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THE CONTRASTING FEATURES OF ASIAN SUMMER MONSOON DURING SURPLUS AND DEFICIENT RAINFALL OVER INDIA

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ABSTRACT

An endeavour is made to distinguish the mean summer monsoon features during surplus and deficient monsoon seasons. Based on all-India summer monsoon rainfall, over 42 years (1958–99), seven surplus and ten deficient monsoon seasons are identified. Making use of daily averaged (00 Z and 12 Z) reanalysis data sets from the National Center for Environmental Prediction–National Center for Atmospheric Research for the corresponding surplus and deficient monsoon seasons, the mean circulation characteristics and large-scale energetics are examined.

The circulation features denote that the cross equatorial flow, low-level jet and tropical easterly jet are stronger during a surplus monsoon. Further, strong Tibetan anticyclonic flow characterizes a surplus monsoon. The large-scale balances of kinetic energy, heat and moisture show a significantly large quantity of diabatic heating, adiabatic generation of kinetic energy, and horizontal convergence of heat and moisture during the surplus monsoon season compared with the deficient state. The regions with statistically significant difference between surplus and deficient monsoon seasons are delineated by a Student's t-test at the 95% confidence level. The remarkable aspect noticed in this study is that the Arabian Sea branch of the monsoon circulation is more vigorous during a surplus monsoon season, whereas the eastern Bay of Bengal branch is stronger during a deficient monsoon. The various large-scale budget terms of kinetic energy, heat and moisture are found to be consistent and in agreement with the seasonal monsoon activity over India. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: monsoon; reanalysis; budget; kinetic energy; heat; moisture

1. INTRODUCTION

The Asian summer monsoon circulation is a longitudinal asymmetric component of the general circulation of the atmosphere, characterized by periodic reversal of wind regimes, movement of high/low-pressure systems and formation of jet streams, etc. The well-known physical mechanism involved in the generation of the monsoon circulation is the thermal contrast between the land and ocean. The monsoon circulation is normally established by the end of May over the Indian seas and peninsular India and prevails till the end of September. The seasonal changes in insolation lead to the formation of a heat low over northwest India. The atmosphere responds to that by setting up a trans-equatorial current. This flow transports ample mass and moisture into the monsoon domain and essentially modulates the amount of rainfall. The convergence of moisture precedes heat over the monsoon region. Both, in turn, give rise to profound cumulus convection and an increase in tropospheric diabatic heating. This leads to the formation of a strong thermal gradient, and the whole circulation continues to intensify through a positive moisture feedback to maintain the monsoon circulation (Mohanty *et al*., 1983; Pearce and Mohanty, 1984). Further, the interaction between the large-scale flow and moisture convection over the monsoon domain is poorly understood. This facet ensures that the study of

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the summer monsoon is more prominent than for other circulations elsewhere. The orientation of orographic barriers over the Indian subcontinent also modifies the circulation considerably.

The monsoon region undergoes substantial variability in the amount of rainfall from one season to another. This seasonal mean rainfall is an integrated view of horizontal and vertical gradients of wind, temperature and moisture that are favourable for the growth of hydrodynamic and thermodynamic instabilities and convective regimes. The daily weather fluctuations are produced by transient weather disturbances that are the manifestations of the growth, decay and propagation of these instabilities. These disturbances can derive their energy from the mean monsoon circulation, and thereby change it. Therefore, a better understanding of the mechanisms involved in the mean evolution of the monsoon and its spatial and temporal variability through the use of diagnostic studies with observational data sets and numerical models is vital to predict/simulate it better on various time scales (Kung and Smith, 1974; Pearce, 1979; Mohanty *et al*., 1982a,b; Krishnamurti *et al*., 1998). To accomplish this, it is crucial to comprehend the mean diagnostic features during the times of surplus and deficient seasonal rainfall of the summer monsoon. Several studies (Joseph, 1975; Krueger and Winston, 1975; Kanamitsu and Krishnamurti, 1978) have been carried out to analyse the contrasting circulation features and energetics of normal and deficient monsoon seasons. Further, a detailed comparison of the evolution of certain parameters, such as outgoing longwave radiation, sea surface temperature, stream function anomalies, divergent circulation and precipitation patterns, etc., was carried out by Krishnamurti *et al*., (1989, 1990) to elucidate some of the differences between dry (1987) and wet (1988) monsoon seasons over India. Ramesh *et al*. (1996) examined the energetics associated with these two extreme monsoon seasons. The data-sparse network over the tropics, especially in the summer monsoon domain, has made studying the finer details of the monsoon difficult. The recent efforts made by National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; hereafter NCEP) in generating the reanalysis data to study the climate trends are laudable. Various studies (Chen *et al*., 1996; Annamalai *et al*., 1999; Ramesh Kumar *et al*., 1999; Sperber *et al*., 2000) carried out making use of NCEP reanalysis confirm the usefulness of these data sets. Annamalai *et al*. (1999) compared the behaviour of the Asian summer monsoon in NCEP and European Centre for Medium-range Weather Forecasts reanalysis data sets. By and large these case studies are restricted to a pair of extreme years, and also certain aspects of large-scale budgets, and are therefore necessarily limited in their scope of enquiry.

In this study, an attempt is made to examine the mean circulation features and energetics associated with the composites of surplus and deficient monsoon seasons over India during the 1958–99 period. The data and scheme of analysis are briefly described in Section 2, followed by the methodology in Section 3. The results and discussion of mean circulation features and energetics of the Asian summer monsoon are provided in Section 4. Finally, a summary of the results is indicated in Section 5.

2. DATA

The database for the study comprises the daily upper air fields of the NCEP reanalysis for the period 1958–99. The NCEP reanalysis project (Kalnay *et al*., 1996) made use of an advanced global data assimilation system (GDAS), which utilized data from diverse sources for the period 1958–99. The use of delayed observations along with a state-of-the art assimilation system provides enhanced reliability to the products of the NCEP. In general, the 42-year NCEP reanalysis provides a consistent and reliable data set for investigating weather and short-term climate phenomena. It provided for the first time a unique database to examine the climate variability of circulation features and energetics of the Asian summer monsoon. The data comprise daily averaged (00 and 12 UTC) reanalysis of meteorological fields for the summer monsoon season of June, July, August and September (JJAS) for seven surplus and ten deficient years (Table I). The data for the Asian summer monsoon domain (15°S–45°N, 30–120°E) are extracted from the global reanalysis of NCEP. The basic meteorological fields considered for the study include geopotential height Z, wind (u and v), temperature T and specific humidity q at 12 mandatory pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa). The vertical velocity fields in this study have been computed from the horizontal wind components (u and v) by using the kinematic method suggested by O'Brien (1970). In this technique,

Table I. Surplus and deficient monsoon years during 1958–99 (the values in parentheses depict the percentage departure from the mean)

Surplus year	Deficient year
1959 (10.76)	1965 (−16.77)
1961 (19.70)	1966 (−13.18)
1970 (10.26)	1968 (−11.47)
1975 (12.95)	1972 (−23.39)
1983 (12.12)	1974 (−12.23)
1988 (12.80)	1979 (−16.96)
1994 (10.07)	1982 (−13.72)
	1985 (−10.86)
	1986 (−12.83)
	1987 (−18.20)

the divergence is adjusted in such a way that its vertically integrated value over the entire column of the atmosphere becomes zero. The complete details of the data assimilation are provided in the study of Kalnay *et al.* (1996). The reanalysis data sets produced at NCEP have a horizontal resolution of 2.5° on a regular latitude/longitude grid. The surplus and deficient monsoon years characterized in this study are based on all-India summer monsoon seasonal rainfall (Parthasarathy *et al.*, 1994). The departure of the rainfall by more (less) than 10% from the long-term mean is considered as being a surplus (deficient) monsoon year.

3. METHODOLOGY

The comprehensive analysis of contrasting dynamical features between surplus and deficient monsoon seasons is carried out through the study of large-scale balances of kinetic energy, heat and moisture. The budget equations are obtained from the prognostic and diagnostic equations of an atmospheric model based on simple mathematical transformations and are represented below in the flux form with pressure as the vertical coordinate. The overbar in the budget equations denotes the composite seasonal mean value of a quantity and prime quantities denote their corresponding deviations from the composite seasonal mean. In this study, the time mean large-scale balance equations are bifurcated into stable mean and transient eddy parts. The primary focus is on the mean component of the budgets, as the tropical circulations are dominated by the mean component of flow.

The kinetic energy budget equation is written as

$$\overline{\frac{\partial K_{\mathrm{M}}}{\partial t}} + (\nabla\cdot H_0 + \nabla\cdot H_1) + \frac{\partial \overline{(K_{\mathrm{M}} + \overline{V}V')\omega}}{\partial P} = -\overline{V}\cdot\nabla\overline{\phi} - C(K_{\mathrm{M}}, K_{\mathrm{T}}) - \overline{V}\cdot\overline{F} \tag{1}$$

where

$$\begin{aligned}
K_{\mathrm{M}} &= \frac{1}{2}\overline{V}^2 \\
H_0 &= K_{\mathrm{M}}\overline{V} \\
H_1 &= \overline{(\overline{V}\cdot V')V'} \\
C(K_{\mathrm{M}}, K_{\mathrm{T}}) &= C_{\mathrm{H}}(K_{\mathrm{M}}, K_{\mathrm{T}}) + C_{\mathrm{V}}(K_{\mathrm{M}}, K_{\mathrm{T}}) \\
C_{\mathrm{V}}(K_{\mathrm{M}}, K_{\mathrm{T}}) &= -\overline{u'\omega'}\frac{\partial \overline{u}}{\partial P} - \overline{v'\omega'}\frac{\partial \overline{v}}{\partial P}
\end{aligned}$$

and

$$C_{\mathrm{H}}(K_{\mathrm{M}}, K_{\mathrm{T}}) = -\frac{\overline{u'u'}}{a\cos\varphi}\frac{\partial\overline{u}}{\partial\lambda} - \frac{\overline{u'v'}\cos\varphi}{a}\frac{\partial}{\partial\varphi}\frac{\overline{u}}{\cos\varphi} - \frac{\overline{u'v'}}{a\cos\varphi}\frac{\partial\overline{v}}{\partial\lambda} - \frac{\overline{v'v'}}{a}\frac{\partial\overline{v}}{\partial\varphi} + \overline{u'u'}\frac{\overline{v}\tan\varphi}{a}$$

The first term on the left in Equation (1) designates the local tendency of kinetic energy. The second and third terms describe the horizontal and vertical flux divergences of kinetic energy. Similarly, the first term on the right of Equation (1) denotes the adiabatic production of kinetic energy. The second term describes the exchange of energy between mean and transient flows through the action of Reynolds stresses. The last term signifies the dissipation of kinetic energy by the turbulent frictional processes.

The heat budget equation in the flux form can be written as

$$\overline{\frac{\partial(C_{\mathrm{p}}T)}{\partial t}} + \nabla\cdot(C_{\mathrm{p}}\overline{TV}) + \frac{\partial(C_{\mathrm{p}}\overline{T}\overline{\omega})}{\partial P} - \overline{\omega\alpha} = \overline{Q}_{\mathrm{H}} \tag{2}$$

In Equation (2), the first term on the left denotes the local variation of enthalpy. The second and third terms designate the horizontal and vertical flux divergences of heat. The fourth term indicates the adiabatic conversion of available potential energy to kinetic energy. Similarly, the term on the right of Equation (2) describes the diabatic heating, which is due to radiation, condensation, turbulent transfer and evaporation of falling rain drops.

The moisture budget equation in the flux form can be expressed as

$$\overline{\frac{\partial(Lq)}{\partial t}} + \nabla\cdot(L\overline{V}\overline{q}) + \frac{\partial(L\overline{\omega q})}{\partial P} = \overline{Q_{\mathrm{L}}} \tag{3}$$

The first term on the left of Equation (3) indicates the local tendency of moisture. The second and third terms designate the horizontal and vertical divergence fluxes of moisture respectively. The term on the right shows the diabatic contributions to latent heat energy or the moisture source/sink due to evaporation and condensation of moisture. All budget terms at each regular latitude/longitude grid point are averaged both in the zonal and the meridional direction over the summer monsoon domain and integrated vertically from 1000 to 100 hPa. Thus, the volume integral of any variable $F(\lambda, \varphi, P)$ for the limited region bounded by meridians λ_1 and λ_2, latitude circle φ_1 and φ_2 and isobaric surfaces P_1 and P_2 may be written as

$$\hat{F} = \frac{1}{g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{P_1}^{P_2} Fa^2\cos\varphi\,\mathrm{d}\lambda\,\mathrm{d}\varphi\,\mathrm{d}P$$

where a is the average radius of the Earth.

The vertical integration of all the budget equations, with the boundary condition that vertical motion ($\omega = 0$) vanishes at the bottom and the top of the atmosphere, leads to the elimination of all the terms representing the vertical flux divergences of various quantities. All the last terms on the right of the budget Equations (1) to (3) represent the contributions from the subgrid-scale physical processes. These terms are evaluated implicitly in this study as residuals of all the other terms in the respective budget equations. Although we evaluated all the budget equations, the discussion in this paper is restricted to the terms that contribute significantly to the budgets and which are thus largely responsible for the maintenance of the summer monsoon circulation. Further, a Student's t-test has been applied to the basic parameters and energetics to identify the most significant zones (95% confidence level). The critical value of the Student's t-test with a 95% confidence level is 1.75. We computed the Student's t-test using the formula

$$t = \frac{\overline{X_{\mathrm{e}}} - \overline{X_{\mathrm{d}}}}{\sigma\sqrt{\dfrac{1}{N_{\mathrm{e}}} + \dfrac{1}{N_{\mathrm{d}}}}}$$

where σ is the standard deviation, and X_e and X_d are the excess and deficient monsoons for the years of N_e and N_d respectively.

4. RESULTS AND DISCUSSION

The comprehensive analysis of the contrasting features of the Asian summer monsoon during surplus and deficient rainfall seasons over India based on the mean circulation features and energetics is presented in this section.

4.1. Circulation features

Numerous studies (Chen *et al*., 1996; Mo and Higgins, 1996; Annamalai *et al*., 1999) have elucidated the suitability of the NCEP reanalysis for diagnostic purposes. However, in order to ensure that the typical mean seasonal characteristics are reflected in NCEP reanalysis, we have compared the NCEP rainfall with Xie–Arkin, as it is the end product of many forcing mechanisms. The seasonal mean (JJAS) precipitation (1979–98) showed by Xie–Arkin, NCEP reanalysis and difference of Xie–Arkin and NCEP reanalysis are depicted in Figure 1. The precipitation of Xie–Arkin is based on rain gauge measurements, satellite estimates from infrared and microwave observations (Xie and Arkin, 1997), and is considered to be reliable in terms of the monthly mean rainfall data available in recent years. Since Xie–Arkin rainfall exists for a 20 year (1979–98) period only, we considered NCEP rainfall for the corresponding period for the comparison purpose. Both precipitation patterns indicate maximum rainfall over western India and Arabian Sea. However, Xie–Arkin magnitudes are comparatively larger over northwest India and the head of the Bay of Bengal (Figure 1(c)). Interestingly, the NCEP reanalysis depicts more precipitation over the oceanic regions. Over the Indian subcontinent both precipitation patterns are in very good agreement, and the difference (Figure 1(c)) over the Indian landmass is marginal. Therefore, at the seasonal scale the NCEP analysis appears to be a reliable one as far as the distribution of rainfall over India is concerned. Figure 2 shows the seasonal mean (JJAS) NCEP precipitation for surplus and deficient monsoon seasons and their difference. The statistically significant regions at the 95% confidence level (based on a Student's t-test) are shaded in Figures 2 to 11. The zones of maximum rainfall are over eastern Arabian and adjoining western India, Bay of Bengal and equatorial Indian Ocean. The difference (Figure 2(c)) indicates more precipitation over the Indian land mass, the equatorial Indian Ocean and a small pocket over the Bay of Bengal during a surplus year. These regions are statistically significant. It is interesting to note the negative values (less rainfall during the surplus year) over northeast India and in the east of the Bay of Bengal. According to Saji *et al.* (1999) and Webster *et al.* (1999), the ocean tropical convergence zone (OTCZ) situated close to Indonesia has the most rainfall under normal and drought monsoon conditions. Nevertheless, when the rainfall maximum shifts to the western Indian Ocean due to anomalous warming there, India receives the maximum rainfall.

The geographical distribution of vector wind difference (surplus − deficient) is illustrated in Figure 3. The lower-level (850 hPa) features (Figure 3(a)) delineated by the difference include a strong cross equatorial flow and low-level jet. Further, intense surface westerlies over the monsoon domain are a characteristic feature of the surplus monsoon season. We noted a statistically significant zone over East Africa, the Arabian Sea and northwest India. The strong low-level jet results in excess rainfall over the west coast of India (Findlater, 1969). It is interesting to note that the most prominent zone of positive wind difference having the required level of statistical significance over the southern Arabian Sea plays an important role in the development of intense convective activity and cloud development during the summer monsoon season. The upper tropospheric circulation (200 hPa) features (Figure 3(b)) reveal a strong and elongated anticyclone over Tibet. On either side of the circulation, an easterly wind regime (the tropical easterly jet (TEJ)) to the south and a westerly wind regime (subtropical westerly jet) to the north are the prominent features. Further, statistically significant zones are observed over East Africa and northwest India.

The temperature difference is depicted in Figure 4. In the lower troposphere (925 hPa), predominant cooling is noticed over the entire Indian region. This may be due to the large evaporation over this region. On the

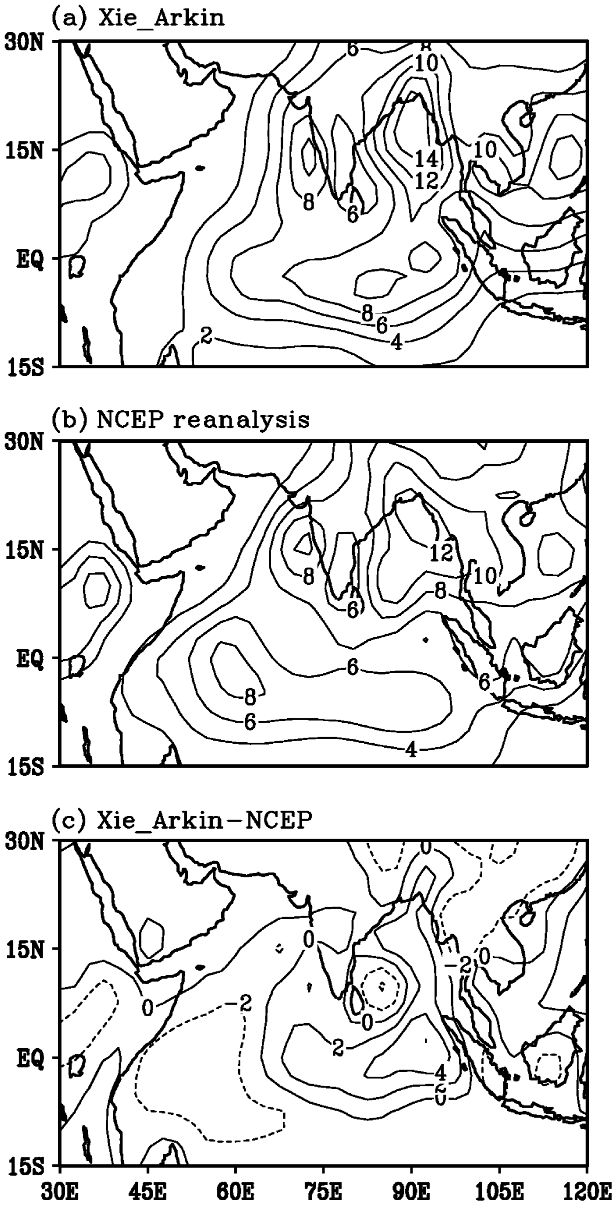

Figure 1. Seasonal mean (JJAS) precipitation (mm day^{-1}) 1979–98 for (a) Xie–Arkin, (b) NCEP reanalysis, (c) Xie–Arkin − NCEP

other hand, over the northwestern region, significant warming is noticed at 700 hPa, and this shifts further northwards at 500 hPa. This is due to the condensation and subsequent release of latent heat, which plays a major role in the monsoon system. The negative temperature difference along the monsoon trough at 920 hPa indicates that a warmer temperature in the lower troposphere is a characteristic feature of a deficient monsoon. Kawamura (1998) showed that in the preceding spring significant low-level cool (warm) temperature anomalies dominate over central Asia to the northwest of the Indian subcontinent for the weak (strong) monsoon years. During summer, a warm (cool) temperature anomaly prevails over the Indian subcontinent for the weak (strong) monsoon years. The significant (warm/cool) temperature difference over the Indian subcontinent modulates the summer monsoon rainfall considerably. At the upper levels (Figure 4(b) and (c)), intense warming is associated with a surplus monsoon. The specific humidity difference (Figure 5) shows a maximum

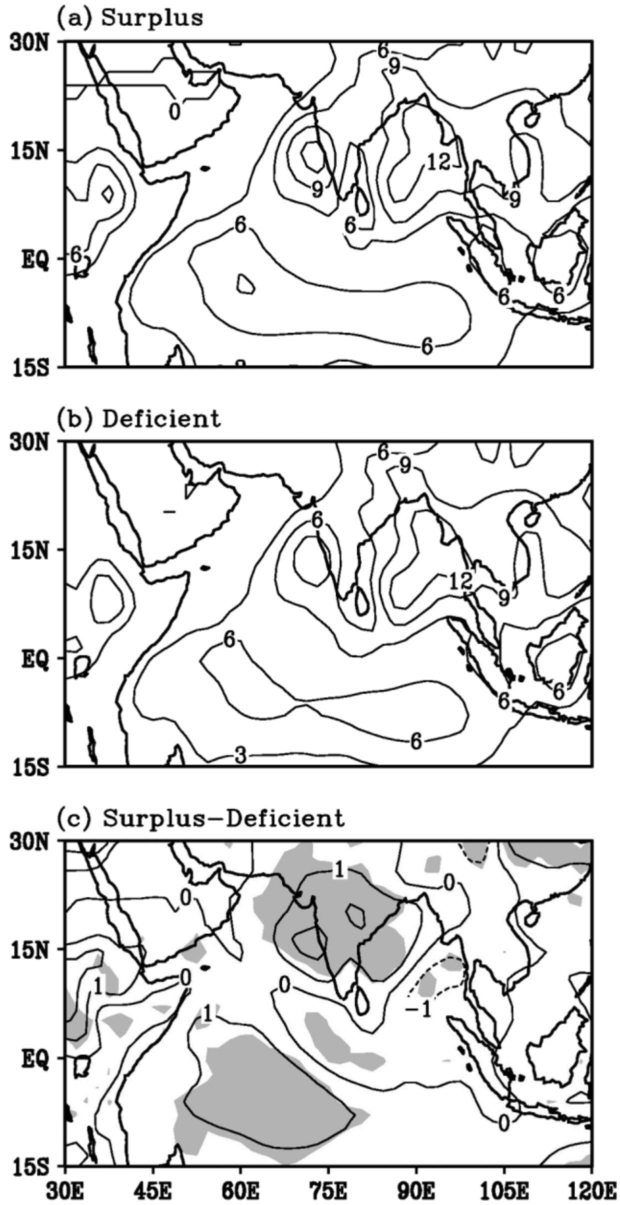

Figure 2. Seasonal mean (JJAS) NCEP precipitation (mm day^{-1}) for (a) surplus, (b) deficient, (c) difference. (Shaded areas denote Student's t-test at the 95% confidence level)

in humidity along western India and the adjoining Arabian Sea, as well as in the South China Sea. These are the zones that receive more rainfall during a surplus monsoon season. Positive values indicate an excess humidity maximum associated with a surplus monsoon. This is further supported by the statistically significant zones. Interestingly, the difference in humidity depicts positive values at all levels of the troposphere.

4.2. Energetics

The maintenance and intensity of the general circulation of the atmosphere depend on the balance between generation and dissipation of the kinetic energy. The kinetic energy of the atmosphere is created through the conversion of available potential energy and is eventually dissipated through irreversible frictional processes.

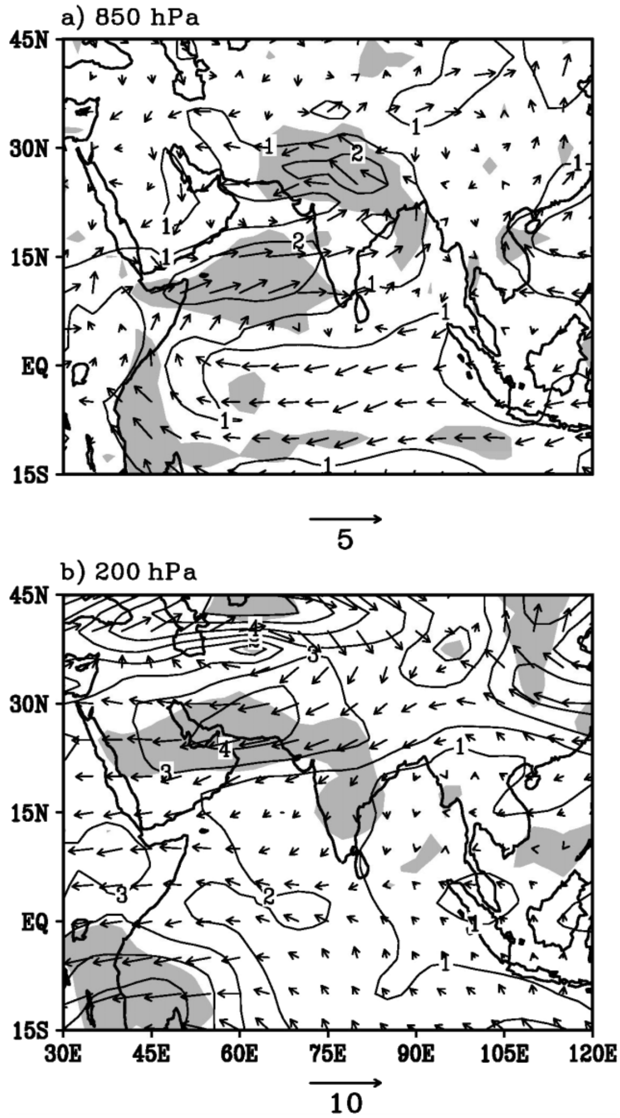

Figure 3. Wind (m s^{-1}) difference between surplus and deficient monsoon season for (a) 850 hPa and (b) 200 hPa

The local balance of kinetic energy is governed by three significant terms, namely the horizontal flux divergence, generation and dissipation of kinetic energy.

The vertically integrated (1000–100 hPa) geographical distributions of significant kinetic energy budget terms are examined to characterize surplus and deficient monsoons. The horizontal flux divergence of kinetic energy is illustrated in Figure 6. In general, during the summer monsoon season, a zone of flux divergence extending all over the south Asian region from the western Pacific to the southeastern Arabian Sea is noticed (Figure 6(a) and (b)). This zone delineates two maxima: one over the Bay of Bengal and one over the Arabian Sea. However, flux convergence of kinetic energy is noticed over the western Arabian Sea, the adjoining Arabia, North Africa and the Indian Ocean. The interesting aspect noted from the difference is that during a surplus monsoon a strong flux divergence occurs over the eastern Arabian Sea and the adjoining peninsula. A surplus monsoon is also characterized by a strong flux divergence of kinetic energy over East Africa. On the contrary, strong flux divergence is noticed over the east of the Bay of Bengal during a deficient monsoon season. These regions are found to be statistically significant at the 95% confidence level. In general, the

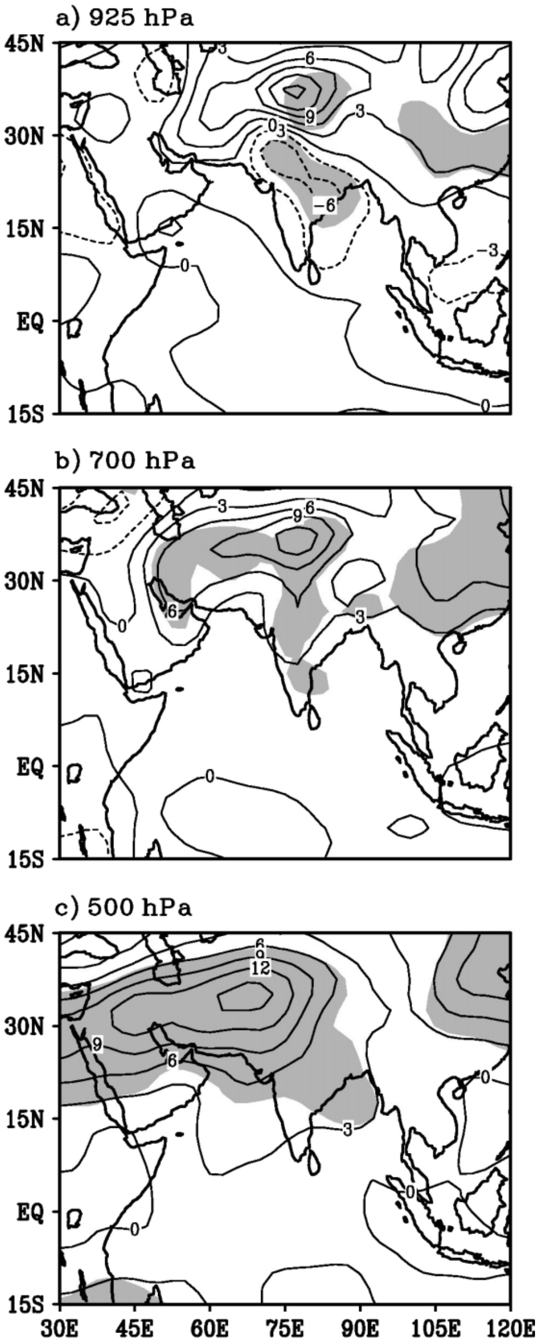

Figure 4. Temperature (10^{-1} K) difference between surplus and deficient monsoon season for (a) 925 hPa, (b) 700 hPa and (c) 500 hPa

dissipation of kinetic energy takes place through the surface friction and viscous stress within the atmosphere; thus, the monsoon circulation is maintained through the release of kinetic energy from available potential energy.

The geographical distribution of vertically integrated generation of kinetic energy is depicted in Figure 7. The kinetic energy is basically produced by the ageostrophic component of the flow. Positive magnitudes signify the generation of kinetic energy from the available potential energy, and negative magnitudes indicate

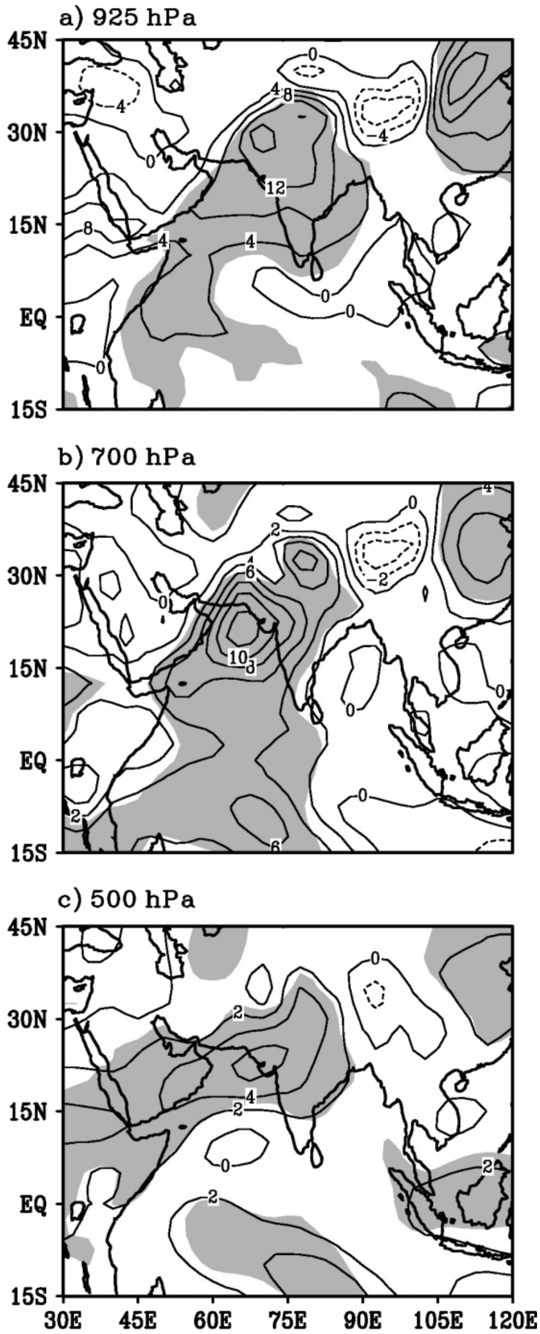

Figure 5. As in Figure 4, but for specific humidity (10^{-1} g kg^{-1})

the conversion of kinetic energy back to available potential energy. It is found that the areas characterized by the flux divergence (convergence) of kinetic energy are the regions of strong generation (less/weak generation) of kinetic energy. The kinetic energy generation depicts maxima over the Somalian coast and the Bay of Bengal. These production maxima are in agreement with the kinetic energy horizontal flux divergence maxima. These generation/dissipation maxima of kinetic energy are further identified as the entrance/exit regions of the TEJ. In an earlier study, Mohanty and Ramesh (1994) found that the existence of two kinetic energy production

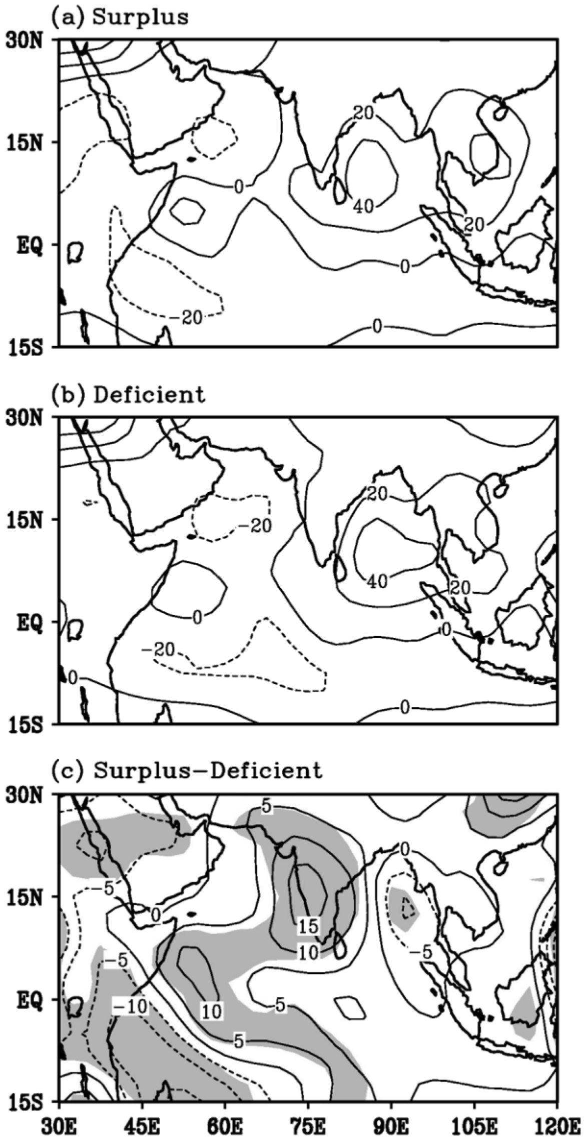

Figure 6. Geographical distribution of vertically integrated horizontal flux divergence of kinetic energy (10^{-1} W m^{-2}) for (a) surplus, (b) deficient and (c) difference

maxima is vital for maintenance of the flux divergence maxima situated over the same location. Hence, in the maintenance of the summer monsoon circulation, the adiabatic production of kinetic energy through the action of pressure force plays a very important role. The difference denotes that the negative generation maximum over the Bay of Bengal and the positive generation maximum over the Arabian Sea and Somalian coast are stronger during a surplus monsoon. Normally, the zonal component contributes to generation in the extra tropics and dissipation in the tropics, and vice versa for the meridional component (Kung, 1971). Nevertheless, the interesting feature delineated by these two components over the monsoon domain is that both contribute to generation. The volume-integrated kinetic energy budget parameters are depicted in Table II. This corroborates some of the features stated earlier. The contribution from the meridional component to the adiabatic generation is significant over the three domains of volume integration considered, namely the Arabian Sea (0–25 °N, 50–75 °E), the Bay of Bengal (0–22.5 °N, 80–100 °E) and the entire monsoon domain.

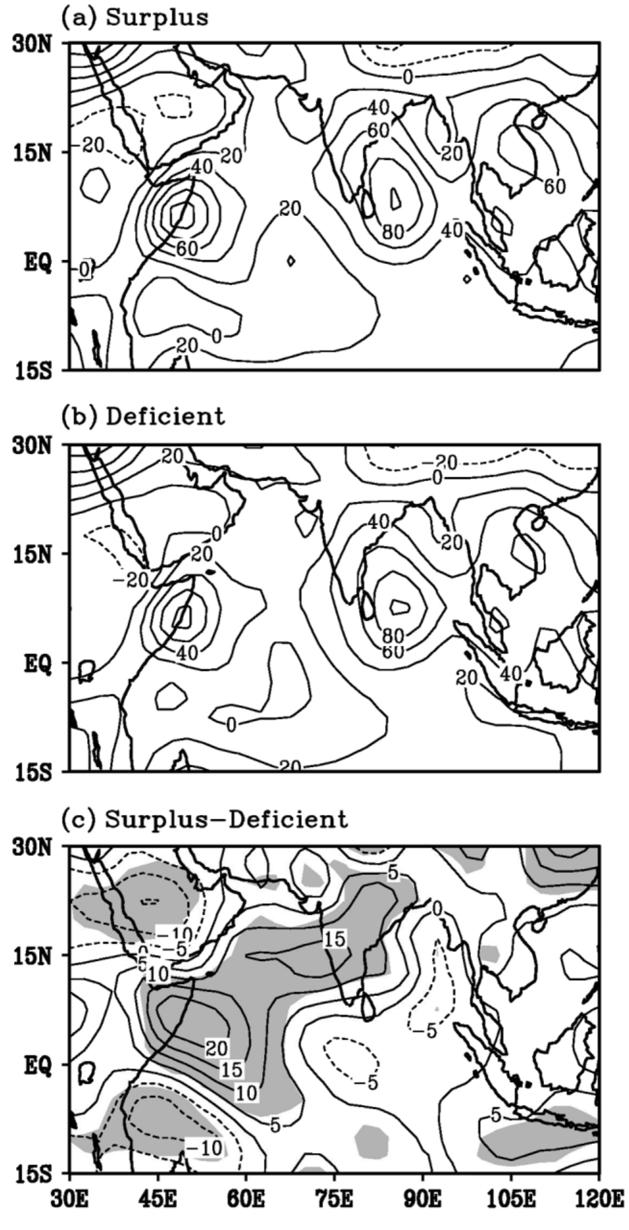

Figure 7. As in Figure 6, but for adiabatic generation of kinetic energy

Further, the changes over the Bay of Bengal and the monsoon domain are significant from the surplus to deficient as far as the zonal component of adiabatic generation is concerned. We noticed a weak/strong zonal generation over the Bay of Bengal and a strong/weak meridional generation over the Arabian Sea during a surplus/deficient monsoon season.

The contrasting features of the summer monsoon are further analysed through heat and moisture budgets. The horizontal flux divergence of heat is depicted in Figure 8. The geographical distributions (Figure 8(a) and (b)) show that the summer monsoon domain is characterized by flux convergence with maxima over the Bay of Bengal and Arabian Sea. A zone of strong flux divergence is noticed off East Africa. These findings are consistent with earlier studies carried out using different analyses (Mohanty and Ramesh, 1994; Ramesh *et al.*, 1996). The difference (Figure 8(c)) indicates strong flux convergence over western India and

Table II. Volume-integrated energy budget (W m^{-2}) terms[a]

Budget	Surplus monsoon			Deficient monsoon		
	Monsoon region	Arabian Sea	Bay of Bengal	Monsoon region	Arabian Sea	Bay of Bengal
$\nabla \cdot H_0 + \nabla \cdot H_1$	0.29	−0.31	3.27	0.24	−0.88	3.65
$\overline{V} \cdot \nabla \overline{\phi}$	1.99	2.59	4.86	1.83	1.80	5.17
$\overline{u}\frac{\delta\overline{\phi}}{\delta x}$	−0.28	−0.54	−1.85	0.34	−0.42	−0.98
$\overline{v}\frac{\delta\overline{\phi}}{\delta y}$	2.28	3.14	6.71	1.50	2.22	6.15
$\nabla \cdot (\overline{V} C_p \overline{T})$	−43.72	−103.94	−579.79	−34.34	−49.31	−638.82
$\overline{\omega}\ \overline{\alpha}$	96.73	89.95	863.53	83.50	21.21	945.80
Q_H	53.01	−13.98	283.78	49.16	−28.10	306.98
$\nabla \cdot (\overline{V}\ \overline{L}_q)$	−17.37	25.82	−176.84	−14.29	37.51	−187.79

[a] Monsoon region: 15 °S-45 °N, 30–120 °E; Arabian Sea: 0–25 °N, 50–75 °E; Bay of Bengal: 0–22.5 °N, 80–100 °E.

the adjoining Arabian Sea. This is a characteristic feature of a surplus monsoon. Further, strong convergence over East Africa is also a conducive feature for excess monsoon rainfall over India. The interesting feature noticed in this study is that the strong convergence of heat flux over the Arabian Sea takes place during a surplus monsoon. On the other hand, over the Bay of Bengal, maximum convergence is depicted during a deficient monsoon season.

The geographical distribution of adiabatic conversion of available potential energy to kinetic energy (Figure 9) shows maxima over the Arabian Sea and Bay of Bengal. Positive magnitudes denote conversion from available potential energy to kinetic energy, and vice versa for negative magnitudes. The entire monsoon domain is dominated by conversion of kinetic energy from available potential energy. As noted earlier, the Arabian Sea and adjoining west India depicts maximum conversion of kinetic energy during a surplus monsoon. Similarly, the Bay of Bengal shows a maximum during a deficient monsoon. The Arabian Sea and Indian peninsula are characterized by intense vertical motions during a surplus monsoon, and more so in the case of the Bay of Bengal during a deficient monsoon.

The diabatic heating pattern (Figure 10) shows excess convective activity over the Bay of Bengal, including the Indian peninsula and part of the eastern Arabian Sea (Figure 10(a) and (b)) and south Indian Ocean, which indicates a predominant rising motion over the monsoon region. During the summer monsoon, strong heating enhances the southwesterlies, and this may be augmented further by precipitation and latent heat release over the land area. These characteristics indicate the complexity of the diabatic forcing and the additional role of dynamic factors that influence the summer monsoon. The difference in diabatic heating (Figure 10(c)) shows a decrease of convective activity in a deficient monsoon season and an increase in convective activity over the Indian region and west equatorial Indian Ocean during a surplus monsoon season. The maximum convective zones correlate well with the precipitation centres. Further, these regions are statistically significant at the 95% confidence level. The geographical distribution of the vertically integrated horizontal divergence flux of moisture (Figure 11) shows that the entire monsoon region is characterized by strong flux convergence with maxima over the Bay of Bengal. The convergence of moisture due to the low-level flow acts as a primary source in developing cumulus convection and ultimately in sustaining the monsoon circulation. Pearce and Mohanty (1984) studied the mean tropospheric moisture flux during May and June 1979, and showed that the build up of the moisture flux over the summer monsoon domain is attributed to transportation from the south Indian Ocean. The difference in the moisture flux (Figure 11(c)) indicates that, during a surplus monsoon, excess convergence of moisture takes place over the east Arabian Sea, the Indian landmass and the west equatorial Indian Ocean. These regions depict the statistical significance at the 95% confidence

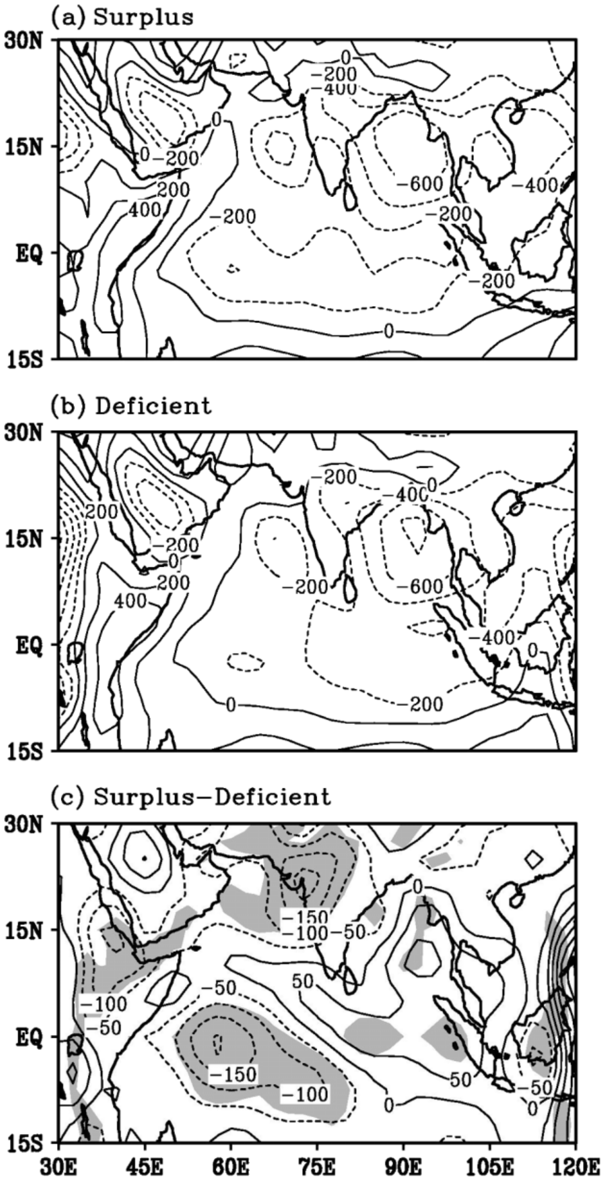

Figure 8. As in Figure 6, but for horizontal flux divergence of heat (W m^{-2})

level. Further, the strong flux convergence zones are identified with excess diabatic heating. Corresponding to this heating, intense convectional activity and rainfall are also noticed over these zones. Thus, the moisture flux convergence plays an important role in determining the diabatic heat patterns that maintain the summer monsoon circulation. The volume-integrated analysis of heat and moisture budgets exposed (Table II) the following features. Apart from the significant increase reflected in all the budget terms from a deficient to a surplus monsoon season, we noticed remarkable changes over the Arabian Sea. A massive increase of the horizontal convergence of heat flux, adiabatic conversion of available potential energy to the kinetic energy and diabatic heating during a surplus monsoon season are noticed.

The see-saw pattern associated with most of the terms in the energetics over the Arabian Sea and Bay of Bengal may be due to the existence of a dipole phenomenon related to sea-surface temperature over the Indian Ocean (Saji *et al*., 1999; Webster *et al*., 1999). The Indian Ocean climatology has the maximum

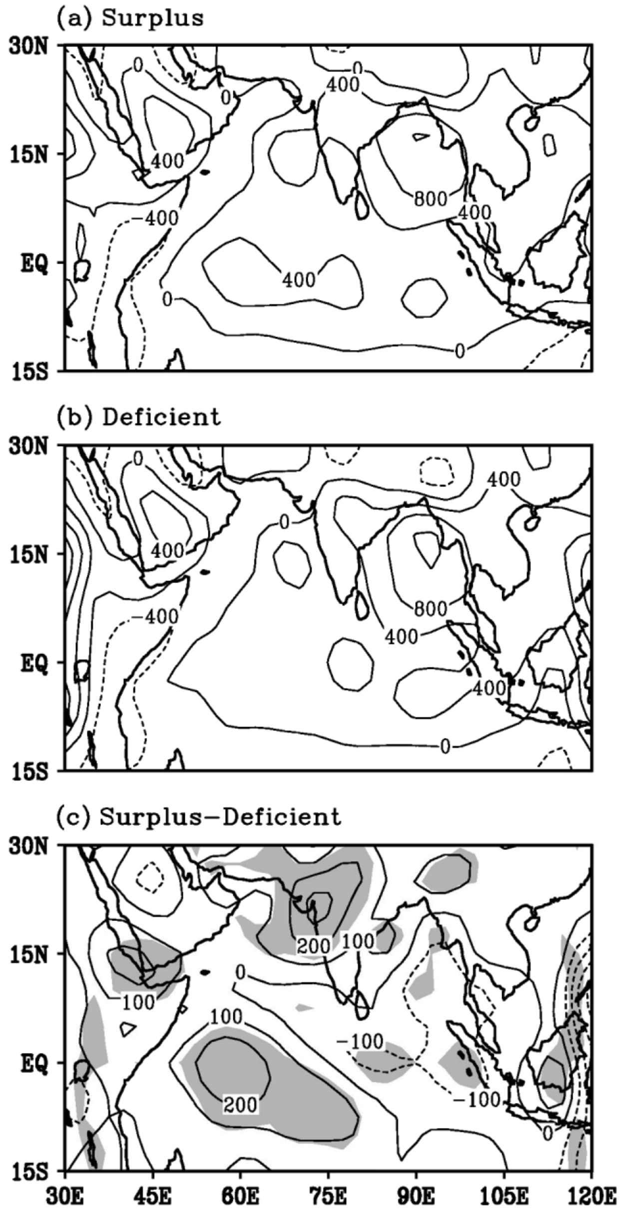

Figure 9. As in Figure 6, but for conversion of available potential energy to kinetic energy (W m^{-2})

rainfall concentration over the Indonesian region. However, during a dipole mode event the rainfall decreases over the OTCZ and increases over the western Indian Ocean. This pattern is dynamically consistent with the divergence/convergence of the pattern of wind shifts and outgoing longwave radiation. In association with these aspects, during normal and deficient rainfall over India, the energetics regime over the Bay of Bengal seems to be pretty intense. On the other hand, during a surplus monsoon season the Arabian Sea portrays a strong regime. During the dipole event, the western Indian Ocean shows anomalous warming. This warming is responsible for ample mass and moisture convergence. This anomalous warming results in an intense influx of heat and the formation of diabatic heat sources. In turn, the Indian subcontinent experiences maximum rainfall. However, during normal and drought monsoons, the western Indian Ocean is cooler in comparison. This inhibits convergence of heat and moisture and the formation of diabatic heat sources. Contrary to that, the

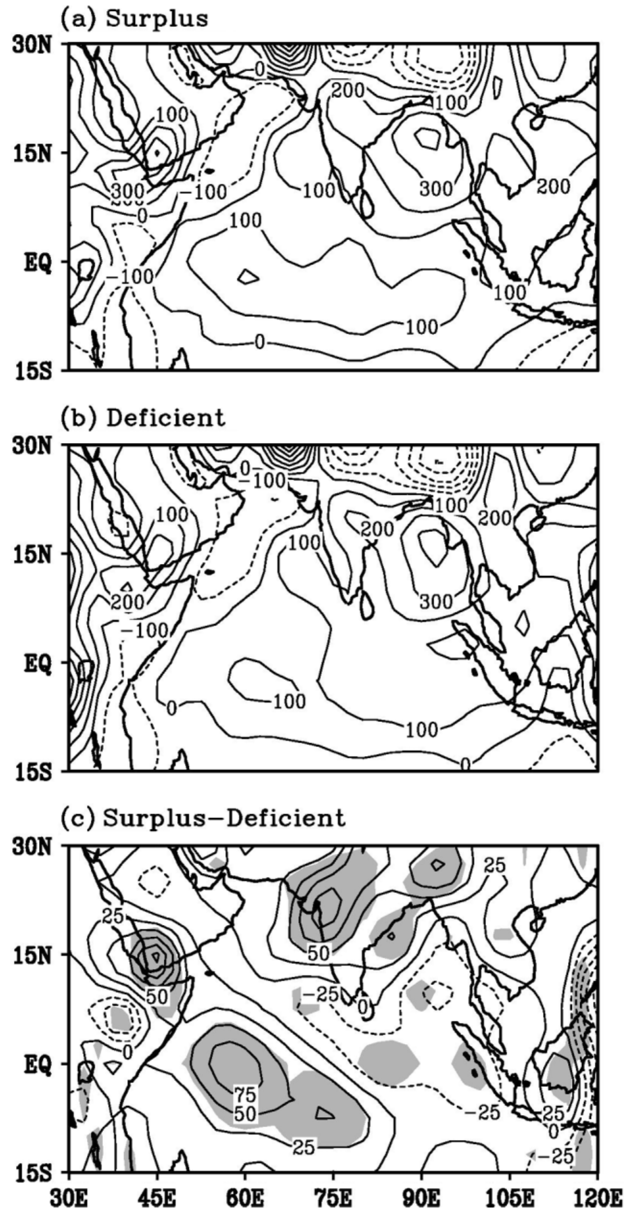

Figure 10. As in Figure 6, but for diabatic heating (W m^{-2})

eastern Indian Ocean is warmer during drought and normal monsoon conditions over India. This warming is responsible for a strong convective regime over the Bay of Bengal and off Indonesia. The outgoing longwave radiation, sea-surface temperature and zonal wind patterns (Saji *et al*., 1999; Webster *et al*., 1999) are proof of this aspect.

5. CONCLUSIONS

The analysis of mean circulation features and energetics during surplus and deficit monsoons allows us to make the following broad conclusions.

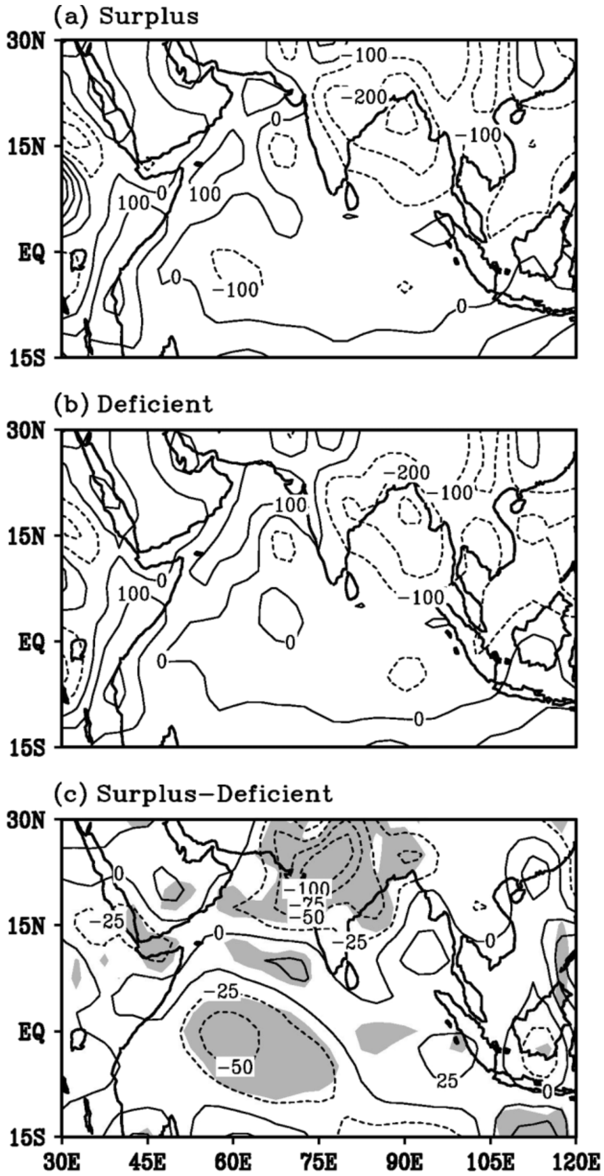

Figure 11. As in Figure 6, but for horizontal flux divergence of moisture (W m^{-2})

A deficient monsoon denotes a weaker cross equatorial and tropical convergence zone. A weaker Tibetan anticyclone is also a characteristic feature of a deficient monsoon season.

The contribution from the meridional component to the adiabatic generation of kinetic energy during a surplus monsoon season is significant. A deficient monsoon shows weak convergence of heat and moisture over the monsoon domain. In effect, the circulation produced by the mean fields of a deficient monsoon is feeble compared with that of a surplus monsoon.

The interesting aspect noticed in this study is that the large-scale balances of kinetic energy, heat and moisture indicate excess magnitudes over the Arabian Sea during a surplus monsoon. On the other hand, the eastern Bay of Bengal exhibits excess magnitude during a deficient monsoon. During the normal and deficient monsoons, the eastern Indian Ocean is relatively warm, compared with its western counterpart. The anomalous warming over the western Indian Ocean during the dipole event is, in principle, responsible for the intense Arabian Sea regime and, in turn, a surplus monsoon over India. In tandem with the warmer eastern Indian Ocean, during a drought and normal monsoon season, the Bay of Bengal branch is pretty intense. This is reflected in the various budget terms we considered in this study.

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