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

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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 $\left[z z K_A C\right]$. Large negative values of the monthly total as well as seasonal total of $\left[z z K_A C\right]$ 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 $\left[E_z A A C\right]$ was positive, but in 2009 its order of magnitude was
energetics aspects of onset, progress, maintenance of dynamically. There are number of studies on the tools for diagnosing many atmospheric phenomena were drought, they differ in many aspects. Although the years 2002 and 2009 rainfall causes concerns to the farmers and other weather dependent activities. Although the years 2002 and 2009 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 ($A_{ij}$), 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 $C(K_z, K_x) > C(A_z, K_x)$. 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 $\psi$ and $\chi$. Results of the study by Wu and Zhang (1998) are in conformation 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. Rao 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 $K_z$ 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 $K_z$ within boundary layer is mostly due to meridional component. The study also indicates that the adiabatic generation ($K_x$) 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 $C(A_z, K_x)$ 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 ($\omega$) 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 $\frac{Q}{C_p}$ rate has been computed using first law of thermodynamics $\frac{Q}{C_p} = \frac{dT}{dt} - \frac{\alpha}{C_p} \omega$. 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:

Zonal average : $\bar{S} = \frac{1}{\lambda_e - \lambda_w} \int_{\lambda_w}^{\lambda_e} S d\lambda$  \hspace{1cm} (1)

Area average : $\bar{S} = \frac{1}{\sin \phi_n - \sin \phi_s} \int_{\phi_s}^{\phi_n} \int S \cos \phi d\phi$  \hspace{1cm} (2)

Departure from area average : $S' = S - \bar{S}$  \hspace{1cm} (3)

Departure from zonal average : $S' = S - \bar{S}$  \hspace{1cm} (4)

Departure of zonal average from area average:

$$S^* = [\bar{S}] - \bar{S}$$  \hspace{1cm} (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:

\[
(A_z) = \int_{100}^{p} \frac{T^*}{2g} dp
\]  
(6)

\[
(A_E) = \int_{100}^{p} \frac{T^*}{2g} dp
\]  
(7)

where, \( g \) is the static stability parameter of the atmosphere.

\[
K_z = \frac{1}{2g} \int_{100}^{p} [u'^2 + v'^2] dp
\]  
(8)

\[
K_E = \frac{1}{2g} \int_{100}^{p} [u'^2 + v'^2] dp
\]  
(9)

\[
[C(A_z, A_E)] = \int_{100}^{p} \left[ \frac{1}{\sigma} T^* \frac{\partial T^*}{\partial \varphi} + \frac{1}{\sigma} \frac{\partial T^*}{\partial \varphi} \right] dp
\]  
(10)

\[
[C(A_z, K_z)] = \int_{100}^{p} \left[ \frac{1}{\sigma} T^* \frac{\partial T^*}{\partial \varphi} \right] dp
\]  
(13)

\[
[C(A_E, K_E)] = -\frac{1}{g} \int_{100}^{p} \frac{R}{\sigma} \frac{\partial T^*}{\partial \varphi} dp
\]  
(12)

\[
G(A_z) = \frac{R_d}{C_p} \int \frac{[\theta] [\theta]^*}{p} \frac{\partial \varphi}{\varphi} dp
\]  
(14)

and

\[
G(A_E) = \frac{R_d}{C_p} \int \frac{\theta [\theta]^*}{p(\partial \varphi)} dp
\]  
(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
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 $1.0 \times 10^{-7}$ J/kg/cm²/sec where as in 2009 there were a number of long spells when the same had exceeded even $1.0 \times 10^{-6}$ 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 $C(A_j, A_e)$ May-Sept: 2002 and 2009

Fig. 2(b). Monthly and seasonal total $C(A_j, A_e)$: 2002 and 2009
Fig. 3(a). Daily $C(AE, KE)$: May-September (2002 and 2009)

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

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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 $C(A_E, K_Z)$ 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.

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