Pure appl. geophys. 162 (2005) 1511–1541
0033 – 4553/05/091511–31
DOI 10.1007/s00024-005-2681-z

Pure and Applied Geophysics

A Study on Climatological Features of the Asian Summer Monsoon: Dynamics, Energetics and Variability

U.C. Mohanty, P.V.S. Raju, and R. Bhatla

Abstract—A continuing goal in the diagnostic studies of the atmospheric general circulation is to estimate various quantities that cannot be directly observed. Evaluation of all the dynamical terms in the budget equations for kinetic energy, vorticity, heat and moisture provide estimates of kinetic energy and vorticity generation, diabatic heating and source/sinks of moisture. All these are important forcing factors to the climate system. In this paper, diagnostic aspects of the dynamics and energetics of the Asian summer monsoon and its spatial variability in terms of contrasting features of surplus and deficient summer monsoon seasons over India are studied with reanalysis data sets. The daily reanalysis data sets from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) are used for a fifty-two year (1948–1999) period to investigate the large-scale budget of kinetic energy, vorticity, heat and moisture. The primary objectives of the study are to comprehend the climate diagnostics of the Asian summer monsoon and the role of equatorial convection of the summer monsoon activity over India.It is observed that the entrance/exit regions of the Tropical Easterly Jet (TEJ) are characterized by the production/destruction of the kinetic energy, which is essential to maintain outflow/inflow prevailing at the respective location of the TEJ. Both zonal and meridional components contribute to the production of kinetic energy over the monsoon domain, though the significant contribution to the adiabatic generation of kinetic energy originates from the meridional component over the Bay of Bengal in the upper level and over the Somali Coast in the low level. The results indicate that the entire Indian peninsula including the Bay of Bengal is quite unstable during the summer monsoon associated with the production of vorticity within the domain itself and maintain the circulation. The summer monsoon evinces strong convergence of heat and moisture over the monsoon domain. Also, considerable heat energy is generated through the action of the adiabatic process. The combined effect of these processes leads to the formation of a strong diabatic heat source in the region to maintain the monsoon circulation. The interesting aspect noted in this study is that the large-scale budgets of heat and moisture indicate excess magnitudes over the Arabian Sea and the western equatorial Indian Ocean during surplus monsoon. On the other hand, the east equatorial Indian Ocean and the Bay of Bengal region show stronger activity during deficient monsoon. This is reflected in various budget terms considered in this study.

Key words: Reanalysis, summer monsoon, kinetic energy, vorticity, heat and moisture.

1. Introduction

The Indian summer monsoon is characterized with rainfall regimes, onset/withdrawal phases, break and active conditions and synoptic disturbances. The basic

Centre for Atmospheric Sciences, Indian Institute of Technology-Delhi, Hauz Khas, New Delhi 110 016, India.

forcing of the Asian summer monsoon is provided by the annual cycle of solar radiation interacting with different heat capacities of the tropical ocean and land areas (LI and YANAI, 1996) and their respective geographical arrangements. The tropical ocean regions, particularly, the Arabian Sea, Bay of Bengal and Indian Ocean act as main reservoirs of heat and moisture in supplying the necessary energy to the establishment and maintenance of the large-scale monsoon circulation and associated monsoon activity over the Indian subcontinent. There is complex feedback between the flow field and the heating, especially through the interaction between moist convection and large-scale flow (MOHANTY *et al.*, 1983), which is poorly understood. The orientation of the orographic barriers over the Indian subcontinent also modifies the circulation considerably, consequently the summer monsoon system becomes a very complex array of weather phenomena. The Tibetan plateau and the Himalayan Mountains play an important role in the observed monsoon, in the form of total barrier to low-level meridional winds. The rainfall is caused mainly as the low-level flow meets the mountain barrier and increases the strength of the heating and confines it to the region south of the Tibetan plateau. At the same time, it has been established that the sensible heating, resulting from the absorption of solar radiation by the elevated Tibetan plateau, provides a heat source which strengthens the upper level anticyclone.

The prominence of diagnostic studies is well recognized as an important component of the Global Atmospheric Research Program in elucidating the dynamics of tropics (PEARCE, 1979; KUNG and TANAKA, 1983; KUNG and SMITH, 1974). Although, several works were reported on atmospheric diagnostics, some studies (MOHANTY *et al.*, 1982a,b; PEARCE and MOHANTY, 1984) elucidated onset and maintenance aspects of the Asian summer monsoon. Presumably, this is due to the paucity of data of the tropics. Nevertheless, the advent of multifarious operational centers around the world having global analysis of meteorological fields, facilitated the understanding of the dynamics of the Asian summer monsoon and its variability. Significant contributions to the diagnostic studies of the atmospheric energetics have been made by LORENTZ (1955), OORT (1964) and NEWELL (1970). Several studies (KRUEGER and WINSTON, 1975; KANAMITSU and KRISHNAMURTI, 1978; RAMESH *et al.*, 1996 and others) have been carried out to analyze 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 long-wave radiation, sea-surface temperature, stream-function anomalies, divergent circulation and precipitation patterns, etc. was made by KRISHNAMURTI *et al.* (1989, 1990) to elucidate some of the differences between deficit (1987) and surplus (1988) monsoon seasons over India. The thermodynamic characteristics of the Asian summer monsoon are studied by RAMESH *et al.* (1999) and RAO *et al.* (2003) with a global analysis-forecast system. They found that the model forecast failed to simulate analyzed atmospheric variability in terms of mean circulation, which is indicated by underestimation of various terms of heat and moisture budgets with an increase in the forecast period. Despite revealing basic information and elucidating the complexity of the problem, these studies evinced the necessity of further detailed studies on the Asian summer monsoon. At this juncture, a need arises to comprehend the multifarious complex mechanisms associated with the monsoon circulation in order to improve prediction in various spatio and temporal scales. Despite a few studies which focused on the Asian summer monsoon, they are limited by the scope of investigation as these are based on a few years of data sets. In recent years the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR, hereafter NCEP) has made an excellent effort to generate a reanalysis of global data sets (KALNAY *et al.*, 1996). The 52-year NCEP reanalysis provides a consistent and reliable data set for investigating dynamics and energetics of short-term climate phenomena. It provided for the first time a unique database to examine climate variability of circulation features and energetics of the monsoon. Recent studies (ANNAMALAI *et al.*, 1999; SPERBER *et al.*, 2000; RAJU *et al.*, 2002) conducted making use of the NCEP reanalysis, confirm the usefulness of these data sets. As a result, understanding the dynamical mechanisms of the monsoon variability in time-scales ranging from weeks to years is an issue of considerable importance.

In the present study, the mean circulation features and energetics of the Asian summer monsoon are studied with 52-years (1948–1999) NCEP reanalysis data sets. Further, the mean circulation features and energetics associated with the composite of surplus and deficient monsoon seasons over India during the 1948–1999 period are examined.

2. Data and Analysis System

The NCEP/NCAR have cooperated in a project to produce a retrospective 52-year (1948–1999) record of global analyses of atmospheric fields supporting the needs of the research and climate monitoring communities. This effort involved the recovery of land surface, ship, rawinsonde, pibal, aircraft, and satellite and other observational data, quality control and immersion of these data in a data assimilation system that is kept unchanged over the reanalysis period. The reanalysis system is continuing with current data on a real time basis (Climate Data Assimilation System or CDAS), so that its products are available from 1948 to the present.

The NCEP/NCAR reanalysis system used a state-of-the-art data assimilation (3-D variational) with the horizontal resolution of T62 (about 210 km) and 28 sigma vertical levels. The model has five levels in the boundary layer and about seven levels above 100 hPa. The model is identical to the global system implemented operationally at NCEP except for the horizontal resolution T126 (105 km) (KANAMITSU, 1989, 1991). The analysis scheme is a three-dimensional variational scheme cast in spectral statistical interpolation (PARRISH and DERBER, 1992). The module contains complex quality control of rawinsonde data including time interpolation checks with confidence corrections of height and temperature (COLLINS and GANDIN, 1990, 1992). Optimal interpolation-based complex quality control is applied for all other data (WOOLEN, 1991; WOOLEN *et al.*, 1994). The model includes parameterization schemes of all major physical processes such as convection, large-scale precipitation, radiation, boundary layer physics, an interactive surface hydrology, and vertical and horizontal diffusion processes. The moist convection is represented by a simplified form of the Arakawa-Schubert parameterization scheme (PAN and WU, 1994) and clouds are diagnosed from the model which generated outgoing long-wave radiation (CAMPANA *et al.*, 1994). The NCEP model uses a three-layer soil scheme based on PAN and MAHRT (1987), in which the bottom layer is set to the annual mean climatological value. A detailed description of the NCEP/NCAR reanalysis project is described by KALNAY *et al.* (1996).

In this study, the daily averaged (00 and 12 UTC) reanalysis data set produced at NCEP with a horizontal resolution of 2.5° on a regular latitude/longitude grid are extracted for the monsoon domain. The basic meteorological fields considered for the study include geopotential height (z), wind (u and v), temperature (T) and specific humidity (q) at twelve pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa). In order to avoid the problems with the divergent wind, the vertical velocity fields in this study have been computed from horizontal wind components (u and v) by using the kinematic method as suggested by O'BRIEN (1970). In this technique the divergence is adjusted to its vertically integrated value zero in the entire column of the atmosphere. The vertical velocity distribution obtained from the kinematic method delineates realistic Hadley circulation over the monsoon domain, compared to the archived field.

3. Methodology

The comprehensive analysis of dynamical features of the Asian summer monsoon is accomplished through the study of large-scale budgets of kinetic energy, vorticity, heat and moisture. The budget equations are obtained from the prognostic and diagnostic equations of the atmospheric model on simple mathematical transformations and 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 general, tropical circulations are driven by the mean flow, while extra tropical circulations are driven by both mean and eddy components. The eddy part in extra tropics is usually more significant than the mean flow. 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.

Following HOLOPAINEN (1978), the kinetic energy budget equation is expressed as

$$\overline{\frac{\partial K_M}{\partial t}} + \nabla.(H_0 + H_1) + \frac{\partial}{\partial P}\overline{(K_M + \overline{V}V')\omega} = -\overline{V}.\nabla\overline{\phi} - C(K_M, K_T) + \overline{V}.\overline{F} \qquad (1)$$

where

$$K_M = \frac{1}{2}\overline{V}^2 \text{ Kinetic energy of the mean flow,}$$

$$K_T = \frac{1}{2}V'^2 \text{ Kinetic energy of the eddy flow.}$$

Various notations used in the equation are given below:

$$H_0 = K_M\overline{V} \qquad ; \quad H_1 = \overline{(\overline{V}.V')V'}.$$

H_0 and H_1 are kinetic energy fluxes due to mean and eddy component of flow, respectively.

$$C(K_M, K_T) = C_H(K_M, K_T) + C_v(K_M, K_T)$$

$$C_H(K_M,K_T) = -\frac{\overline{u'u'}}{a\cos\varphi}\frac{\partial\overline{u}}{\partial\lambda} - \frac{\overline{u'v'}\cos\varphi}{a}\frac{\partial}{\partial\varphi}\left(\frac{\overline{u}}{a\cos\varphi}\right) - \frac{\overline{u'v'}}{a\cos\varphi}\frac{\partial\overline{v}}{\partial\lambda} - \frac{\overline{v'v'}}{a}\frac{\partial\overline{v}}{\partial\varphi} + \overline{u'u'}\frac{\overline{v}\tan\varphi}{a}$$

$$C_V(K_M,K_T) = -\overline{u'\omega'}\frac{\partial\overline{u}}{\partial P} - \overline{v'\omega'}\frac{\partial\overline{v}}{\partial P}.$$

The first term on the left side of equation (1) designates the local tendency of kinetic energy. The second and third terms describe the horizontal and vertical flux divergences of kinetic energy, respectively. Similarly, the first term on the right side of the equation denotes the conversion of available potential energy to kinetic energy through the action of pressure forces (adiabatic generation of kinetic energy). The second term describes the exchange of energy between mean and transient flows that arises from the horizontal and vertical Reynolds stresses. The last term signifies the dissipation of kinetic energy by the turbulent frictional processes.
The vorticity budget equation is designated as

$$\overline{\frac{\partial\zeta}{\partial t}} + \nabla.(\overline{\zeta V}) + \beta\overline{v} + \frac{\partial(\overline{\zeta\varpi})}{\partial P} = -(\overline{\zeta D}) - \overline{k.(\nabla\omega x\frac{\partial v}{\partial P})} + \overline{Z}, \qquad (2)$$

where
$\zeta = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$ is the relative vorticity ; $D = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$ is the divergence.

The first term on the left-hand side of equation (2) denotes the local rate of change of vorticity. The second and third terms indicate the horizontal flux divergences of relative and planetary vorticity, respectively. The fourth term describes the vertical divergence flux of relative vorticity. Similarly, the first and second terms on the right-hand side evince the vorticity generation due to stretching and tilting, respectively. The final term designates the residue of vorticity (i.e., generation/dissipation of vorticity from subgrid scale processes).

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

$$\overline{\frac{\partial(CpT)}{\partial t}} + \nabla.\overline{V}Cp\overline{T} + \frac{\partial}{\partial p}(\overline{\omega}\,Cp\,\overline{T}) - \overline{\omega}\,\overline{\alpha} = \overline{Q}_H. \tag{3}$$

In the equation (3), 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 (3) describes the diabatic heating, which is due to radiation, condensation, turbulent transfer, evaporation of falling raindrops and turbulent transfer of sensible heat.

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

$$\overline{\frac{\partial(Lq)}{\partial t}} + \nabla.\overline{V}\,L\,\overline{q} + \frac{\partial}{\partial p}(\overline{\omega}\,L\,\overline{q}) = \overline{Q}_M. \tag{4}$$

The first term on the left of equation (4) indicates the local tendency of moisture. The second and third terms designate the horizontal and vertical divergence fluxes of moisture, respectively. The right term evinces the diabatic contributions to latent heat energy or the moisture source/sink that arises from diabatic heating due to latent heat release and condensation as well as turbulent transfer of latent heat.

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 last terms on the right of the budget equations (1 to 3) represent the contribution from the subgrid scale physical processes. These terms are evaluated implicitly in this study as residues of all the other terms in the respective budget equations. Although we evaluated all budget equations, the discussion in this paper is restricted to the terms which contribute significantly to the budgets that are largely responsible for the maintenance of the summer monsoon circulation. Further, 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 95% confidence level is 1.75. We computed the Student's *t*-test by using the formula

$$t = \frac{\overline{X}_e - \overline{X}_d}{\sigma\left(\frac{1}{N_e} + \frac{1}{N_d}\right)},$$

where σ is the standard deviation, $\overline{X}_e$ and $\bar{x}$ are the mean of excess and deficient monsoons. N_e and N_d are the total number of excess and deficient monsoon seasons.

4. Results and Discussion

The Indian summer monsoon undergoes substantial variability in the amount of rainfall from one season to another. The average seasonal rainfall in summer monsoon (June-September) over India is 852 mm and standard deviation is 82 mm. Table 1 illustrates the excess (surplus) and deficient (drought) monsoon years during the period 1948–1999. The values of the Indian summer monsoon rainfall are taken from a data source of India Meteorological Department (IMD) and PARTHASARATHY *et al.* (1994) to categorize the surplus and deficient monsoon years. The departure of the rainfall more (less) than 10% from the long-term mean is considered as surplus (deficient) monsoon. Based on the above criteria, 23 (18%) deficient monsoon years and 17 (13%) surplus monsoon years and the remaining 89 (69%) normal monsoon years were recorded during a 129-year (1871–1999) period. In this regard during the recent 52 years (1948–1999) under present study, 8 (15%) surplus and 11 (21%) deficient and 33 (64%) normal monsoon years are identified. Thus, no appreciable changes are found in the mode of occurrence of extreme monsoon events from 1948 to 1999. In this study the large-scale features of kinetic energy, vorticity, heat and moisture and its spatial variability in terms of mean and standard deviation are examined over the Asian summer monsoon using 52-year (1948–1999) NCEP reanalysis data sets. Further, the comprehensive analysis of contrasting dynamical features between eight surplus and eleven deficient monsoon year is also investigated with Student *t*-test at 95% confidence level to identify the statistically significant regions.

4.1 Precipitation, OLR and Net Tropospheric Moisture

The seasonal mean precipitation of NCEP reanalysis is illustrated in Figure 1. The climatology of rainfall (Fig. 1a) indicates maximum rainfall over north Bay of Bengal and the adjoining Indian region, the west Indian coast and the adjoining Arabian Sea. Maximum rainfall is noted over the equatorial Indian Ocean. This pattern is consistent with the rainfall climatology of RAO (1976) and XIE and ARKIN

Table 1

Surplus and deficient monsoon years during 1948–1999

Surplus Year	Deficient Year
1956 (15.12)	1951 (−13.54)
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 values in the bracket depict the percentage departure from the mean)

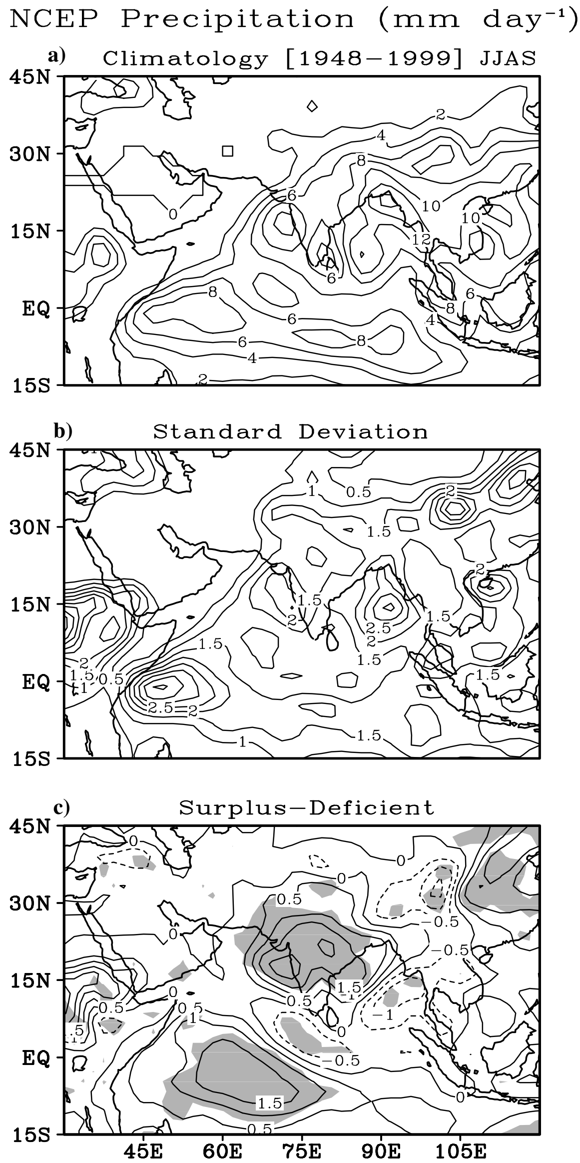

Figure 1
Geographical distribution of seasonal mean (JJAS) NCEP precipitation (mm day^{-1}) a) climatology (1948–1999), b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

(1997). Further, RAJU *et al.* (2002) stated that on a seasonal scale the NCEP precipitation appears to be reliable as regards the distribution of rainfall over India. The variability of rainfall measured in terms of its standard deviation from the climatological average (1948–1999) is shown in Figure 1b. It shows the maximum variability over the Bay of Bengal, the west coast and the western equatorial Indian Ocean. The difference of NCEP precipitation between surplus and deficient monsoon years is shown in Figure 1c. The statistically significant regions at 95% confidence level (based on Student's *t*-test) are shaded. The difference indicates more precipitation over Indian landmass, western equatorial Indian Ocean, small pockets over western Bay of Bengal and east Arabian Sea during surplus monsoon years. These regions are statistically significant. It may be noted that the negative values (less rainfall) during surplus years as compared to deficient years are observed over equatorial east Bay of Bengal off Myanmar and central China. The geographical distribution of outgoing long wave radiation (OLR) is presented in Figure 2. The low value of OLR corresponds to emission from higher levels and hence higher cloud tops (more rain when the clouds are deep). The climatological pattern (Fig. 2a) denotes maximum OLR over the Arabian Peninsula, Iraq and Iran where rainfall amounts are insignificant. The Bay of Bengal, the west Indian coast and the western equatorial Indian Ocean indicate lower OLR values. This is due to the fact that during the summer monsoon season, the lower OLR is associated with higher convective cloudiness and hence the precipitation. The maximum variability of OLR is observed over the equatorial Indian Ocean, north Africa and the south Indian peninsula (Fig. 2b). The difference of OLR between the composite of surplus and deficient monsoon years (Fig. 2c) reveals negative OLR over the equatorial Indian Ocean with its maximum in the western sector. These regions are statistically significant at 95% confidence level. It indicates that these regions are associated with low OLR values during surplus monsoon years. Further, the zones of low OLR values favourably agree with regions of excess precipitation (Fig. 1c). Thus, it is suggested that the equatorial convection, particularly in the western sector, plays an important role in the summer monsoon activity and hence precipitation over India. The geographical distribution of net tropospheric moisture is presented in Figure 3. The climatology of net tropospheric moisture (Fig. 3a) depicts the maximum moisture over the Indian subcontinent extending eastwards to southeast China through Myanmar, with minimum moisture over the Tibetan plateau. The maximum moisture zone is due to the low-pressure system that moves from the Pacific Ocean across Myanmar into the head of the Bay of Bengal, intensifies into depression and moves along the monsoon trough zone. The net tropospheric moisture shows the maximum variability in the monsoon trough zone and the south Arabian Sea (Fig. 3b). In the monsoon trough zone the variability could be due to the movement of monsoon lows/depression, while in the south Arabian Sea, it could possibly be due to pulses in the monsoon current associated with the strengthening and weakening of the monsoon. The difference of surplus and deficient monsoon years (Fig. 3c) indicates that most of the monsoon domain except a few small pockets is characterized by excess net tropospheric moisture during the surplus monsoon season, with a maximum over northwest India and the adjoining Arabian Sea. The

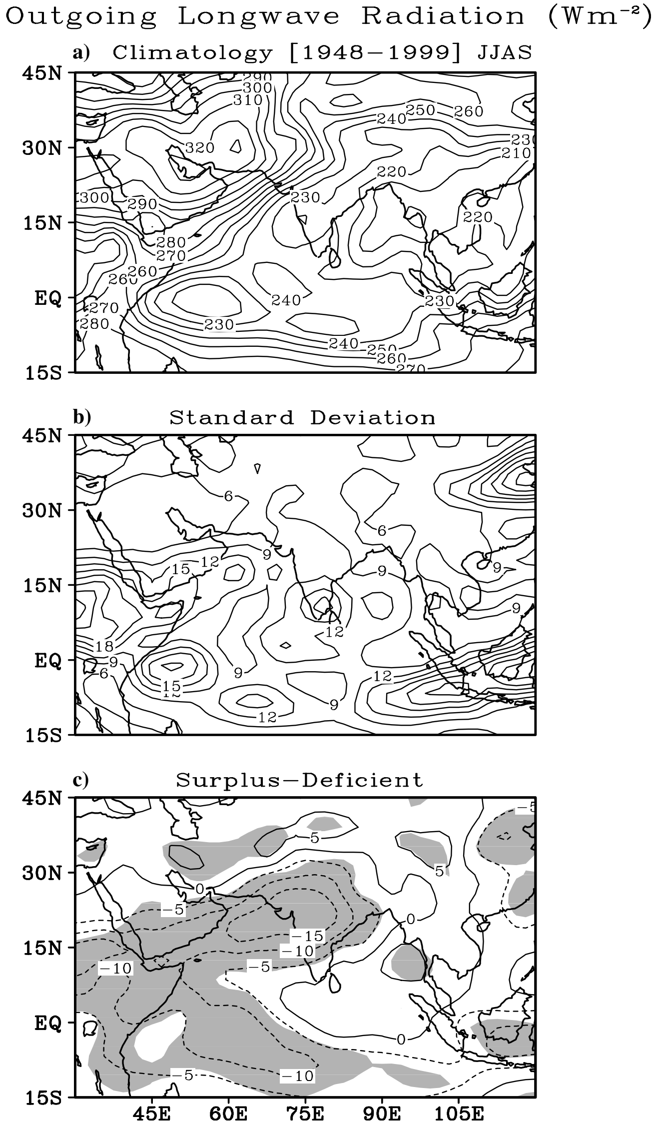

Figure 2
Geographical distribution of outgoing longwave radiation (W m^{-2}) for a) climatology (1948–1999), b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

statistically significant regions are observed over the Arabian Sea extending from the western equatorial Indian Ocean and Indian land mass except northeast India. These regions of statistical significance are in good agreement with regions of negative OLR (Fig. 2c) and excess rainfall (Fig. 1c).

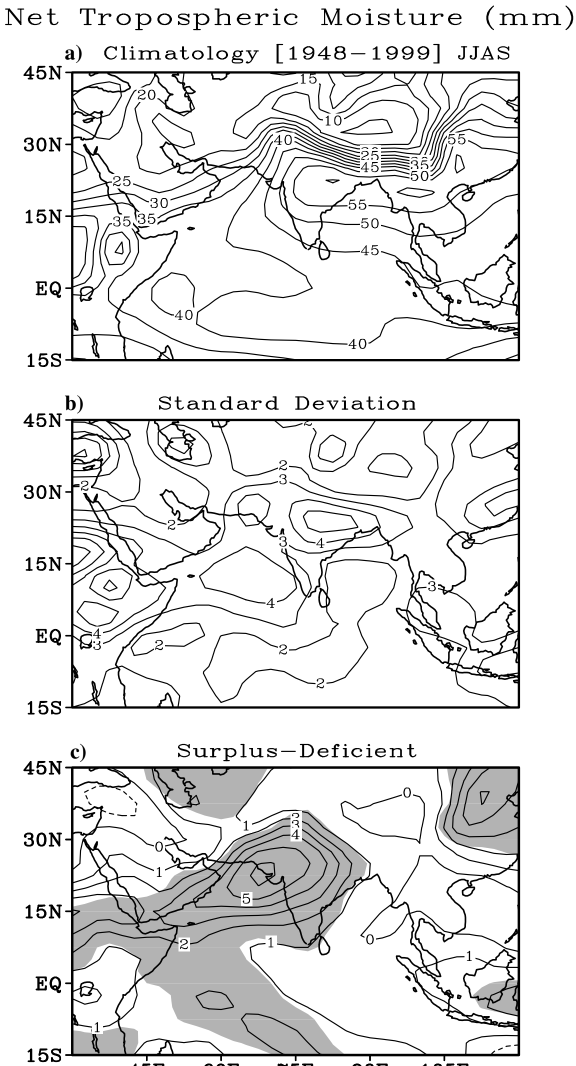

Figure 3
Geographical distribution of net tropospheric moisture (mm) for a) climatology (1948–1999), b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

4.2 Circulation Features

In order to delineate the predominant characteristic circulation features of Asian summer monsoon in the vertical plane, the sectorial mean cross sections of zonal wind, meridional wind over two longitudinal sectors; the Arabian Sea (45°E–75°E) and the Bay of Bengal (85°E–105°E) are considered. Figure 4 depicts the sectorial mean cross sections of zonal wind over Arabian Sea (left panel) and Bay of Bengal (right panels) sectors for JJAS climatology (Figs. 4a,d), standard deviation (Figs. 4b,e) and the difference between surplus and deficient years at 95% significant level (Figs. 4c,f). The significant features of zonal wind over the Arabian Sea (Fig. 4a) include low-level westerly jet (9 ms^{-1}) located around 10°N. The westerlies prevail up to 400 hPa level and above those strong easterlies with a core speed of 27 ms^{-1} around 150 hPa level in the tropics. The characteristic strong lower level easterlies due to southeast trades are monitored in the Southern Hemispheric tropics. In the Bay of Bengal sector (Fig. 4b), the low-level westerly jet is weaker as compared to the Arabian Sea sector that prevails up to 600 hPa, and above strong easterlies are observed. In extra tropics both sectors indicate strong westerlies with a maxima of 30 ms^{-1}. The maximum variability of zonal wind is noted at the upper levels both in the Arabian Sea and the Bay of Bengal sectors between the equator to 10°N. In addition, the Arabian Sea sector also shows substantial variability at 400 hPa over the equator. This variation is possibly due to a change of the wind from westerlies in the lower and middle troposphere to easterlies in the upper troposphere. The difference (surplus and deficient) indicates a stronger low-level westerly jet over the Arabian Sea sectors and weaker westerlies in the Bay of Bengal during surplus monsoon years (Figs. 4c,f). The Arabian Sea sector manifests significant negative differences between 20°N–30°N throughout the troposphere, with a maximum at 250 hPa. In the low level, the westerly jet was noticed between 10°N–20°N, and prevails up to 400 hPa. These regions are statistically significant at 95% confidence level. The mean meridional wind for the Arabian Sea and the Bay of Bengal sectors is illustrated in Figure 5. The salient features pertaining to the meridional component are a low-level convergent flow from the equatorial Indian Ocean to the Indian monsoon domain followed by a strong divergent flow from the monsoon region to the Southern Hemisphere confined to 300–100 hPa. The difference between surplus and deficient monsoon years (Figs. 5c,f) indicates a weakening of divergent flow in the upper level between 15°N–30°N in surplus years over the Arabian Sea sector (Fig. 5c). Over the Bay of Bengal sector (Fig. 5e) shows that a decrease in low-level convergence and upper level divergence between 10°S–10°N results in a decrease in convective activity which agrees favorably with OLR.

4.3 Kinetic Energy

The maintenance and intensity of the general circulation of the atmosphere depend on the balance between the generation and dissipation of the kinetic energy. The kinetic energy of the atmosphere is created through the conversion of available potential energy and eventually is dissipated through irreversible frictional processes. The monsoon circulation is maintained through the release of available potential energy for conversion to kinetic energy. The potential energy in the monsoon zone is provided by direct solar insolation and heating of the atmosphere over the land areas, by evaporation from oceans, developing cumulus cloud and the release of

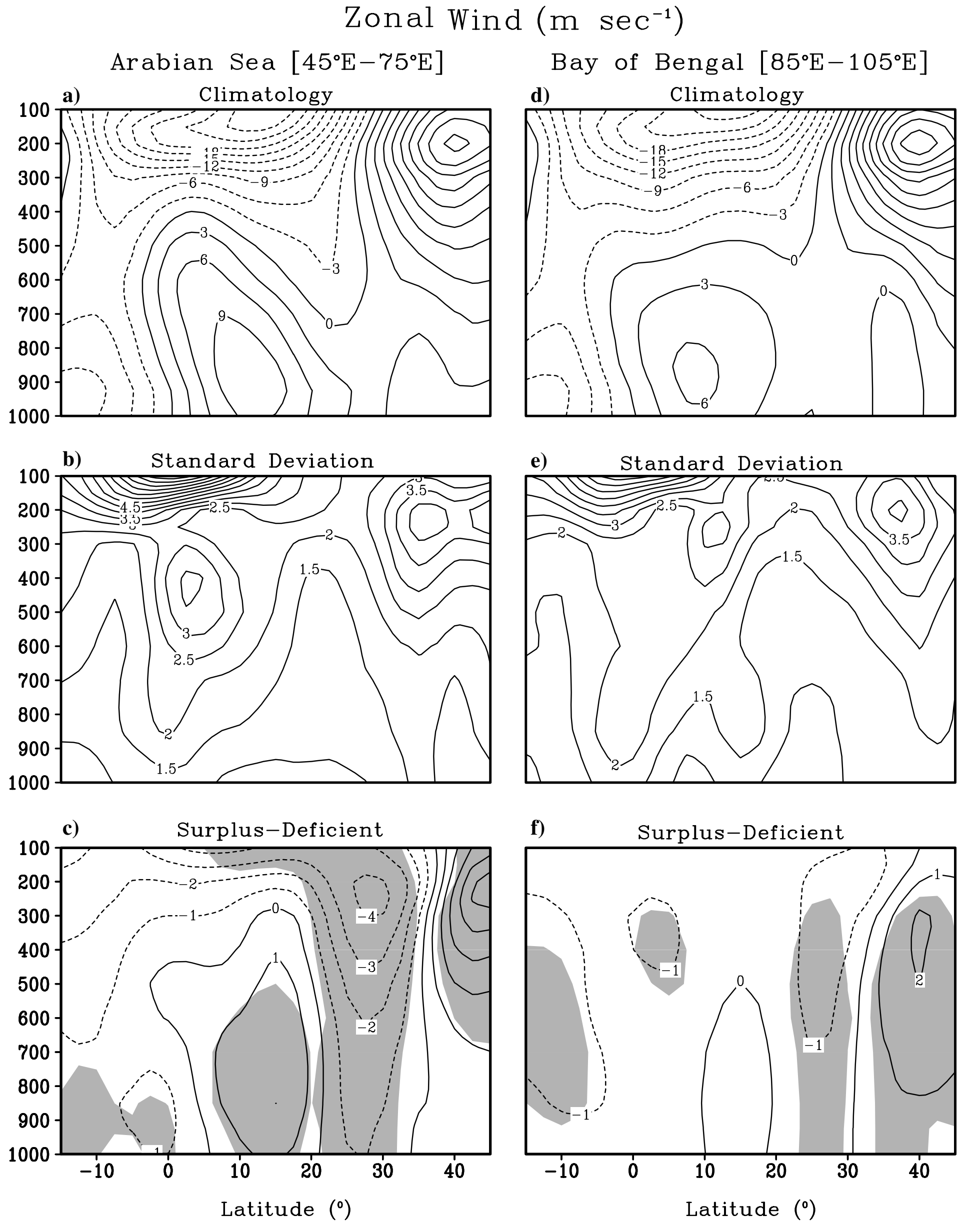

Figure 4

Height-latitude cross sections of zonal wind (m s^{-1}) for the Arabian Sea sector (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and Bay of Bengal sector (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) [shaded region is 95% significant level].

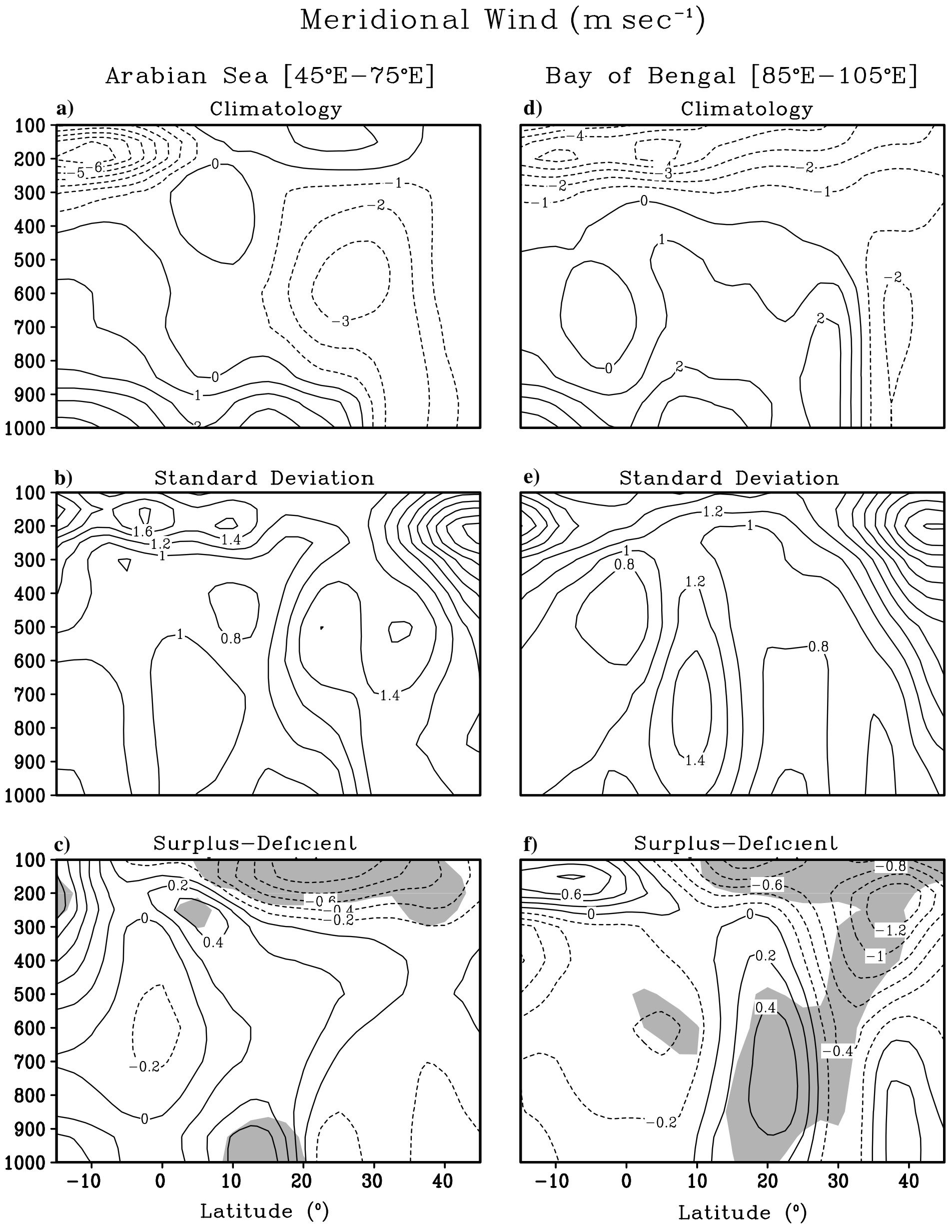

Figure 5

Height-latitude cross sections of meridional wind (m s^{-1}) for the Arabian Sea sector (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and the Bay of Bengal sector (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) shaded region is 95% significant level].

latent heat. Though the potential energy is generated over the entire monsoon domain, the maximum production is expected to be around the monsoon trough zone (ANJANEYULU, 1971) where the maximum precipitation also takes place and is supported by the omega field. The local balance of kinetic energy is governed by three significant terms: namely horizontal flux, generation and dissipation of kinetic energy. In general, the dissipation of kinetic energy takes place through the surface friction and viscous stress within the atmosphere. In this section we examine horizontal flux and generation terms which play a major role in maintaining the monsoon circulation.

The geographical distribution of horizontal flux divergence of kinetic energy at 850 hPa and 150 hPa is shown in Figure 6. The top, middle and bottom panels depict the climatology (1948–1999), standard deviation and the difference between composite surplus and deficient monsoon years, respectively. At the lower level of 850 hPa (Fig. 6a), it is observed that the flux divergence of kinetic energy is over the Somali Coast and the flux convergence of kinetic energy is in the east Arabian Sea. It is associated with the low-level Somali jet entrance and exit regions, respectively. It is ascertained that the maximum variability lies in the same region of the Somali Coast and Arabian Sea (Fig. 6b). Over these regions the strong westerly (low-level jet) prevails during the summer monsoon. The difference between the surplus and deficient monsoon season with 95% significant level is depicted in Figure 6c. The flux divergence is seen over the Somali Coast and western Arabian Sea and convergence flux over the east Arabian Sea and Indian peninsula enhances in surplus years. This low-level jet is responsible for transporting the moisture along with the air mass from the Arabian Sea to the Indian land mass. The distribution of mean kinetic energy flux divergence at 150 hPa (Fig. 6d) over the summer monsoon region indicates that a zone of kinetic energy flux divergence extends over the south Asian region over spreading from the West Pacific to the eastern Arabian Sea with flux divergence maxima situated over the Bay of Bengal and flux convergence over the western Arabian Sea, adjoining the Arabian and eastern African regions. These zones of kinetic energy flux which transport maxima (minima) are situated at the respective entrance (exit) regions of TEJ. It is discovered that the entrance (exit) regions of TEJ are characterized by adiabatic production (destruction) of kinetic energy. Such a nature of kinetic energy production is necessary to maintain the strong outflow (inflow) of energy at the respective locations of TEJ (MOHANTY and RAMESH, 1994). 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. Figure 6e shows the standard deviation of kinetic energy budget at 150 hPa. It can be seen that the horizontal flux of kinetic energy is observed as a large part of the variability over the Bay of Bengal, the southern Arabian Sea and the east African region. The difference between surplus and deficient monsoon years shows that the horizontal flux of kinetic energy at 150 hPa during the surplus monsoon season denotes the strong flux divergence over the Indian peninsula, Arabian Sea and

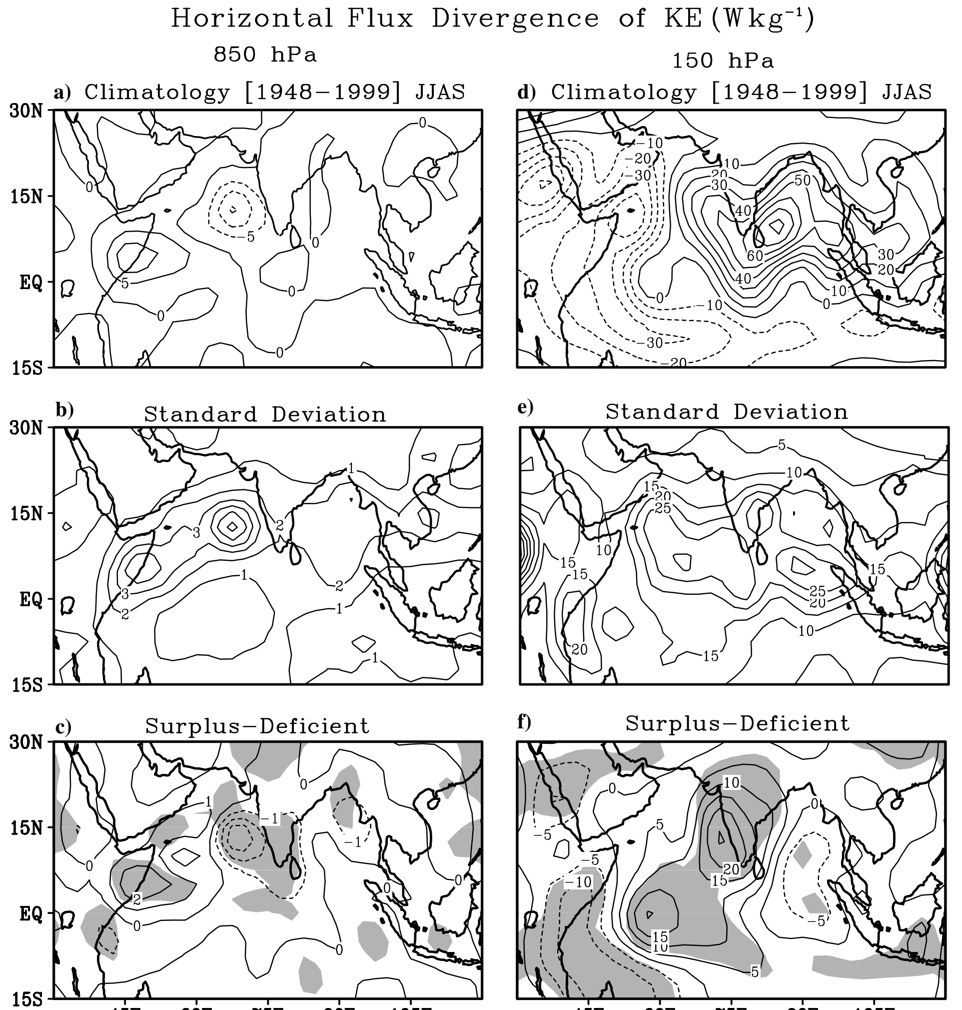

Figure 6
Geographical Distribution of Horizontal Flux Divergence of Kinetic Energy (10^{-4} W kg^{-1}) for 850 hPa (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and 150 hPa (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) [shaded region is 95% significant level].

western Indian Ocean, and the flux convergence over the east African and adjoining Indian Ocean enhances, signifying a large divergence of air mass from the Indian peninsula to the Southern Hemisphere. These regions indicate statistical significance at 95% confidence level (shaded region).

The kinetic energy is basically produced by the ageostropic component of the flow i.e., cross-isobaric flow. Positive magnitudes signify the generation of kinetic

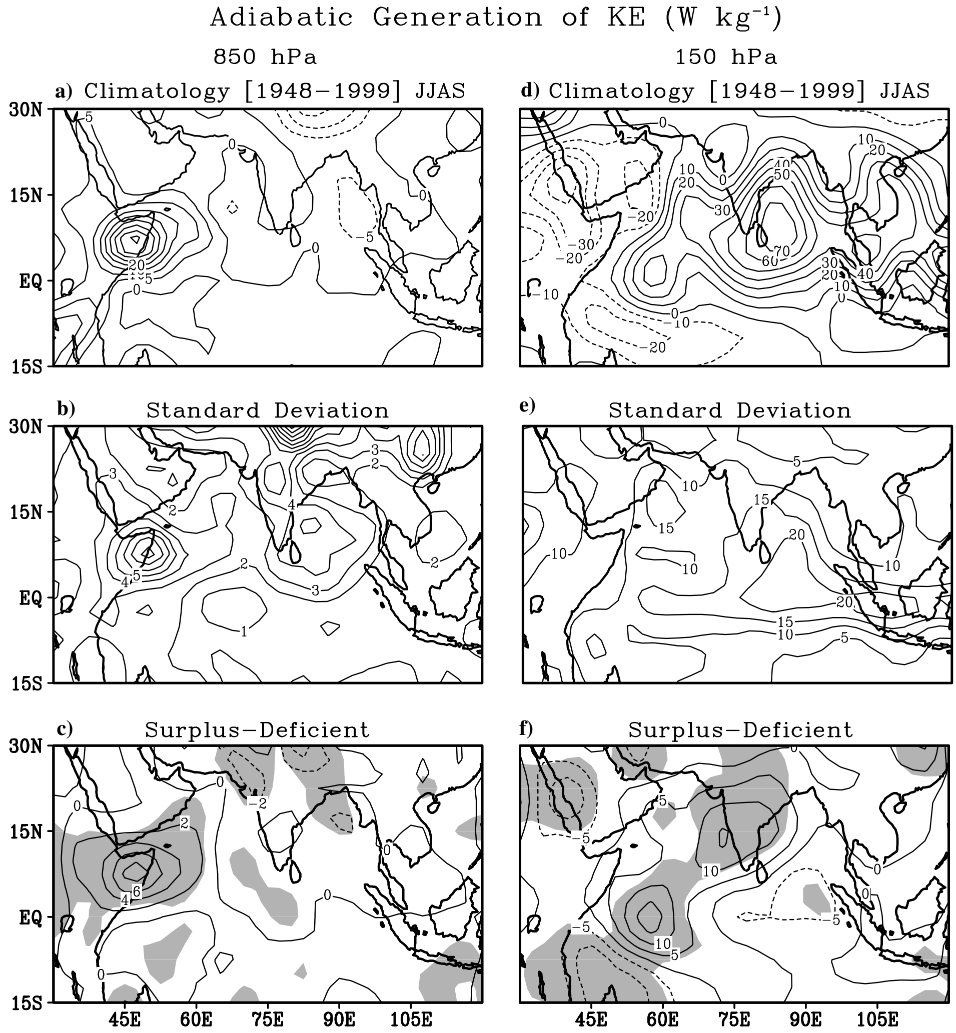

Figure 7
Geographical distribution of adiabatic generation of kinetic energy (10^{-4} W kg^{-1}) for 850 hPa (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and 150 hPa (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) [shaded region is 95% significant level].

energy from the available potential energy, and negative magnitudes indicate the conversion of kinetic energy back to available potential energy. It is determined 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 at 850 hPa (Fig. 7a) depicts maxima over the Somali Coast and is due to the strong ageostropic flow in that region. These production maxima are in agreement with the kinetic energy (horizontal) flux maxima. However, the maximum variability is also observed over the Somali Coast (Fig. 7b). The difference between surplus and deficient monsoon years (Fig. 7c) shows the generation of KE enhanced during surplus years as compared to deficient years over the Somali Coast. The generation of kinetic energy indicates maximum variability over the east equatorial Indian Ocean (Fig. 7e). The difference between surplus and deficient monsoon years (Fig. 7f) demonstrates that the generation of KE enhanced significantly during surplus years, extending from equatorial Indian Ocean to the Indian land mass.

Normally the zonal component contributes to generation in the extra tropics and dissipation in the tropics, and the meridional component *vice versa* (KUNG, 1971). The adiabatic generation of zonal kinetic energy is presented in Figure 8. In the lower tropospheric features (850 hPa) include the generation over the Indian peninsula and the adjacent Arabian Sea and the destruction of kinetic energy over the Bay of Bengal, western Arabian Sea and western Indian Ocean. The strong variability in zonal generation of kinetic energy can be seen over central India, east Bay of Bengal and Somali Coast (Fig. 8b). The difference between surplus and deficient monsoon seasons indicates destruction/negative generation over the Bay of Bengal, northwest India and western Indian Ocean, and the production over northeast Africa. These regions are significant at 95% confidence level. The zonal generation of kinetic energy at 150 hPa is represented in Figures 8d,e,f. The climatological features show that the generation over the Indian peninsula and adjoining Indian Seas of the Arabian Sea, Bay of Bengal and Indian Ocean. The destruction/weak generation is found over the northeast Bay of Bengal and northeast Africa. Further, the entire monsoon region exhibits strong variability, which is represented by standard deviation with the maximum over the Arabian Sea and Bay of Bengal. The difference between surplus and deficient monsoon years is illustrated in Figure 8f. The difference between surplus and deficient years demonstrates the generation over the western Indian Ocean and the destruction over the Bay of Bengal. The zones of maximum generation/destruction are statistically significant at 95% confidence level (shaded region). The meridional generation of kinetic energy at 850 hPa and 150 hPa is represented in Figure 9. In the lower levels at 850 hPa (Fig. 9, left panels), the climatological pattern depicts generation over the Somali Coast and the adjoining Arabian Sea. In addition, the positive generation is observed over the western Arabian Sea and Bay of Bengal. Further, the standard deviation of the meridional component (Fig. 9b) shows maximum variability over the Somali Coast and Bay of Bengal. These regions manifest higher magnitude in the surplus monsoon season. In the upper level at 150 hPa (Fig. 9, right panels), meridional generation of kinetic energy contributes to the production of kinetic energy over the Bay of Bengal and destruction over the western Indian Ocean and Arabian peninsula (Fig. 9d). The difference between surplus and deficient monsoon points out strong generation over the Indian peninsula and the adjoining Arabian Sea and Bay of Bengal. Destruction over the western Indian Ocean and north Arabian peninsula. The interesting feature

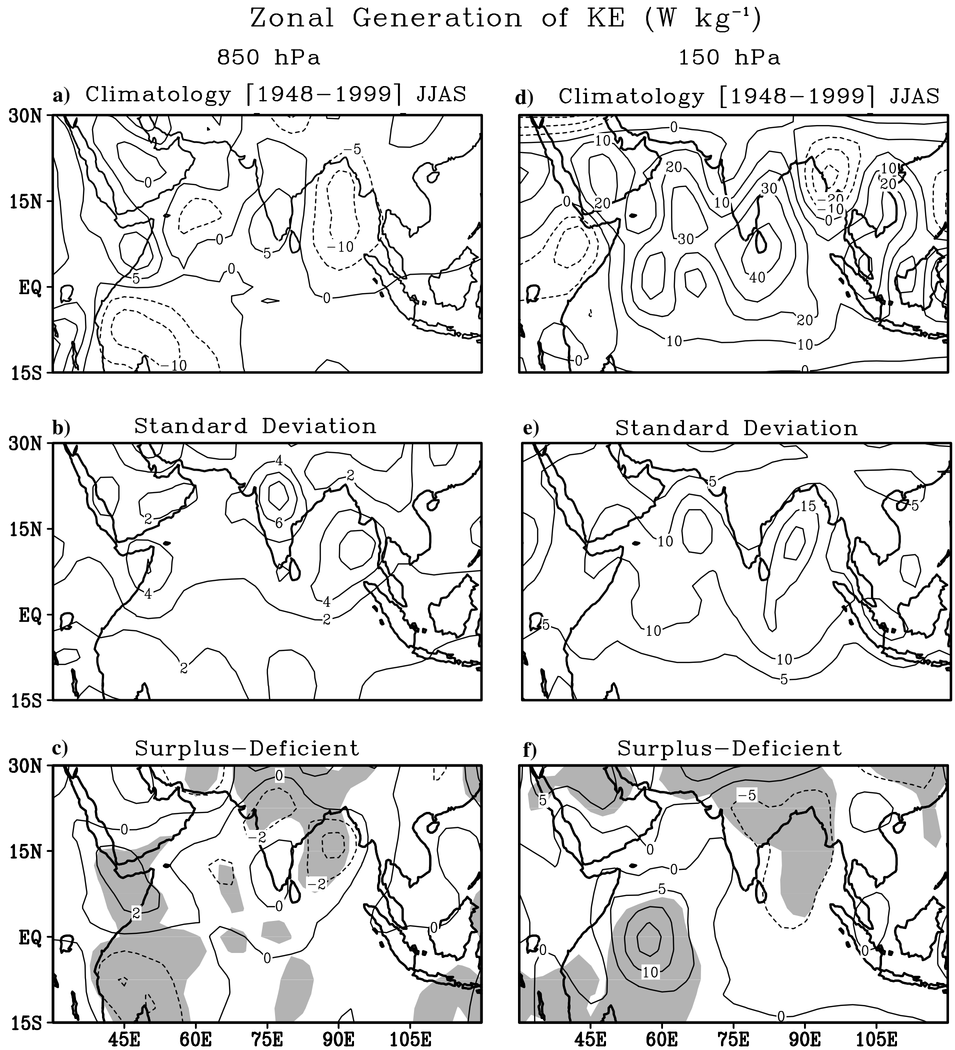

Figure 8
Geographical distribution of zonal generation of kinetic energy (10^{-4} W kg^{-1}) for 850 hPa (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and 150 hPa (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) [shaded region is 95% significant level].

delineated by these two components over the monsoon domain is that both contribute to generation, though the contribution by the meridional component is significantly higher over the Somali Coast and Bay of Bengal.

In this study it is found that the eastern Arabian Sea and southwest Bay of Bengal maxima of kinetic energy production is maintained by the zonal component of the ageostropic flow while that of the Bay of Bengal is maintained by the meridional

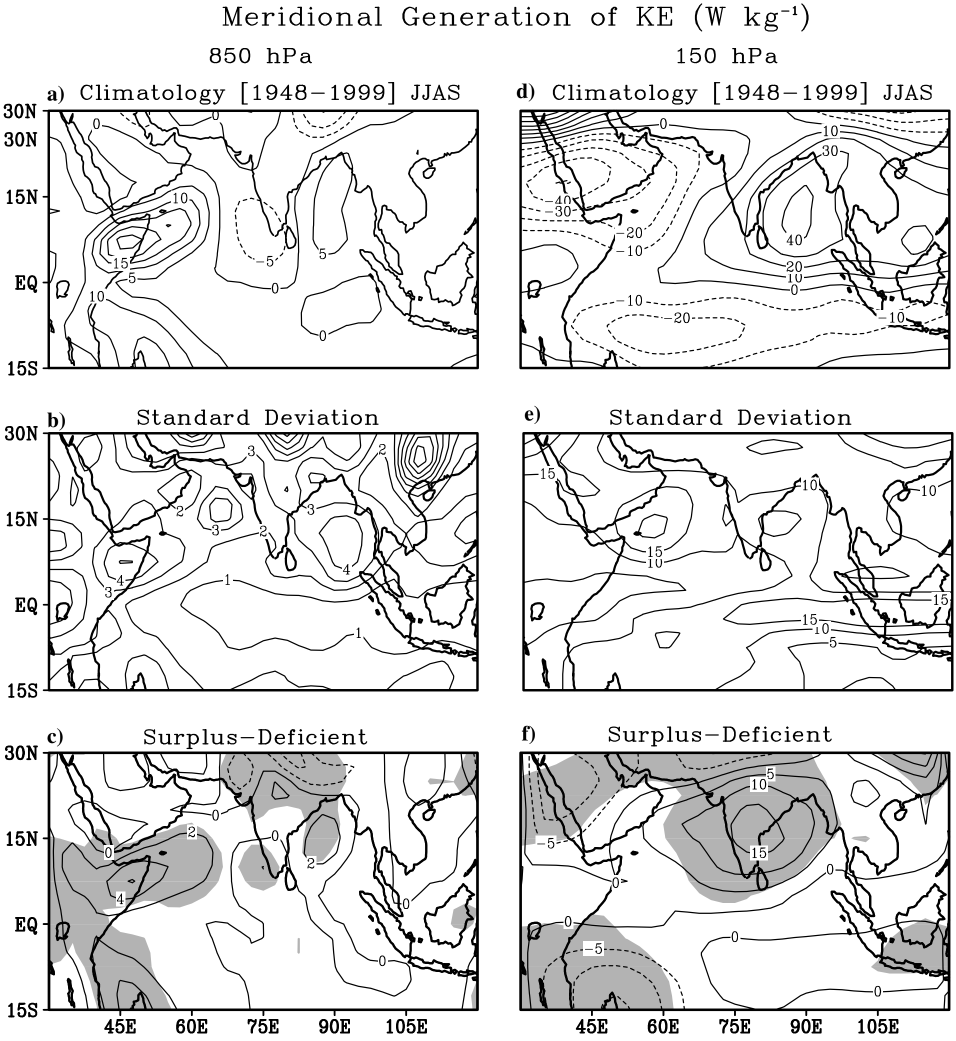

Figure 9
Geographical distribution of meridional generation of kinetic energy (10^{-4} W kg^{-1}) for 850 hPa (left panels), a) climatology, b) standard deviation, c) difference (surplus-deficient) and 150 hPa (right panels), d) climatology, e) standard deviation, f) difference (surplus-deficient) [shaded region is 95% significant level].

component of the ageostropic flow. The major part of the variability over the eastern equatorial Indian Ocean arises from the meridional generation of kinetic energy. It is seen that the zonal and meridional generations of kinetic energy show maximum variability over the Arabian Sea and Bay of Bengal, mainly due to fluctuation in the intensity and location of jets (entrance and exit regions).

4.4 Vorticity

The characteristic features of the monsoon are described with the vorticity budget. In general, the vorticity transport and generation terms are the most significant in the vorticity budget (HOLOPAINEN and OORT, 1981; CHU *et al.*, 1981). DAGGUPATY and SIKKA (1977) stated that the lower tropospheric vorticity budget is balanced by advection of vorticity and frictional effects. In the lower troposphere, the divergence term contributes to the generation of cyclonic vorticity while in the upper troposphere it contributes to the generation of anti-cyclonic vorticity. The horizontal advection of planetary vorticity (Fig. 10) delineates positive advection over the Bay of Bengal and east Africa and adjoining west Indian Ocean. It manifests negative advection over the eastern equatorial Indian Ocean, south peninsular India and Arabian peninsular region. It is apparent that both these advections oppose each other over the summer monsoon. Also, over the south Indian peninsula and extending up to east Bay of Bengal considerable variability of horizontal advection of relative vorticity is exhibited. The difference between surplus and deficient years in horizontal advection of planetary vorticity (Fig. 10c) depicts flux divergence over the Indian peninsular region, western equatorial Indian Ocean, and east Asian region during the surplus monsoon season. The flux convergence is observed over east Arabia and the adjoining Arabian Sea in the surplus monsoon season. Further, these zones are identified as statistically significant.

The vorticity generation due to stretching is illustrated in Figure 11. It indicates that the generation of cyclonic vorticity dominates the Indian peninsula, Bay of Bengal and Arabian peninsula. However, the anti-cyclonic vorticity generation is observed over the equatorial Indian Ocean and the northwest sector of the Arabian Sea. The persistent convergence over the subcontinent sustains the circulation produced by interaction of the large-scale flow with the orographic barriers. This generation is crucial in order to sustain the cyclonic circulation in the lower troposphere. Further, the strong divergent circulation in the upper troposphere over the summer monsoon region is responsible for the generation of anti-cyclonic vorticity. The maximum variability of vorticity generation is detected over the north Indian region and southern Arabian Peninsula. The generation of vorticity (Fig. 11c) for the contrasting monsoon season shows that during the surplus monsoon season, there is a strong generation of vorticity over the entire Indian region. However, over the equatorial Indian Ocean and central Bay of Bengal weak generation/destruction of vorticity was observed. These regions are perceived at a 95% significant level.

4.5 Heat and Moisture

The mean climatological features of the summer monsoon are further analyzed through heat and moisture budgets. Also, the variability of the Asian summer monsoon is examined in terms of the standard deviation from the climatological average (1948–1999). The horizontal flux divergence of heat is depicted in Figure 12.

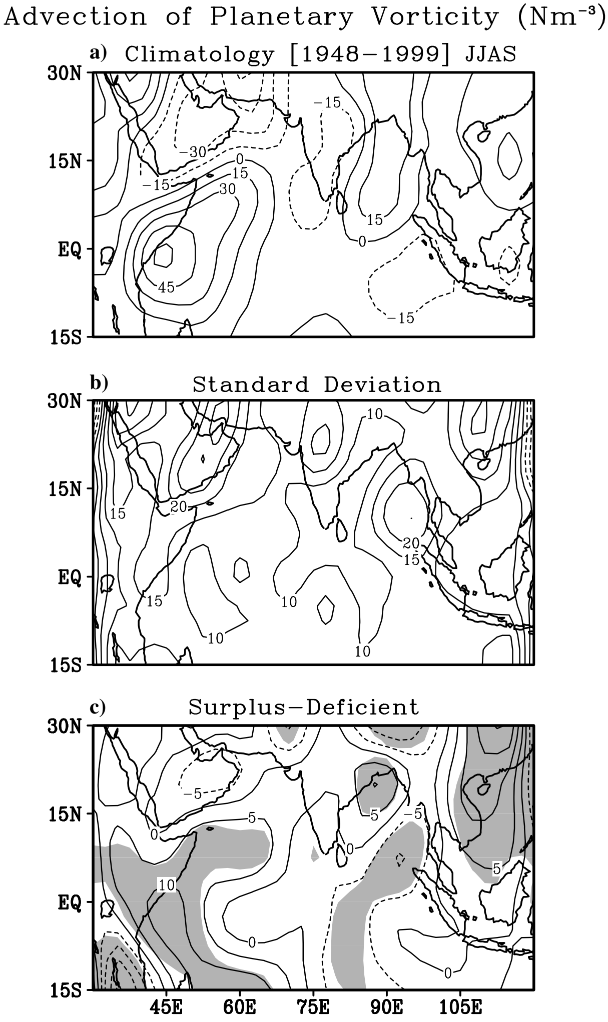

Figure 10
Geographical distribution of vertical integrated horizontal advection of planetary vorticity (10^{-8} Nm^{-3}), a) climatology, b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

The geographical distribution of horizontal flux divergence of heat (Fig. 12a) indicates that the summer monsoon domain is characterized by flux convergence with maxima over the Bay of Bengal and Arabian Sea. A zone of flux convergence of heat extends from the western Pacific to the Arabian peninsula across the Bay of Bengal and Arabian Sea. This is the region of monsoon trough/ITCZ. A zone of strong flux divergence is recognized off east Africa. The heat flux convergence in the monsoon trough/ITCZ region is essential to increase potential energy, which is available for conversion into kinetic energy and hence maintenance of the monsoon circulation.

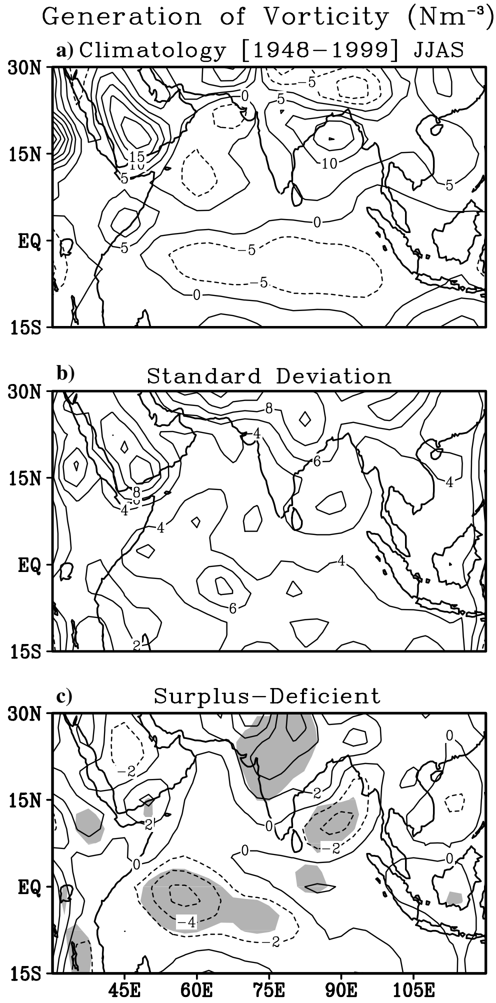

Figure 11
Geographical distribution of vertical integrated generation of vorticity (10^{-8} Nm^{-3}), a) climatology, b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

These are consistent with earlier studies carried out using different analyses (MOHANTY and RAMESH, 1994). The horizontal flux divergence of heat shows the zone of maximum variability over the central Arabian Sea, Bay of Bengal, central India and the western equatorial Indian Ocean. These zones observe maximum variability in conversion of available potential energy to kinetic energy. The difference of horizontal flux divergence of heat (Fig. 12c) is reflected of strong flux convergence over western India and the adjoining Arabian Sea. This is a characteristic feature of surplus monsoon. Further, strong convergence over east

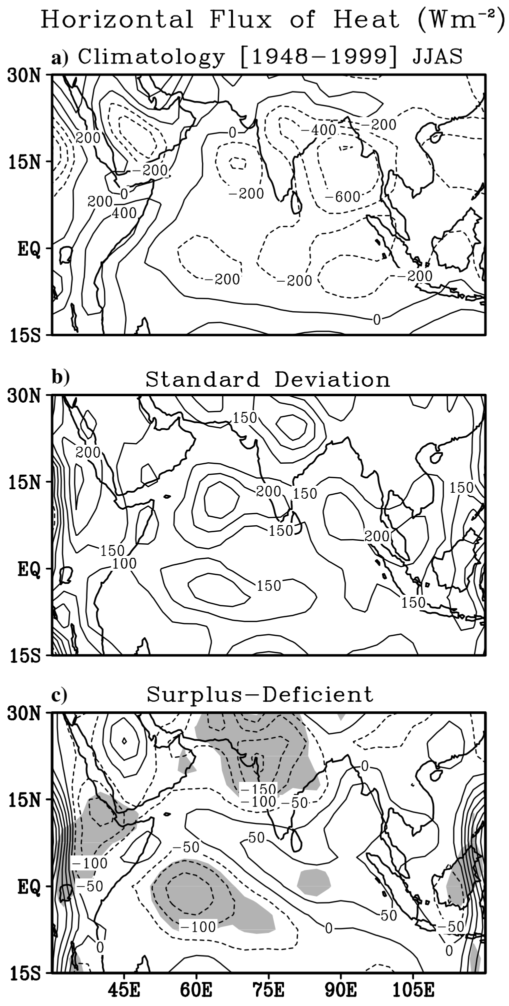

Figure 12
Geographical distribution of vertical integrated horizontal flux divergence of heat (Wm^{-2}), a) climatology, b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

Africa is also a conducive feature for excess monsoon rainfall over India. The interesting feature noted in this study is the strong convergence of heat flux over the western equatorial Indian Ocean during surplus monsoon season. On the other hand, convergence decreases over the eastern equatorial Indian Ocean and adjoining Bay of Bengal.

The diabatic heating pattern (Fig. 13a) connotes an excess of convective activity over the Bay of Bengal including the Indian peninsula and part of the eastern Arabian Sea and south Indian Ocean, which indicates the predominant rising motion and convective cloud formation over the summer monsoon region. During the

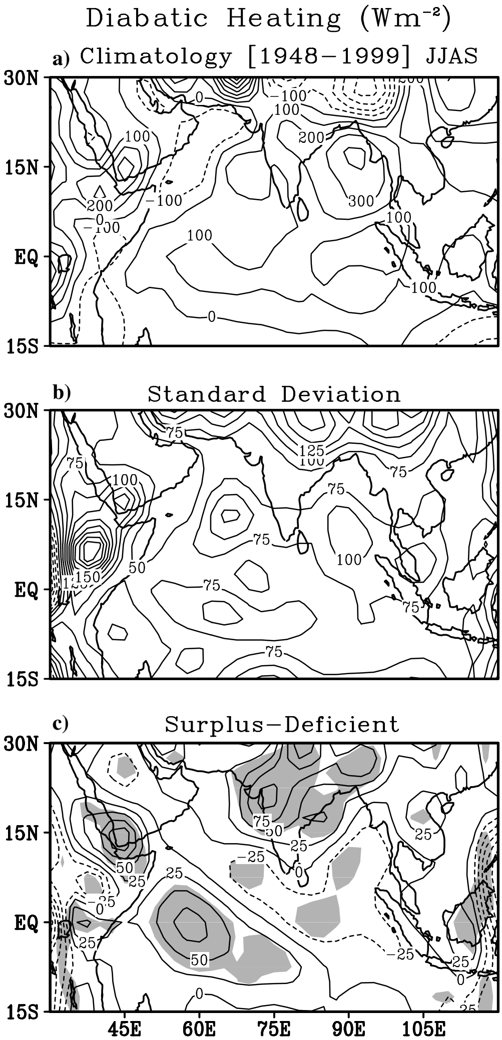

Figure 13
Geographical distribution of vertical integrated diabatic heating (Wm^{-2}), a) climatology, b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

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 forces and the additional role of dynamic factors that influence the summer monsoon. In addition, considerable variability of diabatic heating is observed over the Arabian Sea, the Bay of Bengal and the western equatorial Indian Ocean. The difference of diabatic heating pattern (Fig. 13c) connotes the decrease of convective activity in the deficient monsoon season and the increase of convective activity over the Indian region and western equatorial Indian Ocean during the surplus monsoon season. The maximum convective zones are correlated well with the precipitation centers. Further, these regions are statistically significant with 95% confidence level. The decreased diabatic heating over eastern equatorial Indian Ocean and adjoining east Bay of Bengal during surplus years is also consistent with precipitation and convective activity.

The geographical distribution of vertically integrated horizontal flux divergence of moisture (Fig. 14a) delineates that the entire monsoon region is characterized by strong flux convergence with maxima over the Bay of Bengal. The convergence of moisture is due to the monsoon trough and rapid cyclonic turning of low-level wind, which acts as a primary source for developing cumulus convection and ultimately sustains the monsoon circulation. PEARCE and MOHANTY (1984) studied the mean tropospheric moisture flux during May and June 1979 and showed that the buildup of the moisture flux over the summer monsoon domain could be attributed to the transportation from the south Indian Ocean. Further, the strong flux convergence zones are identified with excess diabatic heating. Corresponding to this heating, intense convective activity and rainfall are also observed over these zones. Thus, the moisture flux convergence contributes importantly in determining the diabatic heat patterns, which maintains the summer monsoon circulation. In addition, substantial variability of diabatic heating and horizontal flux divergence of moisture is noticed over the Arabian Sea, Bay of Bengal and western Indian Ocean. The difference (surplus-deficient) of vertically integrated horizontal flux divergence of moisture (Fig. 14c) indicates that during the surplus monsoon, excess convergence of moisture occurs over the east Arabian Sea, Indian landmass and the western equatorial Indian Ocean. These regions are statistically significant at 95% confidence level. A substantial decrease in convergence over the eastern equatorial Indian Ocean and adjoining Bay of Bengal is consistent with diabatic heating patterns and rainfall.

The seesaw pattern associated with most of the terms in the energetics over the equatorial western Indian Ocean and equatorial eastern Indian Ocean and adjoining Bay of Bengal may be due to the existence of the dipole phenomenon related to SST over the Indian Ocean (WEBSTER *et al.*, 1999 and SAJI *et al.*, 1999). The Indian Ocean climatology denotes maximum rainfall concentration over the tropical convergence zone of the Indonesian region. However, during the dipole mode event (positive SST anomaly over the western Indian Ocean and negative SST anomaly over the eastern Indian Ocean), rainfall decreases over the eastern Indian Ocean and increases over the western Indian Ocean. This pattern is dynamically consistent with divergence/convergence of patterns of wind shifts and outgoing long-wave radiation. In association with these aspects, during normal and deficient rainfall over India, the energetics regime over the Bay of Bengal seems to be intense. On the other hand, during the surplus monsoon season, the Arabian Sea delineates strong regime. During the dipole event the western Indian

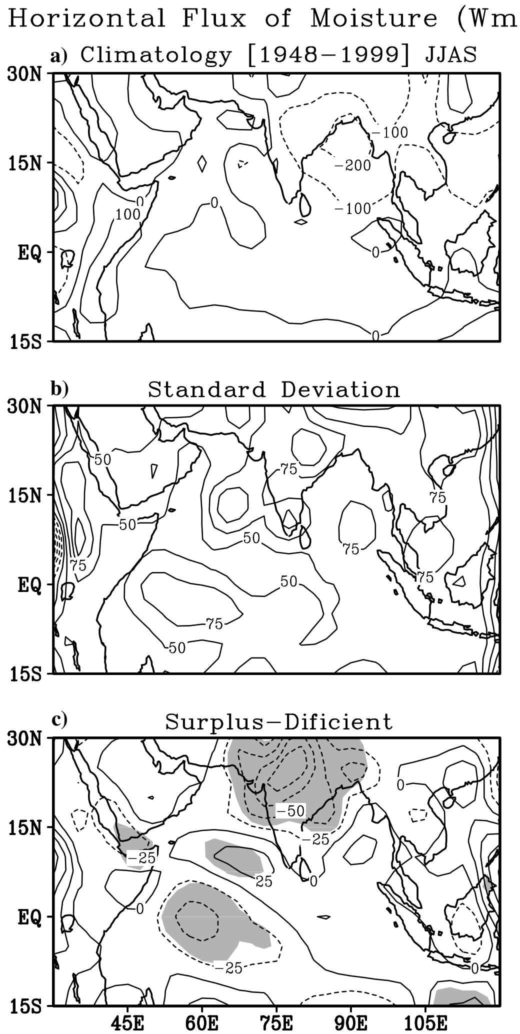

Figure 14
Geographical distribution of vertical integrated horizontal flux divergence of moisture (Wm^{-2}), a) climatology, b) standard deviation, c) difference (surplus-deficient) [shaded region is 95% significant level].

Ocean manifests anomalous warming. This warming is responsible for ample mass and moisture convergence. This anomalous warming produces 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 monsoon the western Indian Ocean is relatively cooler. This inhibits the convergence of heat and moisture and the formation of diabatic heat sources. Contrary to that, the eastern Indian Ocean is warmer during drought and normal monsoon conditions over India. This warming is responsible for strong convective regime over the Bay of Bengal and off Indonesia. The outgoing long-wave radiation, SST and zonal wind patterns (WEBSTER *et al.*, 1999 and SAJI *et al.*, 1999) adduce this aspect.

5. Conclusions

The analysis of mean circulation features and energetics of the Asian monsoons renders the following broad conclusions.

The difference of OLR between the composite of surplus and deficient monsoon years shows negative OLR over the equatorial Indian Ocean with a maximum in the western sector. These zones of low OLR values are in good agreement with regions of excess precipitation. This suggests the possible relation between the equatorial Indian Ocean, particularly the western sector and the summer monsoon activity over India.

The entrance/exit regions of the TEJ are characterized by the production/destruction of the kinetic energy, which is essential to maintain outflow/inflow prevailing at the respective location of the TEJ. The significant contribution originates from the meridional component over the Bay of Bengal to adiabatic generation of kinetic energy during the summer monsoon season.

The results indicate that the whole Indian Peninsula including the Bay of Bengal is unstable during the summer monsoon with the production of vorticity within the domain itself for maintaining the circulation. This production is manifested through subgrid-scale processes such as cumulus convection, unlike other regions where the balance is between the transportation and stretching term.

The summer monsoon evinces strong convergence of heat and moisture over the monsoon domain. In addition, considerable heat energy is generated through the action of adiabatic processes. The combined effect of these processes leads to the formation of strong diabatic heat sources in the region to maintain the monsoon circulation.

The interesting aspect presented in this study is that the large-scale budgets of kinetic energy, heat and moisture indicate excess magnitudes over the equatorial western Indian Ocean and Arabian Sea during the surplus monsoon. Conversely, the equatorial eastern Indian Ocean and adjoining east Bay of Bengal indicate excess magnitude during the deficient monsoon. During the normal and deficient monsoon the eastern Indian Ocean is relatively warmer compared to its western counterpart. The anomalous warming over the western Indian Ocean during the dipole formation is in principle responsible for intense energy flux transport over the Arabian Sea regime, leading to, surplus monsoon over India. In tandem with the warmer eastern Indian Ocean, during drought and normal monsoon season, the Bay of Bengal branch is intense. This is reflected in various budget terms considered in this study.

Acknowledgements

The authors sincerely acknowledge the NCAR for providing the NCEP/NCAR reanalysis data set. The authors express their thanks to two anonymous reviewers for their valuable comments enhancing the manuscript. Financial support from the Department of Science and Technology, Govt. of India is acknowledged.

References

Anjaneyulu, T.S.S. (1971), *Estimates of Kinetic Energy over the Indian Monsoon Trough Zone*, Quart. J. Roy. Met. Soc. *97*, 103–109.

Annamalai, H., Slingo, J.M., Sperber, K.R., and Hodges, K. (1999), *The Mean Evolution and Variability of the Asian Summer Monsoon: Comparison of ECMWF and NCEP-NCAR Reanalysis*, Mon. Wea. Rev. *127*, 1157–1186.

Campana, K.A., Hou, Y.T., Mitchell, K.E., Yang, S.K., and Cullather, R. (1994), *Improved Diagnostic Cloud Parameterization in NMC's Global Model,* Preprints, Amer. Meteor. Soc. 324–325.

Chu, J.H., Yanai, M., and Sui, C.H. (1981), *Effects of Cumulus Convection on the Vorticity Field in the Tropics. Part-I. The Large-Scale Budget,* J. Met. Soc. Japan, *59*(4), 535–546.

Collins, W.G., and Gandin, L.S. (1990), *Comprehensive Hydrostatic Quality Control at the National Meteorological Centre*, Mon. Wea. Rev. *118*, 2754–2767.

Collins, W.G., and Gandin, L.S. (1992), *Complex Quality Control of Rawinsonde Heights and Temperatures at the National Meteorological Center,* NMC office Note 390, 30 pp.

Daggupaty, S.M., and Sikka, D.R. (1977), *On the Vorticity Budget and Vertical Velocity Distribution Associated with a Life Cycle of Monsoon Depression,* J. Atmos. Sci. *33*, 773–792.

Holopainen, E.O. (1978), *A Diagnostic Study of Kinetic Energy Balance of the Long-Term Mean Flow and the Associated Transient Fluctuations in the Atmosphere*, Geophysica *15*, 125–145.

Holopainen, E.O., and Oort, A.H. (1981), *Mean Surface Stress Curl over the Oceans as Determined from the Vorticity Budget of the Atmosphere*, J. Atmos. Sci. *33*, 773–792.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deavan, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D. (1996), *The NCEP/NCAR 40-year Reanalysis Project*, Bull. Amer. Meteor. Soc. *77*, 437–471.

Kanamitsu, M. (1989), *Description of the NMC Global Data Assimilation and Forecast System*, Wea. Forecasting, *4*, 335–342.

Kanamitsu, M. (1991), *Description of the Global Data Assimilation and Forecast System*, Wea. Forecasting, *4*, 334–342.

Kanamitsu, M., and Krishnamurti, T.N. (1978), *Northern Summer Tropical Circulation during Drought and Normal Rainfall Months,* Mon, Wea. Rev. *10*, 331–347.

Krishnamurti, T.N., Bedi, H.S., and Subramaniam, M. (1989), *The Summer Monsoon of 1987,* J. Climate *2* (4), 321–340.

Krishnamurti, T.N., Bedi, H.S., and Subramaniam, M. (1990), *The Summer Monsoon of 1988,* Meteorol. Atmos. Phys., *42*, 19–37.

Krueger, A.F., and Winston, J.S. (1975), *Large-Scale Circulation Anomalies over the Tropics during 1971—72,* Mon. Wea. Rev. *103*, 465–473.

Kung, E.C. (1971), *A Diagnosis of Adiabatic Production and Destruction of the Kinetic Energy by the Meridional and Zonal Motion*, Quart. J. Roy. Meteor. Soc. *97*, 61–74.

Kung, E.C., and Tanaka, H. (1983), *Energetics Analysis of the Global Circulation during the Special Observation Periods of FGGE,* J. Atmos. Sci. *40*, 2575–2592.

Kung, E.C., and Smith, P.J. (1974), *Problems of Large-scale Kinetic Energy Balance, a Diagnostic Analysis in GARP,* Bull. Amer. Meteor. Soc. *55*, 768–777.

LI, C., and YANAI, M. (1996), *The Onset and Interannual Variability of the Asian Summer Monsoon in Relation to Land-sea Thermal Contrast,* J. Climate *9*, 358–375.

LORENTZ, E. N. (1955), *Available Potential Energy and Maintenance of the General Circulation*, Tellus *7*, 157–167.

MOHANTY, U.C., and RAMESH, K.J. (1994), *A Study on the Dynamics and Energetics of the Indian Summer Monsoon,* Proc. Indian National Science Academy *60, A, 1*, 23–55.

MOHANTY, U.C., DUBE, S.K., and SINHA, P.C. (1982a), *On the Large-scale Energetics in the Onset and Maintenance of Summer Monsoon – I: Heat Budget*, Mausam *33*, 139–152.

MOHANTY, U.C., DUBE, S.K., and SINHA, P.C. (1982b), *On the Large-scale Energetics in the Onset and Maintenance of Summer Monsoon – II: Moisture Budget*, Mausam *33*, 285–294.

MOHANTY, U.C., DUBE, S.K., and SINGH, M. P. (1983), *A Study of Heat and Moisture Budget over the Arabian Sea and their Role in the Onset and Maintenance of Summer Monsoon*, J. Meteorol. Soc. Japan *61*, 208–221.

NEWELL, R.E. (1970), *The Energy Balance of the Global Atmosphere, Global Circulation of the Atmosphere*, G.A. Corby Ed., Roy. Met. Soc., 42–90.

O'BRIEN, J.J. (1970), *Alternative Solutions to Classical Vertical Velocity Problem,* J. Appl. M, *9*, 197–203.

OORT, H. (1964), *On Estimation of the Atmospheric Energy Cycle*, Mon, Wea. Rev. *92*, 483–493.

PAN, H.L., and MAHRT (1987), *Interaction between Soil Hydrology and Boundary Layer Development,* Bound. Layer Meteor. *38*, 185–220.

PAN, H.L., and WAN-SHU WU (1994), *Implementing a Mass Flux Convective Parameterization Package for the NMC Medium-range Forecast Model,* Preprints, Amer. Meteor. Soc. 96–98.

PARTHASARATHY, B. MUNOT A.A., and KOTHAWALE, D.R. (1994), *All India Monthly and Seasonal Rainfall Series 1871—1993,* Theor. Appl. Climatol. *45*, 217–224.

PARRISH, D.F., and DERBER, J.C. (1992), *The National Meteorological Center's Spectral Statistical Interpolation Analysis System*, Mon. Weather Rev. *120*, 1747–1763.

PEARCE, R.P. (1979), *On the Concept of Available Potential Energy,* Quart. J. Roy. Meteor. Soc. *104*, 737–755.

PEARCE, R.P., and MOHANTY, U.C. (1984)*, Onsets of the Asian Summer Monsoon 1979—1982,* J. Atmos. Sci. *41*(9), 1622–1639.

RAMESH, K.J., MOHANTY, U.C., and RAO, P.L.S. (1996), *A Study on the Distinct Features of the Asian Summer Monsoon during the Years of Extreme Monsoon Activity over India*, Meteo. Atmos. Phys. *59* (3-4), 173–183.

RAMESH, K.J., RAO, P.L.S., and MOHANTY, U.C. (1999), *A Study on the Performance of the NCMRWF Analysis and Forecasting System during of the Asian Summer Monsoon: Thermodynamic Aspects,* Pure Appl. Geophys. *154*, 141–162.

RAJU, P.V.S., MOHANTY, U.C., RAO, P.L.S., and Bhatla, R. (2002), *The Contrasting Features of the Asian Summer Monsoon during Surplus and Deficit Rainfall Years over India,* Int. J. Climatology *22*(15), 1897–1914

RAO, Y.P. (1976), *Southwest Monsoons*, Meteor. Monogr. No.1, Indian Meteorological Department, 1–367.

RAO, P.L.S., MOHANTY, U.C., RAJU, P.V.S., and IYENGAR, G. (2003): *The Indian Summer Monsoon as Revealed by the NCMRWF System,* Proc. Indian Acad. Sci. (Earth and Planet. Sci.), *112*(1), 95–111.

SAJI, N.H., GOSWAMI, B.N., VINAYACHANDRAN, P.N., and Yamagata, T. (1999), A *Dipole Mode in the Tropical Indian Ocean,* Nature *401*, 360–363.

SPERBER, K.R., SLINGO, J.M., and ANNAMALAI, H. (2000), *Predictability and the Relationship between Subseasonal and Interannual Variability during the Asian Summer Monsoon,* Quart. J. Roy. Meteor. Soc. *126*, 2545–2574.

WEBSTER, P.J., LOSCHINIGG, J.P., MOORE, A.M., and LEBEN, R.R. (1999), *The Great Indian Ocean Warming of 1997–1998: Evidence of Coupled Oceanic-atmospheric Instabilities*. Nature. *401*, 356–360.

WOOLEN, J.S. (1991), *New NMC Operational OI Quality Control,* Preprints, Ninth Conf. on Numerical Weather Prediction, Denver, CO, Amer. Meteor. Soc, 24–17.

WOOLEN, J.S., KALNAY, E., GANDIN, L., COLLINS, W., SAHA, S., KISTLER, R., KANAMITSU M., and CHELLIAH (1994), *Quality Control in the Reanalysis System*. Preprints, Amer. Meteor. Soc. 2417–2419.

XIE, P., and ARKIN, P. (1997), *Global Precipitation: A 17-year Monthly Analysis Based on Gauge Observations, Satellite Estimates and Numerical Model Outputs,* Amer. Meteor. Soc. *78*, 2539–2558.

(Received January 20, 2004, accepted April 30, 2004)