}{g} \int_{100}^{P_s} \frac{R}{p} \overline{\omega^*T'^*} dp \quad (13)$$

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

and

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

Above computations have been made daily from 1st May to 30th September in 2002 and 2009. From the daily value, monthly total and Pentad total of them have also been computed.

4. Results

In this section we present the results obtained from analysis of different energetic parameter for two drought years, viz., 2002 and 2009.

4.1. $C(A_z, K_z)$

Daily variation of $C(A_z, K_z)$ during May-September 2002 and 2009 are given in Fig. 1(a). From Fig. 1(a), it is seen that in 2009, after an early onset over Kerala on 23rd May 2009, there were long spells during 29th May - 13th June, 16th June - 12th August and 17th August - 11th September when $C(A_z, K_z)$ was negative. The long hiatus in June and failure of monsoon during other months in 2009 may be attributed to the above. In 2002 the longest spell with negative $C(A_z, K_z)$ was during 14-29 September only. There are other spells in 2002, with negative $C(A_z, K_z)$, the duration of which varies from 2-8 days only. Variation of pentad total of $C(A_z, K_z)$ for May 2002 and 2009 are shown in Fig. 1(b). In both years a rise in $C(A_z, K_z)$ during onset can be noticed. But in 2002 in all the pentads it was positive, whereas in 2009, in 4 out of 6 pentads, it was negative. Even the positive values in 2002 are about four times more than those in 2009.

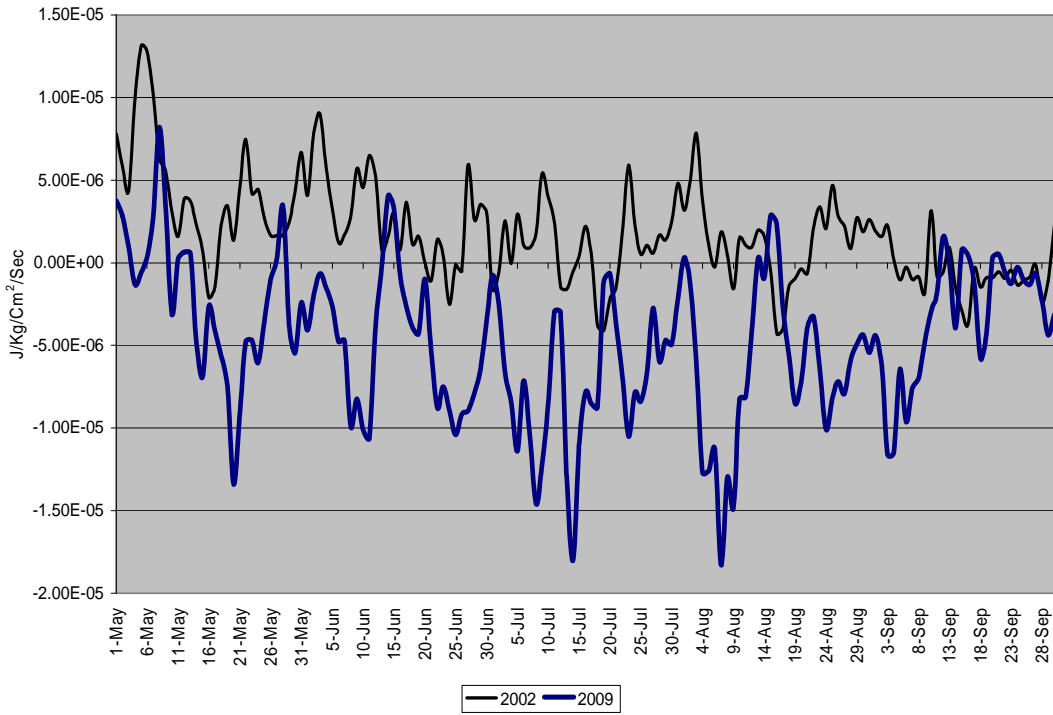


Fig. 1(a). Daily $C(A_z, K_z)$ May-September 2002 and 2009

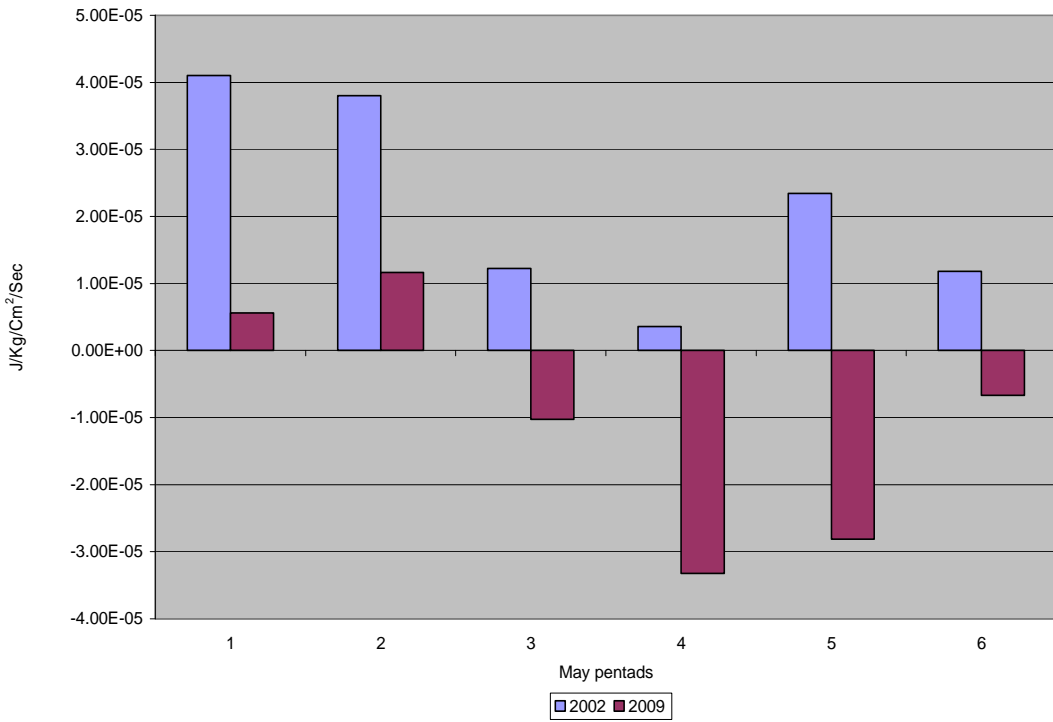


Fig. 1(b). Pentad total of $C(A_z, K_z)$ in May: 2002 and 2009

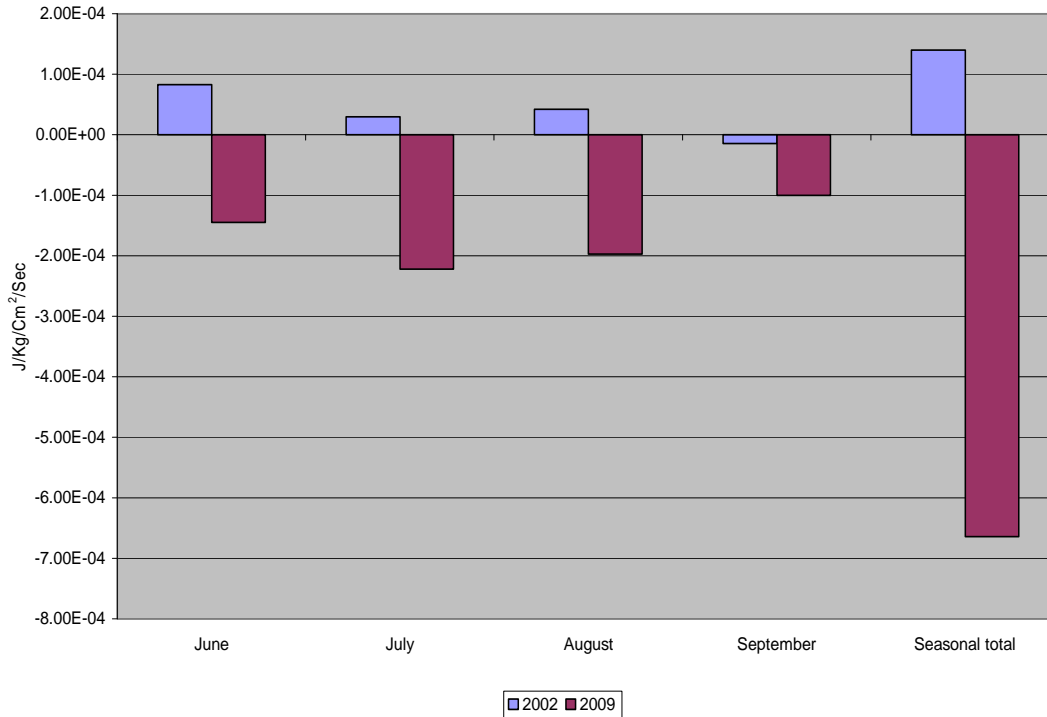


Fig. 1(c). Monthly and seasonal total $C(A_Z, K_Z)$: 2002 and 2009

Monthly total value of $C(A_Z, K_Z)$ for the above two years are shown in Fig. 1(c). From Fig. 1(c) it can be seen that in 2002 monthly total $C(A_Z, K_Z)$ was positive in all months except in September, whereas in 2009 in all months (June-September) $C(A_Z, K_Z)$ was negative. It is also worth noticing that the magnitude of negative value of monthly total $C(A_Z, K_Z)$ in 2009 was about double the magnitude of positive value of monthly total $C(A_Z, K_Z)$ in 2002. The figure also indicates that the seasonal total $C(A_Z, K_Z)$ was positive in 2002 where as it was negative in 2009. In 2009 the order of magnitude of negative $C(A_Z, K_Z)$ was one order more than the order of magnitude of positive $C(A_Z, K_Z)$ in 2002.

4.2. $C(A_Z, A_E)$

Daily variation of $C(A_Z, A_E)$ during May-September for the years 2002 and 2009 has been shown in Fig. 2(a). From Fig. 2(a) it can be seen that, in 2002 the positive value of $C(A_Z, A_E)$ was within 1.0×10^{-7} J/kg/cm²/sec where as in 2009 there were a number of long spells when the same had exceeded even 1.0×10^{-6} J/kg/cm²/sec.

Monthly total as well as the seasonal total value of $C(A_Z, A_E)$ during June-September for the above two years is shown in Fig. 2(b). From the Fig. 2(b) it appears that in each month during June-September, the monthly total value of $C(A_Z, A_E)$ in 2009 is positive and also it is at least one order of magnitude more than that in 2002. The seasonal total in 2009 is also about two orders of magnitude more than that in 2002.

4.3. $C(A_E, K_E)$

Daily variation of $C(A_E, K_E)$ during May-September for the years 2002 and 2009 are given in Fig. 3(a). From Fig. 3(a) it can be seen that in both the drought years there were long spells when $C(A_E, K_E)$ was negative, in conformity with the findings of Mohanty *et al.* (2003), but in 2009 there was comparatively large negative $C(A_E, K_E)$ over a number of comparatively longer spells.

The monthly total value of $C(A_E, K_E)$ along with seasonal total during June-September for 2002 and 2009 are given in Fig. 3(b). From Fig. 3(b) it can be seen that

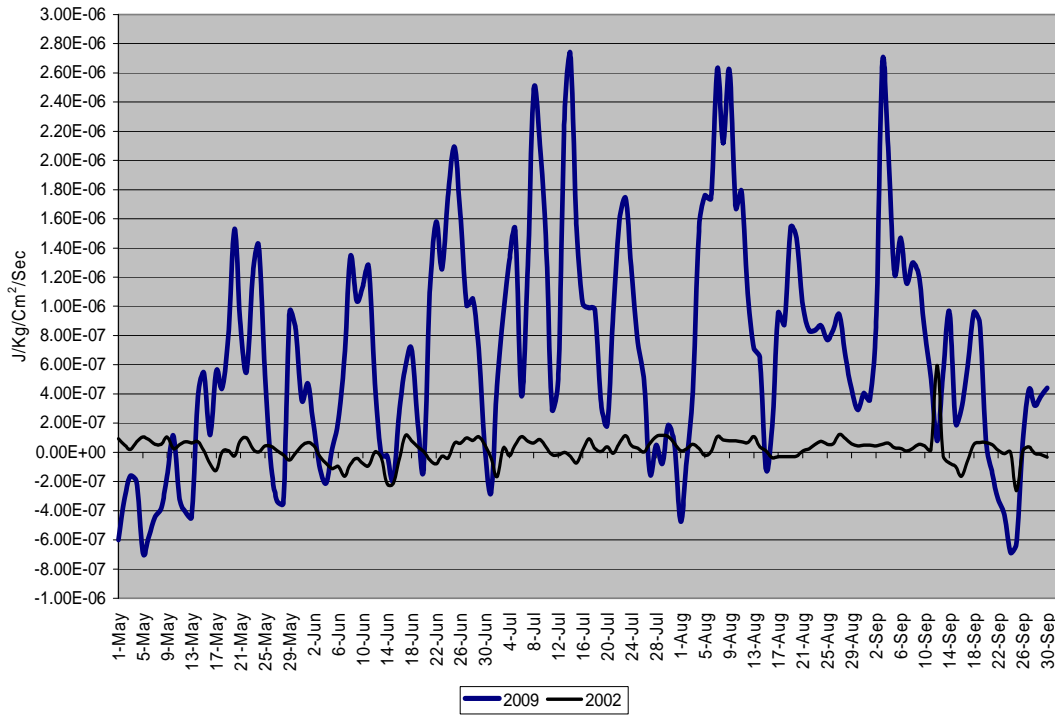


Fig. 2(a). Daily $C(A_z, A_E)$ May-Sept: 2002 and 2009

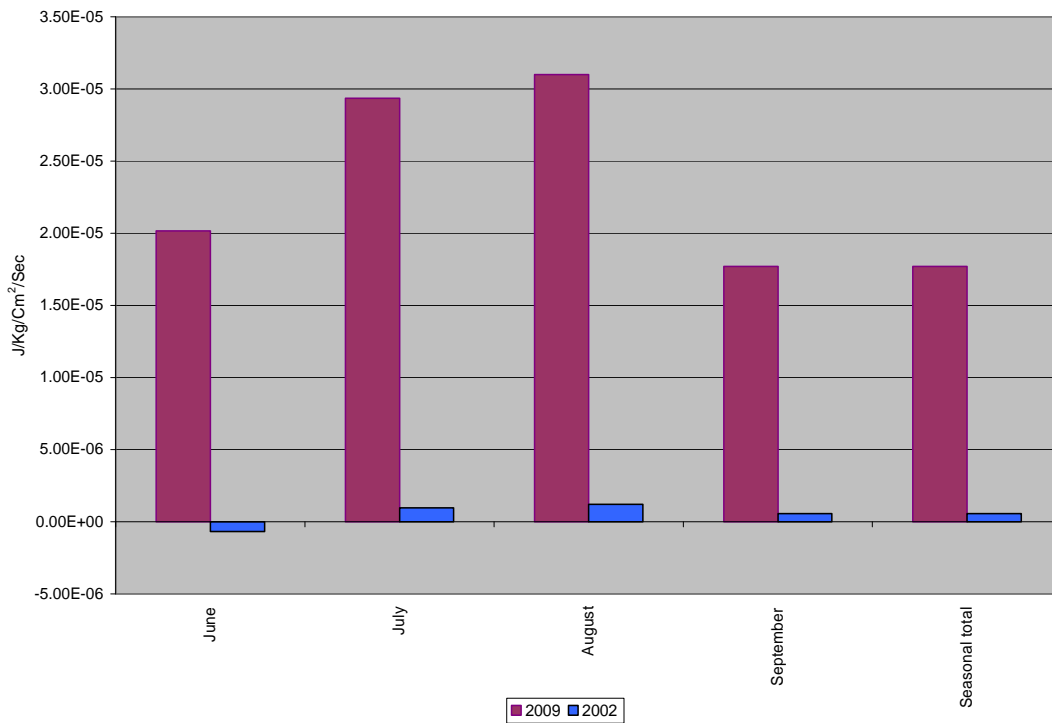


Fig. 2(b). Monthly and seasonal total $C(A_z, A_E)$: 2002 and 2009

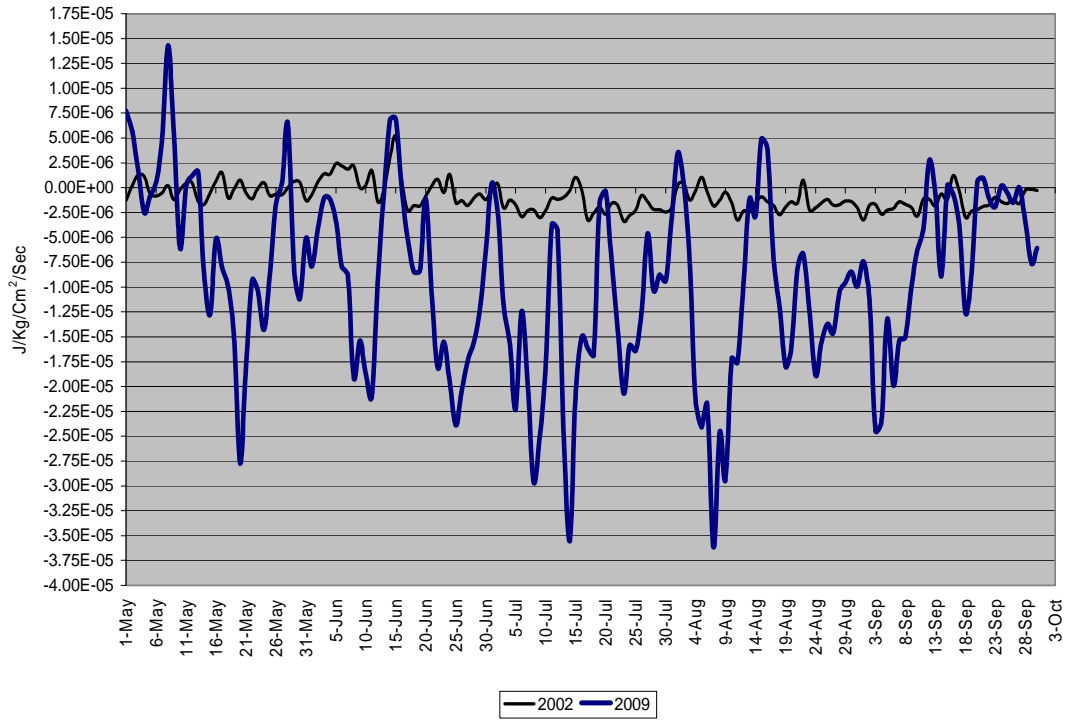


Fig. 3(a). Daily $C (A_E, K_E)$: May-September (2002 and 2009)

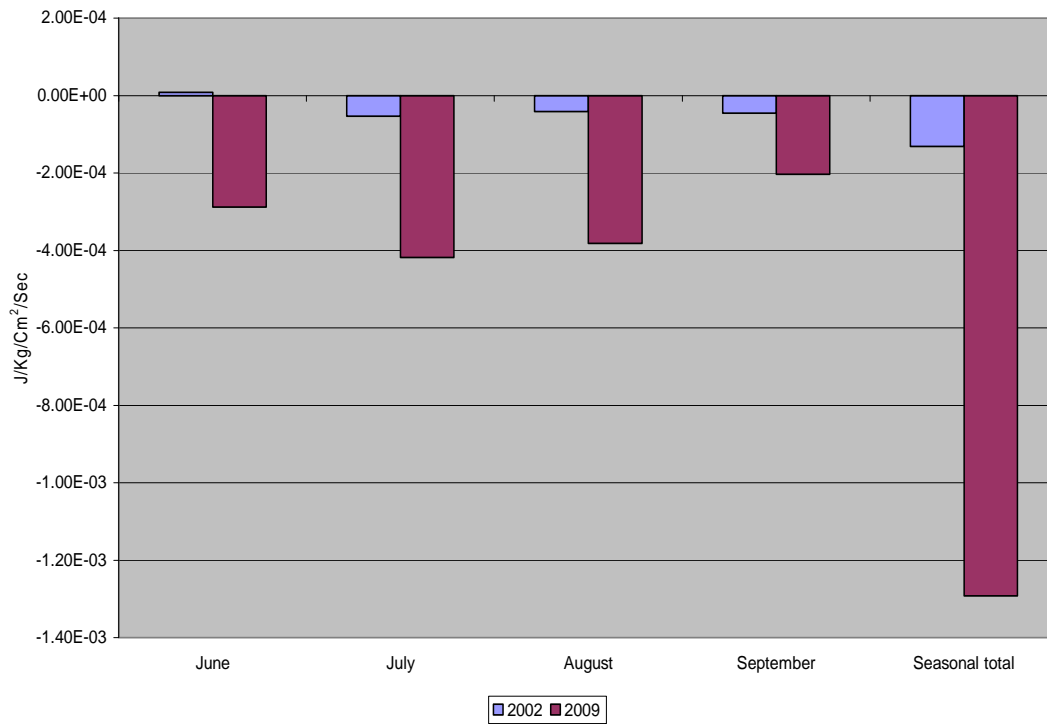


Fig. 3(b). Monthly and seasonal total $C (A_E, K_E)$: 2002 and 2009

monthly total $C(A_E, K_E)$ was negative in all months in both the years, except in June 2002, when it was positive, but in 2009 this negative value was much more. Negative value of $C(A_E, K_E)$ in 2009 was one order magnitude more than that in 2002.

5. Discussion

In the recent decade (2000-2009) two drought years, *viz.*, 2002 and 2009, have been witnessed. In 2002, seasonal rainfall was 19% below and in 2009 it was 22% below than its long period average.

In 2002 the advance of monsoon took place on near normal dates until the first hiatus in its northern limit during 13th to 19th June. There after the progress was rather sluggish and it took nearly two months for the monsoon current to cover the northern parts of central India and northwest India. The coverage of entire country by 15th August with a delay of one month from normal has been the longest delay in the recorded history of the monsoon. In 2002, during the season not a single low pressure system like depression/cyclonic storm formed over the Indian seas. The lack of monsoon depressions was an unusual feature of the season, as no similar case had been found in the recorded account past 130 years.

In 2009 the onset over Kerala took place one week before normal date, on 23rd May. In 2009, during June there was a prolonged hiatus in the advance of the monsoon. However, later the monsoon advanced rapidly and covered the entire country on 3rd July, well before its normal date of 15th July, due to strong monsoon currents. In 2009, during June, there was a prolonged hiatus in the advance of monsoon from 8th to 20th June. In 2009, 4 depressions (2 each formed over Arabian Sea and the Bay of Bengal) formed during the season. The duration over land of most of the systems formed during the season was very short and therefore did not help in persistent rainfall activity.

Thus, we have seen that although rainfall wise difference is not very significant, still 2009 year was worse than 2002, in spite of the fact that the year 2009 had 4 depressions but 2002 did not have any depression. In 2002, only in July monsoon failed very badly, whereas in 2009, monsoon failed all most in all months, except in July. It appears that the mean monsoon flow itself was much weaker in 2009.

In the previous section, we have seen that in 2009 South west monsoon season (SWMS), during a number of very long spells, $C(A_Z, K_Z)$ was negative where as it was negative during comparatively very shorter spells in 2002

SWMS. We have also seen that the monthly total value of $C(A_Z, K_Z)$ was positive in each months during 2002 SWMS, whereas the same was negative in each months during 2009 SWMS. The seasonal total of $C(A_Z, K_Z)$ was also positive in 2002 SWMS and the same was negative in 2009 SWMS. Now if we see the expression for $C(A_Z, K_Z)$, then it can be seen that it is positive if there is net rising motion ($\omega' < 0$) of relatively warmer air ($T' > 0$) and net sinking motion ($\omega' > 0$) of relatively colder air ($T' < 0$) in the vertical. During summer, northern latitude is warmer and southern latitude is colder. Then rising motion over warmer north and net sinking motion of colder south sets up a solenoidal circulation. This maintains the mean monsoon circulation. So positive $C(A_Z, K_Z)$ indicates direct monsoon circulation. So if $C(A_Z, K_Z)$ is negative then monsoon circulation is either reversed or weakened. So the mean monsoon circulation during 2009 was much weaker than 2002 in daily, monthly and in seasonal scale also. The above result is in conformity, in principle, with earlier findings of Krishnamurti (1985), Rajamani (1985-II), Krisnamurty *et al.* (1998). We have also seen that in all pentads during May 2002, the conversion from A_Z to K_Z was positive where as during May 2009, except in first two pentads, it was negative, where as earlier findings of Krishnamurti (1985), Rajamani (1985-II) and Krisnamurty *et al.* (1998) suggest that during onset there should be large positive conversion from A_Z to K_Z . Thus it appears that in 2009, SWM started its journey with a meager amount of energy.

Now question is how this mean monsoon circulation is disturbed. From the expression of $C(A_Z, K_Z)$ it appears that the mean monsoon circulation can be weakened or reversed if in the vertical net $\overline{\omega^* T^*} > 0$. It can happen if there is anomalous cooling of rising air at north or anomalous heating of sinking air at south or both. To explore either of these possibilities we can see the behavior of the parameter $C(A_Z, A_E)$ in daily, monthly as well as in seasonal scale. In monthly and seasonal scale we have seen that in both the years it was positive. But in 2009 it was 3 to 5 times more than that in 2002 in monthly and seasonal scale both. First of all a positive value of $C(A_Z, A_E)$ ensures the presence of mid latitude baroclinic westerly waves (Holton 2004). From the expression of $C(A_Z, A_E)$ it appears from the first term in the integrand of (10) that a high positive value of $C(A_Z, A_E)$ requires

$\frac{\partial T^*}{\partial y}$ and $\overline{v'T'}$ to be of opposite sign. Now they may be of opposite signs if normal north south temperature gradient in the region of study is reversed in presence of growing

mid-latitude baroclinic wave or if there is decaying baroclinic wave in presence of normal north south temperature gradient. From the second term in the integrand of (10), it appears that a high positive value of $C(A_Z, A_E)$ also requires $\frac{\partial T^*}{\partial p}$ and $\overline{\omega'T'}$ to be of opposite signs. Since $\frac{\partial T^*}{\partial p} > 0$ in the troposphere, hence $\overline{\omega'T'} < 0$.

This implies that over warm part of the eddy there is rising motion and cold part there is sinking motion, which in turn again converts A_E to K_E , a typical characteristics of mid latitude baroclinic westerly waves (Holton 2004). Whatever it may be, these baroclinic waves advect cold northerly wind to the northern latitude and thus causing anomalous cooling there. So this conversion term may be thought to quantify the influence of mid-latitude westerlies on monsoon circulation. Larger magnitude of positive value of $C(A_Z, A_E)$ in 2009 in daily, monthly and seasonal scale indicates passage of comparatively more penetrating mid latitude westerly systems over Indian longitudes. This may be a possible reason for anomalous cooling over north latitude as mentioned earlier. Another important point, worth noticing, is that in 2009 the rate of conversion from A_Z to A_E exceeds at least 10 times that of from A_Z to K_Z . But in 2002, the rate of conversion from A_Z to A_E was at least two orders less than that of from A_Z to K_Z . In the above discussions already we have seen the possibility of presence of mid-latitude westerly systems [high positive $C(A_Z, A_E)$]. In such case $C(A_E, K_E)$ may have large negative value if there is rising motion of cold air and sinking motion of warm air, which is possible when the thermal trough leads ahead of contour/streamline trough by $\frac{\pi}{2}$.

Thus, from the above discussions it appears that in 2009, there was comparatively more northerly cold air over warm region and southerly warm air over cold region, due to frequent passage of mid-latitude systems, resulting in large reduction rather reversal of $C(A_Z, K_Z)$, which in turn made the mean monsoon circulation itself weaker than that in 2002.

6. Summary and conclusions

Atmospheric energetic of the two monsoon droughts, *i.e.*, 2009 and 2002 droughts over India have been studied using NCEP reanalysis. Persistent highly negative anomaly for July 2002 occurred due to prolonged hiatus of monsoon which had set up by end of June due to which monsoon could not advance over the Gangetic plains till mid July. This was to some extent attributed to the lack of

proper SST gradient between equatorial Indian Ocean and North Bay of Bengal (Rao and Sikka 2005). Significant for the season of 2009, there was profound hiatus in the monsoon advance in the first week of June to 3rd week of June. Only coastal Karnataka resulted in phenomenal deficiency of rainfall for July. Also in both the seasons the evolution of warm El-Nino during the season kept synoptic scale activity rather much suppressed. 2009 drought has been studied by Sikka *et al.* (2010) in terms of evolution in circulation features associative with evolution of warm phase of ENSO during the monsoon season and spells of rainfall deficiency.

This paper has made an attempt to examine the evolution of these droughts by studying atmospheric energetics on seasonal, monthly and daily scales. Regional energetics on daily scale was examined in this study to understand the energy conversions within the two seasons. The differences in monsoon energetics are significantly large even though the seasonal rainfall deficiency is similarly large in both the years. This is because the energetics is controlled by the intra-seasonal oscillation in the circulation regime which differed the two years. Therefore even though the seasonal rainfall deficiency in the monsoon rainfall may be similar, it is the evolution of energetics which provides the information about the possible causes for large deficiency in rainfall. However, the important aspect is that the conversion of A_Z to K_Z is below the normal in different prolonged spells during the ISO of the monsoon.

From the study of atmospheric energetic following conclusions are made:

- (i) Mean monsoon (June to September) circulation in 2009 was weaker than that in 2002, which is reflected by large negative seasonal total (June-Sept) as well as monthly total value of $C(A_Z, K_Z)$ in 2009, whereas the same conversion in 2002 was positive.
- (ii) Magnitude of Seasonal negative total $C(A_Z, K_Z)$ in 2009 was of 10^{-3} J/kg/cm²/sec more than that of positive $C(A_Z, K_Z)$ in 2002 (10^{-4} J/kg/cm²/sec). Thus the conversion of zonal available potential energy into zonal kinetic energy was much smaller in 2009 than in 2002.
- (iii) In the daily distribution there was long spells in 2009 when $C(A_Z, K_Z)$ was negative (29th May - 13th June, 16th June - 12th August and 17th August - 11th September) indicating weaker and rather reverse energy conversions. In 2002 the longest spell with negative $C(A_Z, K_Z)$ was during 14-29 September only. There are other spells in 2002, with negative $C(A_Z, K_Z)$, the duration of which varies from 2-8 days only.

(iv) In both the years, the seasonal total (June-September) of $C(A_Z, A_E)$ was positive, but in 2009 its order of magnitude was 10^{-4} J/kg/cm²/sec whereas that in 2002 was 10^{-6} J/kg/cm²/sec. This indicated that the influence of mid latitude westerly was much stronger in 2009 compared to 2002.

(v) In 2002 the conversion from A_Z to K_Z dominated the conversion from A_Z to A_E , whereas in 2009, it was just reversed by a large magnitude. Thus the contribution of A_Z to maintain the mean monsoon circulation was much weaker in 2009 compared to 2002.

(vi) In 2009, month wise total as well as seasonal total of $C(A_E, K_E)$ had larger negative value than in 2002.

(vii) In daily distribution $C(A_E, K_E)$ had larger negative values during comparatively longer spells in 2009.

Acknowledgement

NCEP Daily Global Analyses data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.esrl.noaa.gov/psd/>. The Authors gratefully acknowledge DDGM (Training), IMD, Pune and Director, IITM for providing the facilities in carrying out this study. Useful discussions with Dr. U. S. De, Retired ADGM(R), IMD is duly acknowledged with thanks. First author is thankful to all officers and staffs of Central Training Institute, IMD, Pune for their kind co-operation.

References

- Awade, S. T. and Bawiskar, S. M., 1982, "Meridional transport of sensible heat in contrasting monsoon activity : Spherical harmonic analysis", *PAGEOPH*, **120**, 229-248.
- Awade, S. T., Totagi, M. Y. and Bawiskar, S. M., 1985, "Interaction of monsoon with northern hemisphere mid-latitude circulation", *Proc. Ind. Acad. Sc. (Earth and Planet Science)*, **94**, 147-157.
- Biswas, N. C., De, U. S. and Sikka, D. R., 1998, "The role of Himalayan massif Tibetan plateau and mid-tropospheric sub-tropical ridge over north India during the advance phase of the south west monsoon", *Mausam*, **49**, 285-300.
- Dutta, Somenath, De, U. S. and Sunitha Devi, 2009, "A diagnostic study on the energetic aspects of Hiatus in the advance of southwest monsoon", *Mausam*, **60**, 4, 427-436.
- George, L. and Mishra, S. K., 1993, "An observational study on the energetics of the onset monsoon vortex, 1979", *Quart. Jour. Royal. Met. Soc.*, **119**, 755-778.
- Holton, J. R., 2004, "An Introduction to Dynamic Meteorology", Elsevier Academic Press, USA. p242.
- Keshavamurty, R. N. and Awade, S. T., 1970, "On the maintenance of the mean monsoon trough over north India", *Mon. Wea. Rev.*, **98**, 315-320.
- Krishnamurti, T. N. and Ramanathan, Y., 1982, "Sensitivity of monsoon onset of differential heating", *J. Atmos. Sci.*, **39**, 1290-1306.
- Krishnamurti, T. N., 1985, "Summer monsoon experiment - A review", *Mon. Wea. Rev.*, **113**, 1590-1626.
- Krishnamurti, T. N. and Surgi, N., 1987, "Observational aspects of summer monsoon", *Monsoon Meteorology*, Edited by C. P. Chang and T. N. Krishnamurti, Oxford University press, 3-25.
- Krishnamurti, T. N., Sinha, M. C., Jha, Bhaskar and Mohanty, U. C., 1998, "A Study of South Asian Monsoon Energetics", *Journal of the Atmospheric Sciences*, **55**, 15, 2530-2548.
- Krishnamurti, T. N. and Bounoua, L., 2000, "An introduction to Numerical Weather Prediction Techniques", CRC press Inc., 1-286.
- Mohanty, U. C., Rao, P. L. S., Raju, P. V. S. and Bhatla, R., 2003, "A study on diagnostic aspects of South Asian Summer Monsoon", *Proceedings of Indian National Science Academy*, **69**, A, No-5, 505-521.
- Rajamani, S., 1985-I, "Energetics of the monsoon circulation over south Asia:I-Diabatic heating and generation of available potential energy", *Mausam*, **36**, 7-12.
- Rajamani, S., 1985-II, "Energetics of the monsoon circulation over south Asia : Part - II - Energy terms and energy transformation terms", *Mausam*, **36**, 405-412.
- Raju, P. V. S., Mohanty, U. C., Rao, P. L. S. and Bhatla, R., 2002, "The contrasting features of Asian summer monsoon during surplus and deficient rainfall over India", *International Journal of Climatology*, **22**, 1897-1914.
- Raju, P. V. S., Mohanty, U. C. and Bhatla, R., 2005, "Onset characteristics of the southwest monsoon over India", *Int. Journal of Clim.*, **25**, 2, 167-182.
- Rao, K. V. and Rajamani, S., 1972, "Study of heat sources and sinks and the generation of available potential energy in the Indian region during southwest monsoon", *Mon. Wea. Rev.*, **100**, 383-388.
- Rao, P. L. S., 2006, "The Kinetic energy budget of Asian summer monsoon", *Theor. Appl. Climatol.*, **84**, 191-205.
- Rao, P. L. S. and Mohanty, U. C., 2007, "Temporal characteristics of the Indian southwest monsoon", *Natural Hazards*, **42**, 2, 335-344.
- Rao, P. S. and Sikka, D. R., 2005, "Intra-seasonal variability of the summer monsoon over north Indian Ocean as revealed by the BOBMEX and ARMEX field programmes", *Pure and Applied Geophysics*, **162**, 1481-1510.
- Sikka, D. R., Tyagi, Ajit and Ram, L. C., 2010, "Large scale fluctuation of the continental tropical convergence zone (CTCZ) during pilot CTCZ phase-2009 and the evolution of monsoon drought in 2009", *Mausam*, **61**, 1, 47-74.

Yanai, M., Li, C. F. and Song, Z. S., 1992, "Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian Summer monsoon", *J. Meteor. Soc. Jap.*, **70**, 319-351.

Wu, G. and Zhang, Y., 1998, "Tibetan plateau forcing and the monsoon onset over south Asia and Southern China sea", *Mon. Wea. Rev.*, **126**, 913-927.
