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The evolution and retreat features of the summer monsoon over India

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The motivation for this study stems from the fact that there are no uniform criteria to identify the onset of the summer monsoon at a particular location. Furthermore, proper understanding of the events that culminate in the onset of the monsoon is crucial to allow its prediction over various time scales. An attempt is made to elucidate the characteristics of the onset and retreat of the monsoon using a global data assimilation and forecast system. For this purpose, the time series of net tropospheric large-scale budgets of kinetic energy, heat and moisture are examined over the Arabian Sea, Bay of Bengal and some land locations in India. The study makes use of daily data comprising operational analysis (0000 UTC) and forecasts (day1 through day5) produced by the National Centre for Medium Range Weather Forecasting, India, for the summer season of 1994.

The sequence of events associated with the advent of the monsoon is noticeably different at various locations. The horizontal fluxes of heat and moisture produce a divergence regime prior to the evolution and change to convergence during the onset of monsoon over the Arabian Sea. Similarly, intense diabatic cooling is noticed prior to the onset of monsoon and changes to heating subsequently. On the other hand, heat and moisture fluxes remain in the convergence regime well before the arrival of the monsoon over the Bay of Bengal. In turn, diabatic heating is noticed prior to the onset here. Onset characteristics at Bombay and Nagpur are similar to those of the Arabian Sea. However, features at Calcutta are identical to those over the Bay of Bengal. Further, the budgets of kinetic energy, heat and moisture depict monotonic decrease at various land locations corresponding to the retreat. Interestingly, the signature of retreat is very similar at the various locations considered here. These changes are observed in the analysis and further corroborated by the model forecasts. Despite the systematic biases, the model captures the essential signature of the onset at various forecast ranges.

1. Introduction

The Asian summer monsoon represents conspicuous changes in the general circulation of the atmosphere characterised by periodic reversal of wind regimes, formation of jet streams and movements of semi-permanent high/low pressure areas. It is known that the basic drive of the summer monsoon circulation is provided by the differential heating between the warmer continental areas of South Asia and adjoining tropical oceans. The complex feedback between the flow field and the heating, especially through the interaction between the large-scale flow and moist convection is not well understood. In addition, the peculiar orography of the Indian subcontinent modifies the monsoon circulation considerably. These facets ensure the prominence of the monsoon. The summer monsoon is the principal rainy season of the South Asian region. For instance, India receives 80% of its total annual rainfall during the summer monsoon. Because of this, the vagaries of the monsoon have severe ramifications: small variations in the timing and quantity of rainfall have the potential to create significant societal consequences. A weak monsoon (drought) generally corresponds to low crop yields, while a strong monsoon (flood) usually produces abundant crops. In addition to the strength of the monsoon in a particular year, forecasting its onset and retreat enables effective planning of the economy. Although the annual rainfall amount may be normal, any ill-timed rainfall can produce devastating effects. Consequently, the forecasting of the monsoon at various time scales (a few days to years ahead) is a crucial issue. In particular, accurate forecasting of the arrival of the monsoon at various locations is of great help in planning agricultural activities. Prediction of the onset and retreat of the monsoon helps farmers to select the most suitable crops and to prepare the land. The time of sowing and thinning out of seedlings depends on the prediction of the onset, while similar situations prevail at the time of retreat. Heavy rains or damp conditions after the harvest can lead to a substantial reduction in output. Prediction of these events can help to reduce their impact.

The onset of the summer monsoon, normally around the beginning of June over the southern tip of India, is very significant as it provides the basis for measuring the subsequent advancement across the subcontinent. Although, there is no precise definition for the onset of the monsoon, usually noted by a change of wind direction, Indian meteorologists conventionally identify the onset over the Kerala coast by a sharp increase and characteristic persistency in the rainfall (Ananthakrishnan et al. 1968). They also use empirical rules to define the onset over different parts of the country. These are based on pentad rainfall, wind direction and net tropospheric moisture (Das 1987). Further, these rules are designed to ensure that the observed rain is monsoonal and is not merely a transient phenomenon.

Krishnamurti et al. (1981) established that there was an increase in low level (850 hPa) kinetic energy during the evolution of the summer monsoon over the Arabian Sea. Krishnamurti & Ramanathan (1982) found that the evolution of the monsoon circulation is quite sensitive to the intensity and location of the diabatic heating in the troposphere. Pearce & Mohanty (1984) summarised the evolution of the monsoon over the Arabian Sea in two stages: moisture build up, during which synoptic and meso-scale transient disturbances develop, followed by a rapid intensification of winds and a substantial increase in latent heat release, essentially a large-scale feedback process. Soman & Kumar (1993) observed a sudden and sharp increase in rainfall composites over the peninsula excluding east-coast stations. Despite most of the above studies focusing on the onset mechanism, none indicated the changes associated with its evolution over the Bay of Bengal and India. Further, no uniform characteristic features exist to date to identify the arrival of the monsoon at a location.

In this study, the detailed features associated with the evolution of the monsoon at various locations are investigated using a global data assimilation forecast system. The onset is examined through the time series of net tropospheric energetics over the sea and land. Furthermore, these large-scale changes are corroborated with empirical results in terms of observed rainfall.

2. Data and the scheme of analysis

2.1. Analysis module

The National Centre for Medium Range Weather Forecasting (NCMRWF) has been providing operational medium range forecasts and agro-advisory information to the farming community of India since June 1994. The global data assimilation and forecast system (GDAFS) of the NCMRWF is adapted from the National Centers for Environmental Prediction (NCEP) in the USA. An intermittent type of assimilation at 6-hourly intervals is used for maximising the data input. In the analysis cycle, however, data received within the 3-hourly period on either side of the analysis hours are included. The data assimilation system is based on spectral statistical interpolation scheme (Parrish & Derber 1992). The horizontal resolution of the forecast model is T80 (1.5° latitude/longitude in the regular grid) with 18 layers in the vertical. The model includes parameterisations of various physical processes such as convection including large-scale precipitation and shallow convection, gravity wave drag, radiation with diurnal cycle and interaction with clouds, boundary layer physics, surface hydrology, and vertical and horizontal diffusion processes. These processes are widely used in multifarious global spectral models.

The short and long wave radiation schemes are based on Lasis & Hansen (1974) and Fels & Schwarzkopf (1975). Further, the model uses the modified Kuo (Anthes 1977) convective parameterization. The shallow convection in the model is indicated by the Tiedtke scheme (1989) and the large-scale condensation is indicated by the Manabe-modified parameterization (Manabe et al. 1965) based on saturation. The cloud generation scheme is due to Slingo (1987). In addition, Kessler's scheme (1969) denotes rainfall evaporation. The land surface processes are represented by Pan's parameterization (1990). The model uses a simple land-surface scheme which includes: (1) exchange coefficients computations based on Monin-Obhukov similarity theory, (2) the Penman-Monteith method of evapo-transpiration over land which includes vegetation effects, (3) prognostic surface temperature equation of Arakawa (1972), (4) three layers of surface and soil temperature prediction, (5) interactive bucket hydrology, (6) evaporation by bulk method over the ocean, and (7) Charnock's roughness length computation over ocean. The climatological values of sea surface temperature and albedo are prescribed in this study. The comprehensive details of the model are provided in an earlier study (Kanamitsu 1989).

2.2. Data

The data comprise the daily 0000 UTC operational analyses and forecasts (day1 through day5) for May, June and September 1994. The geopotential height (Z), temperature (T), specific humidity (q) and horizontal wind fields (u and v) over the monsoon domain (15°S–45°N, 30°E–120°E) at ten pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100 hPa) are all considered in the present study.

2.3. Methodology

The strategy adapted to discern the arrival and retreat of the monsoon is as follows. The time series of net tropospheric (volume integrated) large-scale budgets of kinetic energy, heat and moisture are monitored at various locations. The budget equations can be obtained from the equations of motion, thermodynamics, mass and moisture continuity equations on simple mathematical transformations. These are expressed in flux form with pressure as the vertical coordinate.

$$\frac{\partial K}{\partial t} + \nabla \cdot VK + \frac{(\partial \omega K)}{\partial P} + V \cdot \nabla \phi = V \cdot F \quad (1)$$

$$\frac{\partial (C_P T)}{\partial t} + \nabla \cdot (C_P T V) + \frac{\partial}{\partial P}(C_P T \omega) - \omega \alpha = Q_H \quad (2)$$

$$\frac{\partial}{\partial t}(Lq) + \nabla \cdot (LqV) + \frac{\partial}{\partial P}(Lq\omega) = Q_L \quad (3)$$

The notations have their usual meaning. In the above equations, the first, second and third terms on the left connote the local variation, horizontal and vertical flux divergences of any energy parameter (e.g. kinetic energy, sensible heat etc). The fourth term in equation (1) represents the adiabatic generation of kinetic energy due to cross-isobaric flow and in equation (2) it denotes the adiabatic conversion of available potential energy to kinetic energy, respectively. Similarly, the terms on the right signify the dissipation of kinetic energy by the turbulent frictional processes in equation (1), the diabatic heating due to radiation, condensation, evaporation of falling raindrops and turbulent transfer of heat in equation (2), as well as the source/sink of latent heat in equation (3). In the above equations, the terms on the right include contributions from the subgrid-scale physical processes. In this study, these terms are evaluated as residues of all the other terms in the respective budget equations.

The budget terms at each regular latitude-longitude grid points with 1.5° resolution are averaged both in zonal and meridional directions over the respective regions and integrated vertically from 1000 to 100 hPa. Thus, the volume integral of any variable F (λ, Φ, P) for a limited region bounded by meridians λ_1 and λ_2, latitude circles φ_1 and φ_2, and isobaric surfaces P_1 and P_2 may be designated as

$$\langle F \rangle = \frac{1}{8} \int_{\lambda_1}^{\lambda_2} \int_{\phi_1}^{\phi_2} \int_{P_1}^{P_2} F \, \alpha^2 \cos\phi \, d\lambda \, d\phi \, dP \quad (4)$$

In the above budgets, the contributions from local variation and vertical flux terms are insignificant compared to other terms (Kung 1966: Pearce & Mohanty 1984). Although, the time series of volume integrals of all budget terms are investigated, the discussion is restricted to significant terms in various budgets, which govern the balance and are also responsible for the maintenance of the monsoon. In this study, the vertical motion is estimated by kinematic techniques with vertical adjustment of divergence over each column as suggested by O'Brien (1970) and used to compute various budget terms. It is known that the representation of the Hadley cell is crucial over the monsoon domain and we compared the renditions of the Hadley cell represented by the archived and kinematic vertical motion. Since the latter is close to the monsoon climatology, we resorted to using kinematic vertical motion. All the budget terms are computed at each grid point of the analysis/forecast system of 1.5° latitude/longitude resolution for each day at 0000 UTC. For this purpose, the analysis and forecasts (day1 to day5) valid for a given time period are used to obtain each budget term. The various space derivatives are evaluated by centered difference scheme (second order). Further, the trapezoidal rule is used in the vertical integrations.

In view of the fact that changes in tropical weather take place slowly and the data contain inherent diurnal/short term fluctuations, the pentad (5-day) running mean variations are considered to represent various budget terms in the study. This smoothes random errors and maintains the broad basic characteristics. The budget terms are calculated from instantaneous data for each day and subsequently applied to the five-day (running mean) smoother to filter out high-frequency variance, random errors and noise to depict the stable monsoon circulation characteristics.

A detailed examination of the time series of volume integrated budget parameters of kinetic energy, heat and moisture over the Arabian Sea (5°N–15°N, 45°E–75°E), Bay of Bengal (10°N–25°N, 80°E–95°E) and some locations on the land mass namely Bombay (19°N, 72°E), Calcutta (22°N, 88°E) and Nagpur (21°N, 79°E) is carried out to study the evolution process of the monsoon over India. Also, the time series of net tropospheric moisture and mean tropospheric temperature are examined. Further, the temporal variation of kinetic energy at 850 hPa is also presented to discern the changes taking place in the low-level flow.

Before interpreting the results, it is necessary to know the systematic biases of the model (Rao et al. 1998; Ramesh et al. 1999). The lower level (850 hPa) flow field denotes weakening of southeasterly trades. The cross-equatorial flow into the northern hemisphere is weakened (2–4 ms^{-1}) with increases in the forecast period. The upper level (200 hPa) flow field biases include weakening of the Tibetan anticyclone, reduction of the return flow into the southern hemisphere, and intensification of the easterly core over the north Indian Ocean (5–7 ms^{-1} by day5). The temperature forecasts of the model exhibit a predominant cooling tendency (less than 2 °C). The moisture forecasts suggest a general drying of the model atmosphere in the lower and middle troposphere of the monsoon domain.

3. Results and discussion

The climatological normal characteristics of the monsoon provide some insight regarding its advancement over the Indian subcontinent. The summer monsoon normally sets in over the Bay of Bengal before it reaches the Arabian Sea. The circulation then becomes established over the coast of south Kerala by 1 June. It further advances along the west coast and reaches northeast India by the first week in June. By the middle of June, the monsoon covers most of the peninsula, northeast and parts of central India. By the middle of July, the monsoon circulation covers the whole of India. However, the advance of the monsoon stalls at times, and these are temporary lulls or breaks in its progress. The detailed isochronal description of the onset and advancement of the monsoon in 1994 is reproduced in Figure 1 from the Monsoon Weather Summary (De et al. 1995). The results below are organised on the basis of the monsoon's progress over the Arabian Sea and Bay of Bengal and then over the land locations.

3.1. The monsoon over the Arabian Sea

The remarkable promptness of the summer monsoon's arrival over the Arabian Sea is well known. The climatological onset date of the monsoon over the Arabian Sea is 1 June with a standard deviation of eight days (Soman & Kumar 1993). The onset dates of the 1994 summer monsoon are provided in Table 1. The time series of net tropospheric moisture corresponding to analysis and model forecasts are presented in Figure 2a. The temporal variation of moisture indicates an increasing trend from the first week of May. The changes in seasonal insolation lead to the warming of the South Asian land mass and then to the formation of a heat low over northwestern India and the adjoining land mass. The atmosphere responds to these changes by setting up a transequatorial current. This current transports ample mass and moisture into the monsoon domain from the southern hemisphere. The persistent low-level convergence over the Indian subcontinent is conducive to unstable motions. However, convective instability develops only after the net tropospheric moisture attains a value of about 40 mm (Pearce & Mohanty 1984). Once the moisture attains the minimum level, it triggers instability and leads to the formation of meso/synoptic-scale systems. The development of profound convective activity subsequently leads to release of latent heat, which causes a general increase of tropospheric heating

Table 1. *Onset dates of the summer monsoon in 1994.*

Location	Onset date
Bay of Bengal	21 May
Arabian Sea	28 May
Calcutta	5 June
Bombay	6 June
Nagpur	12 June

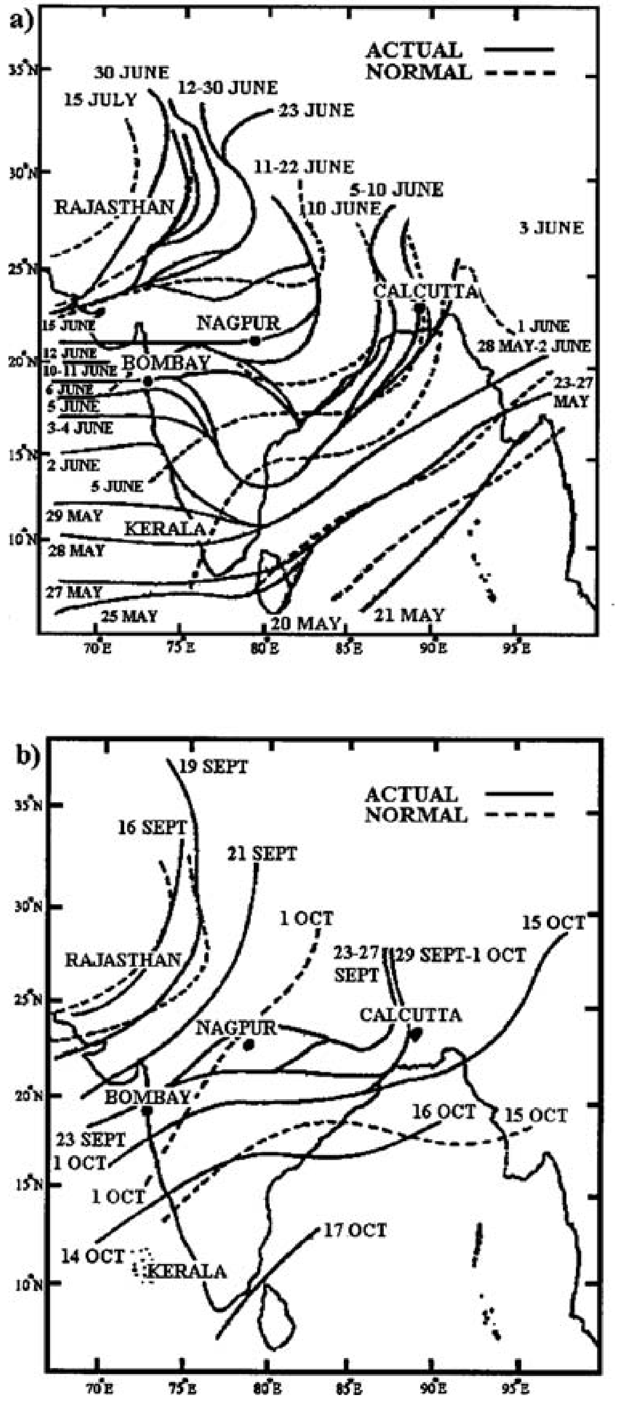

Figure 1. *Isochrone description of the summer monsoon, 1994. (a) onset; (b) retreat.*

followed by a rise in atmospheric enthalpy. With these processes, the moisture-holding capacity of the atmosphere rises. This, in turn leads to an intensification of low-level flow due to enhancement of low-level convergence and surface moisture flux. The moisture build-up (Figure 2a) is accompanied by intermittent falls once the net tropospheric moisture content increases by a certain amount. This is because of transient convective activity, which is organised and developed in association with the local meso/synoptic-scale systems (Krishnamurti & Ramanathan 1982; Pearce & Mohanty

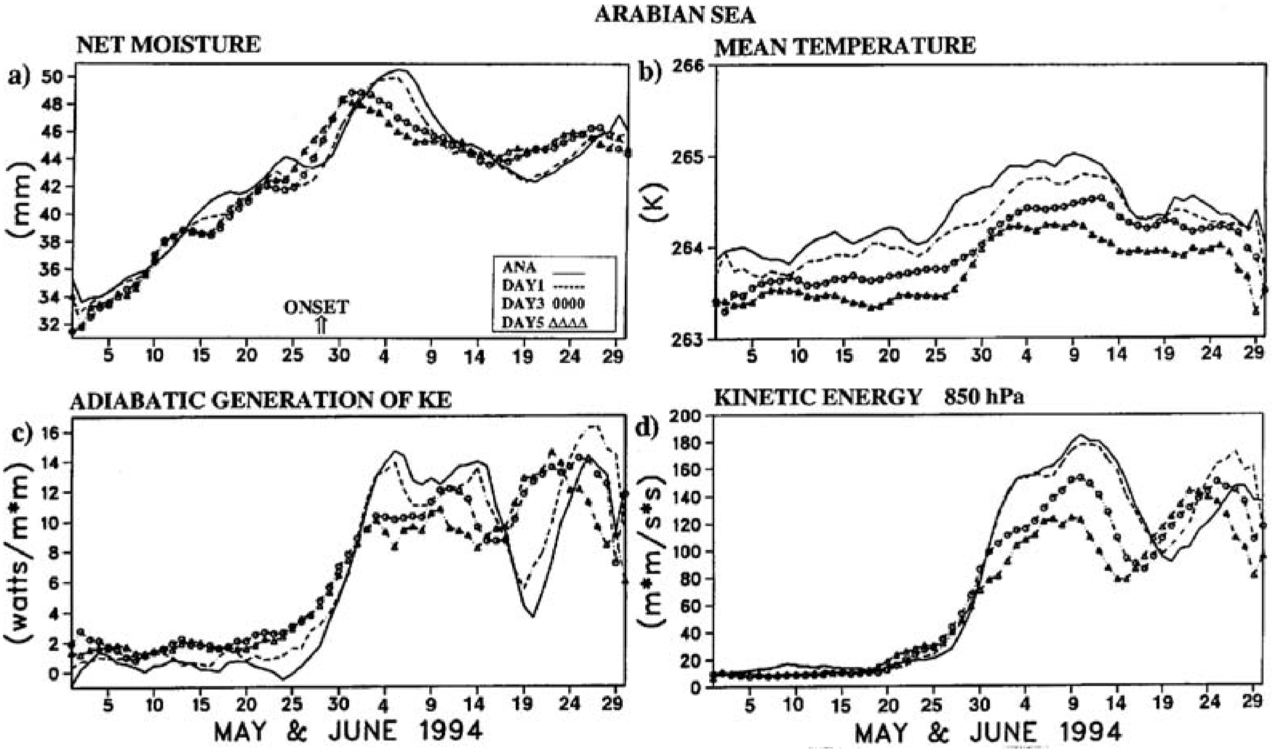

Figure 2. *Time series over the Arabian Sea for May and June 1994. (a) net tropospheric moisture (mm); (b) mean tropospheric temperature (°K); (c) adiabatic generation of kinetic energy (Watt m^{-2}); (d) kinetic energy at 850 hPa (m^2 s^{-2}).*

1984). Though a persistent rise in mean tropospheric temperature (Figure 2b) starts in the second week of May, this tendency increases substantially after the net tropospheric moisture levels reached about 40 mm. The arrival of the monsoon over the Arabian Sea as well as the Kerala coast is marked by a sudden and steep rise in low-level (850 hPa) kinetic energy (Figure 2d), which is in agreement with earlier studies (Krishnamurti et al. 1981; Pearce & Mohanty 1984). In association with the onset of the monsoon over the southern tip of the Indian subcontinent, a fall in the tropospheric moisture content is noticed. It is interesting to note that the sharp rise in kinetic energy is strongly supported by a persistent rise in the adiabatic production of kinetic energy from the available potential energy, which starts rising synchronously with the kinetic energy (Figure 2c). This steep rise in kinetic energy generation is attributed to the formation of the low tropospheric (Somali) Jet and upper tropospheric Tropical Easterly Jet (TEJ). Thus, the adiabatic production of kinetic energy is also a good indicator of the onset of monsoon over the Arabian Sea and Kerala coast. Hsu et al. (1999) suggest that the onset of the monsoon is indicated by some circulation changes such as cyclonic circulation in the lower troposphere over the Indian subcontinent and the adjoining Arabian Sea and Bay of Bengal, as well as anticyclonic circulation aloft.

The evolution features of the monsoon are further perceived via significant parameters of the heat and moisture budgets. The time variation in the horizontal flux divergence of heat (Figure 3a) indicates a sustained rise in convergence. Further, the temporal variation in the horizontal flux divergence of moisture (Figure 3b) also indicates a similar trend. It is to be noted that prior to the onset of the monsoon, there is no appreciable influx of heat and moisture over the Arabian Sea. The horizontal flux divergences of heat and moisture transform from a high divergence to a low divergence/convergence regime. These fluxes depict an increasing trend during the onset of the monsoon and its northward advancement over the Indian subcontinent (Figures 3a and b). The initial build-up of moisture is largely due to evaporation (Rao et al. 1981), and the later build-up is due to an increase in the influx of moisture compared to other seas. In effect, there exists a characteristic difference in the mechanism of moisture increase. In tandem with other thermodynamical characteristics, the diabatic heating (Figure 3c) also changes from cooling to heating. This change was adduced by Hsu et al. (1999). The diabatic heating distribution shows cooling prior to the onset and subsequently changes to heating during the onset. The increase in diabatic heating is sustained during the advancement of the monsoon. As indicated by these heat and moisture budget parameters, there are some small variations from divergence to convergence and vice versa. These variations should not be misconstrued as signalling a monsoon. During the monsoon season, owing to prevailing instability, many local and mesoscale systems form and dissipate. The temporal variations of net tropospheric energetics capture these high frequency variations. Nevertheless, the broad monsoon signature is persistent, unlike these transient systems. Consistency in the number of

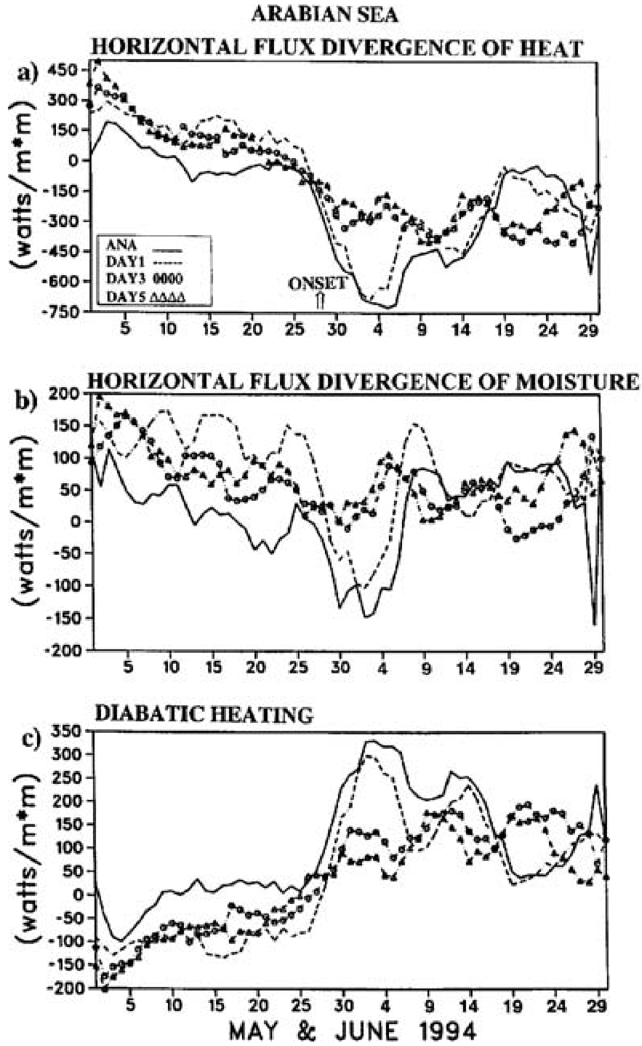

Figure 3. *Time series of energetics over the Arabian Sea for May and June 1994 (Watt m^{-2}). (a) horizontal flux divergence of heat, (b) horizontal flux divergence of moisture, (c) diabatic heating.*

parameters is another sign of the evolution/onset of the monsoon over the Arabian Sea.

In order to investigate how the model responds to the changes in the analysed atmosphere, the time series of net tropospheric energetics and other parameters calculated from forecasts (day1 through day5) are presented in these figures. The features found in the analyses are maintained to a large extent in the forecasts, despite underestimation of energetics due to systematic biases of the model. In agreement with the systematic drying of the model atmosphere (Ramesh et al. 1999), the net tropospheric moisture is underestimated in the forecasts. However, the variations indicated by the analyses are maintained in the forecasts. Similarly, the temperature forecasts indicate systematic cooling over the monsoon domain. Due to this error the temperature forecasts are underestimated though they effected the changes associated with the various stages of the monsoon. The systematic errors in the flow field (Rao et al. 1998) are reflected in the kinetic energy and its generation. The combined effect of the systematic biases of the model are observed in the horizontal flux divergences of heat and moisture as well as diabatic heating. The model forecasts represented the changes associated with the stages of the monsoon reasonably well despite their underestimation due to systematic errors of the forecast model. The changes associated with the arrival of the monsoon over the Arabian Sea may be expounded as follows. The net tropospheric moisture starts rising from the first week of May. After attaining the net tropospheric moisture level above 40 mm, convection gets triggered due to local instability, which leads to a release of latent heat, in turn, increasing the mean tropospheric temperature (enthalpy). This is followed by an increase in the adiabatic generation of kinetic energy due to cross-isobaric flow. Subsequently, the rise in horizontal convergence of moisture and heat takes place. It is also reflected in terms of a rise in diabatic heating. These processes culminate at the onset of the monsoon with a steep rise in kinetic energy. In spite of interannual variability, these changes are represented by monsoon circulation in a sequence. The timing and magnitudes depend on the interplay between the internal dynamics and boundary forcings such as SST, snow cover, soil moisture, etc.

3.2. The monsoon over the Bay of Bengal

The isochronal description (Figure 1) shows that the monsoon normally arrives over the Bay of Bengal around the fourth week of May. The onset dates of the 1994 monsoon are provided in Table 1. The time series of net tropospheric moisture is presented in Figure 4a. In accordance with the arrival of the monsoon, the moisture levels were high (above 40 mm) from early May. But a persistent increase in tropospheric moisture is apparent from the third week of May. The increase is more than 10 mm in 10 days. The moisture starts rising persistently between the second and third week of May under the influence of the monsoon circulation. This increase in net tropospheric moisture is attributed to an increase in the horizontal influx of moisture over the Bay of Bengal prior to the onset. The subsequent increase in moisture after the arrival of the monsoon is associated with the strengthening of the flow field (Figures 4c and d). This intensification takes place around the first week of June. Unlike the situation over the Arabian Sea, the flaring of convective activity starts early over the Bay of Bengal.

The build-up of moisture is followed by an increase in the mean tropospheric temperature (Figure 4b). A persistent rise in convective activity leads to an increase in mean tropospheric temperature. This could be attributed to the release of latent heat through condensation of water vapor and turbulent transfer of sensible heat. The presence of meso/synoptic-scale systems situated over the Bay of Bengal have a large bearing on the temporal variation of the temperature.

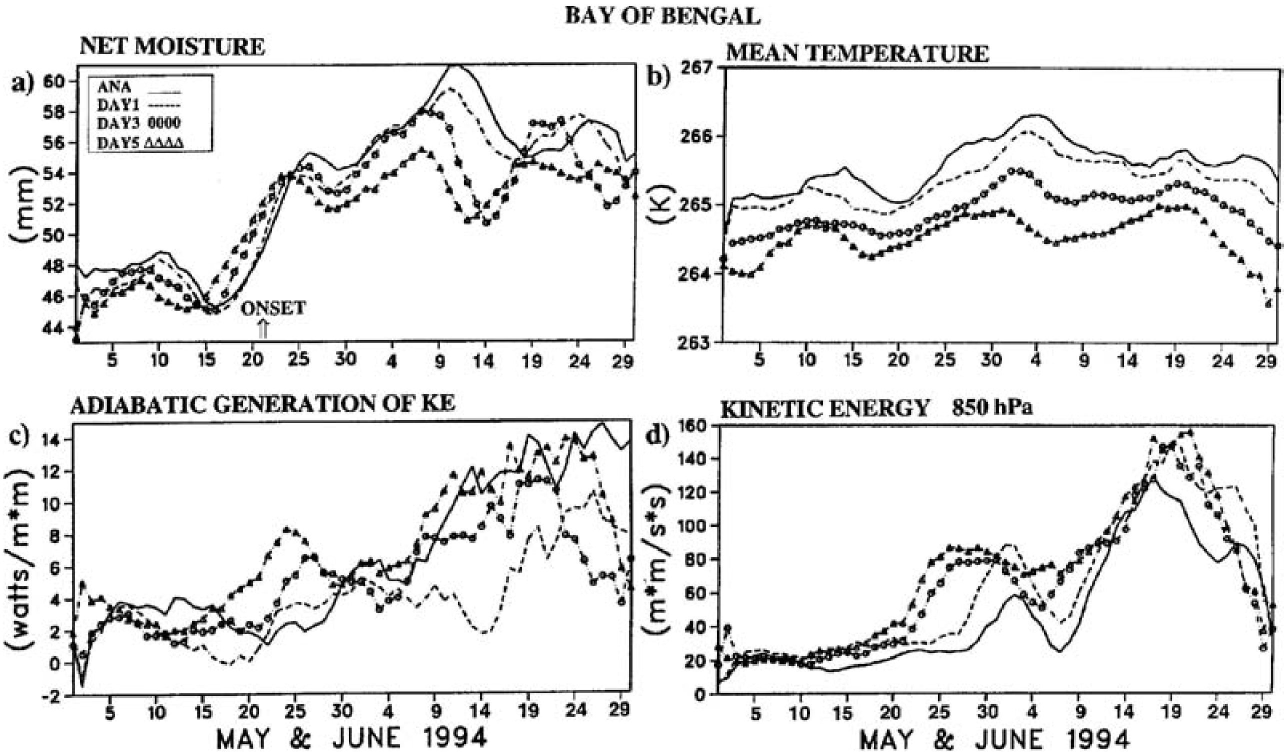

Figure 4. *As Figure 2, but for the Bay of Bengal.*

Although, a rise is observed, the scale of the rise may not be similar every year and to a large extent is governed by the internal dynamics. The rise in temperature depends on the increase in diabatic heating, and convergence of heat and moisture. The advancement of the monsoon is further examined through the temporal variation of adiabatic generation of kinetic energy (Figure 4c). The adiabatic generation of kinetic energy appears to maintain a steady enhancement suggesting dynamical support for the flow amplification. It shows a sustained rise from the third week of May, although the increase is marginal at times. The advent of the summer monsoon brings strong lower level cross-isobaric flow, which enables the production of kinetic energy. This generation is crucial for maintaining the monsoon circulation. The low-level (850 hPa) kinetic energy (Figure 4d) does not indicate a steep and persistent hike similar to that over the Arabian Sea. The area mean values of kinetic energy are of the order of 20–25 $m^2 s^{-2}$ during the onset. It appears that this strength of the flow field is essential to initiate convection. The increase in kinetic energy is gradual over the Bay of Bengal. The adiabatic generation of kinetic energy (Figure 4c) is a good indicator of the arrival of monsoon as it clearly demonstrates the change in terms of steep rise and persistence.

The time variation of the horizontal flux divergence of heat (Figure 5a) shows a convergence regime from the beginning of May. However, a persistent increase in the heat flux convergence is apparent from the third week of May. Further, the horizontal flux divergence of moisture (Figure 5b) also depicts a variation, which is similar to that of the heat flux divergence. Although, flux convergence of moisture is observed from the first week of May, the arrival of the monsoon air mass leads to a sustained increase. It is interesting to note that the increase in the flux convergence of moisture precedes the heat by a day or so and these characteristics are well represented. In response to the changes, a monotonic increase in the convergence of horizontal flux of heat as well as moisture is apparent from the first week of May under the influence of the monsoon circulation. Prior to the onset of the monsoon, the influx regime of heat and moisture is observable and this is a characteristic feature over the Bay of Bengal. Persistent increase is depicted by the horizontal fluxes of heat and moisture (Figures 5a and 5b) from the third week of May. Under the influence of the persistent influx of heat and moisture, profound convective activity takes place in turn, and diabatic heating also increases. The rise from the third week of May is due to the advancement of the monsoon and is persistent.

The diabatic heating consists of heating due to physical processes of the atmosphere which includes radiative transfer, release of latent heat due to condensation, evaporation of falling rain drops and turbulent transfer of sensible heat from the surface layer. Of all the diabatic effects, it is argued that the latent heat release due to condensation/precipitation (the convective heating in the model) and turbulent transfer from the surface layer are the major contributors over the tropics (Riehl 1979). The influx regime of heat and moisture contributes to the enhancement of the convective activity. These aspects are conducive to the increase of

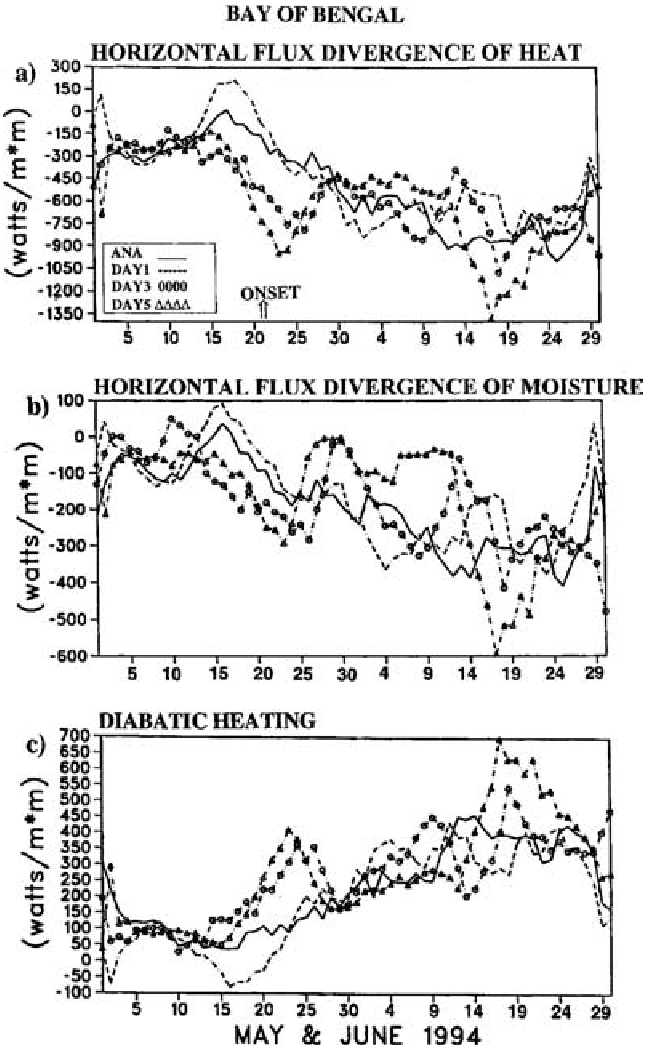

Figure 5. *As Figure 3, but for the Bay of Bengal.*

vertical moisture transport into the middle troposphere. It leads to the development of intense convective activity followed by the condensation/precipitation and release of latent heat. The diabatic heating indicates an increase associated with the monsoon circulation. Moreover, the diabatic heating pattern is in agreement with observations by Hsu et al. (1999) of the warming of the Bay of Bengal during the evolution phase.

The variation of net tropospheric moisture noticed in the analysis (Figure 4a) is found to be similar and persistent in the forecasts as well. Further, in agreement of the systematic drying of the model atmosphere, the forecasts underestimate the moisture. Similarly, the mean tropospheric temperature forecasts are underestimated and agree with overall systematic errors of the model (Figure 4b). The forecasts of the model are found to have a westerly bias at 850 hPa (Rao et al. 1998) over the Bay of Bengal, which tend to increase from day1 to day5. In view of this systematic tendency, the low level kinetic energy is overestimated in the forecasts compared to the respective analyses (Figure 4d). In the case of horizontal flux divergence of heat and moisture, the forecasts indicate enhanced flux convergence in day3 and day5 forecasts. Moreover, the model forecasts indicate a lead of a day or two in reflecting these changes. The increasing trend in diabatic heating represented by the forecast fields is noticed prior to that of the analyses by 1 to 2 days. This could be due to rapid intensification of westerlies over the Bay of Bengal in day3 and day5 forecasts. Nevertheless, day3 and day5 forecasts indicate a persistent increase in the influx of heat and moisture about a couple of days in advance of the onset of the monsoon.

The changes associated with the onset of the monsoon over the Bay of Bengal are noticeably different to those of the Arabian Sea. A sustained low-level (850 hPa) flow strength in the form of kinetic energy around 20–25 m^2s^{-2} along with net tropospheric moisture above 40 mm is crucial to sustain convection. This facilitates the low-level convergence and vertical transfer of moisture into the free atmosphere. Both processes lead to the commencement of precipitation, which, in turn, increases the tropospheric enthalpy. Sustained convective activity is supported by the persistent influx of heat and moisture as well as a rise in diabatic heating. These factors suggest that the rainfall associated with the advancement of the monsoon occurs between the third and fourth week of May over the Bay of Bengal. The remarkable difference in the onset mechanism between the Arabian Sea and Bay of Bengal is that the former is driven by local mesoscale processes and the latter by large-scale processes. This is further supported by studies of Krishnamurti & Ramanathan (1982), Pearce & Mohanty (1984) as well as Hsu et al. (1999). The differences in the onset process of the monsoon are represented reasonably well by the analysis and forecasts in the case of the Arabian Sea as well as the Bay of Bengal.

3.3. Monsoon at selected locations over India

The monsoon takes about six weeks (Figure 1) to cover the entire country after its arrival at Kerala. Its subsequent progress over India is associated with replacement of a low-level north-easterly flow by a strong south-westerly regime, as well as an increase in convective activity and rainfall (Rao 1976). The possible link between the northward advancement of the monsoon and changes in thermodynamical characteristics in terms of horizontal flux divergences of heat and moisture, as well as diabatic heating of the monsoon air mass, is examined at several locations over India. Nevertheless, for the sake of brevity, the results are presented for Bombay, Calcutta and Nagpur (Figure 1) as these three locations represent different regimes of the monsoon circulation, intensity of convective activity and rainfall. Bombay and Calcutta lie on the west and east coasts of India respectively, while Nagpur is located in central India.

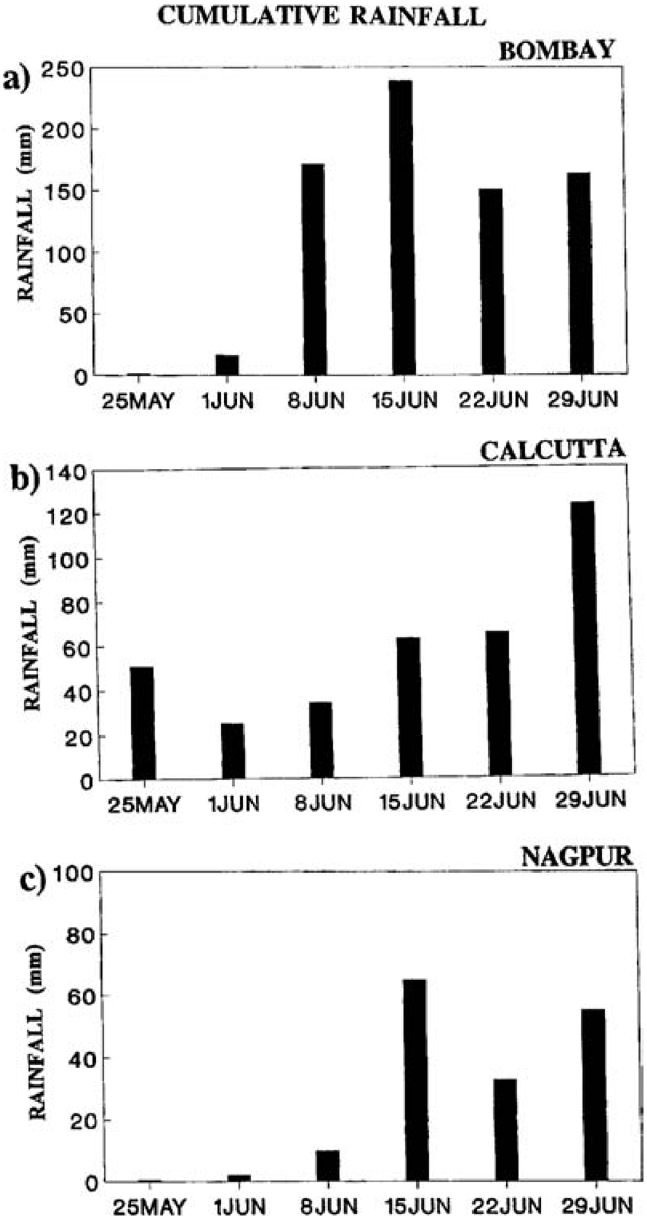

Figure 6. *Weekly cumulative rainfall for selected locations of India for May and June 1994 (mm). (a) Bombay, (b) Calcutta, (c) Nagpur.*

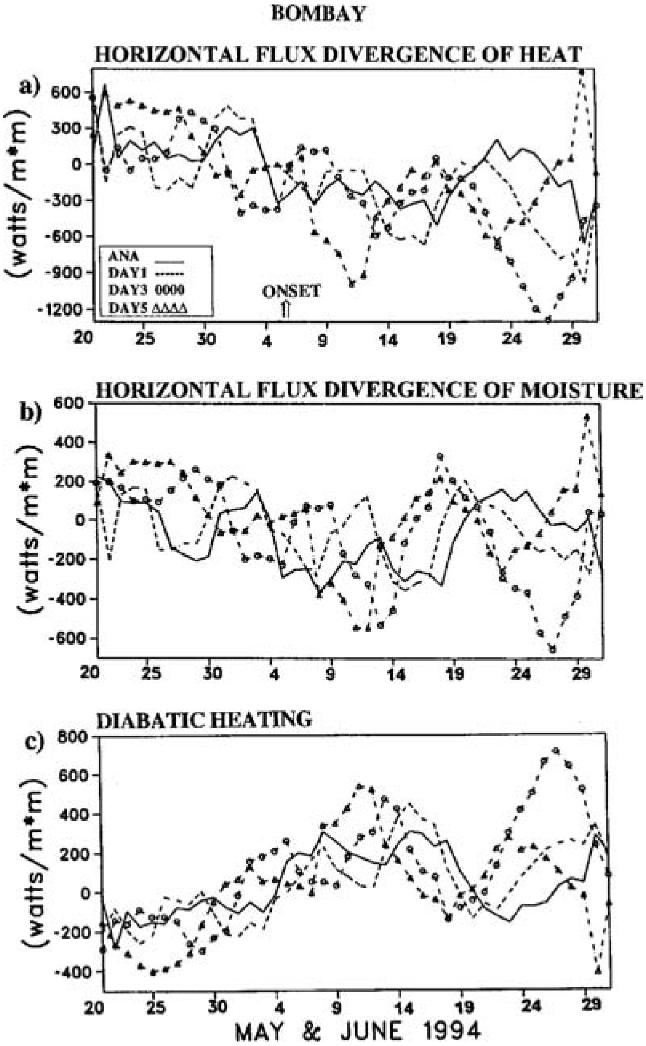

Figure 7. *Time series of energetics at Bombay for May and June 1994 (Watt m^{-2}). (a) horizontal flux divergence of heat; (b) horizontal flux divergence of moisture; (c) diabatic heating.*

The development of circulation and the invasion of air masses are the basic criteria which favour more frequent and increased amounts of rain over India during the arrival of the monsoon (Rao 1976). The India Meteorological Department (IMD) determines the northward advancement of the monsoon based on sharp changes in low-level wind direction and increase in rainfall for a consecutive period of two days (Das 1987). In this regard, maximum importance is accorded to precipitation. The observed weekly-accumulated rainfall over the geographical regions (known as meteorological subdivisions) representing the three locations i.e., Bombay (Konkan and Goa), Nagpur (Vidarbha) and Calcutta (Gangetic West Bengal) during May and June is depicted in Figure 6. It is found that the increase in rainfall is massive (around seven- to ten-fold) at Bombay and Nagpur during the week of the monsoon's advance. However, at Calcutta such a sharp increase in rainfall is not observed, because this region experiences prolonged pre-monsoon thunderstorms (Das 1987). Nevertheless, a marginal increase in rainfall is noticed corresponding to the onset.

The time series of the net tropospheric energetics are presented in Figure 7 for Bombay. According to IMD, the onset was reported on 6 June. The energetics delineate the corresponding changes. The horizontal flux divergences of heat and moisture indicate a changeover of divergence to convergence regime during the onset. Further, this convergence also increases. The model forecasts captured this behaviour of the monsoon well. A persistent rise in the influx of heat and moisture follows the increase in diabatic heating (Figure 7c). Prior to the onset, it followed a cooling regime and during the onset it changes to the heating regime. The changes are more or less similar to that of Arabian Sea. However, the steep hikes in low-level kinetic energy and the adiabatic generation of kinetic energy (not

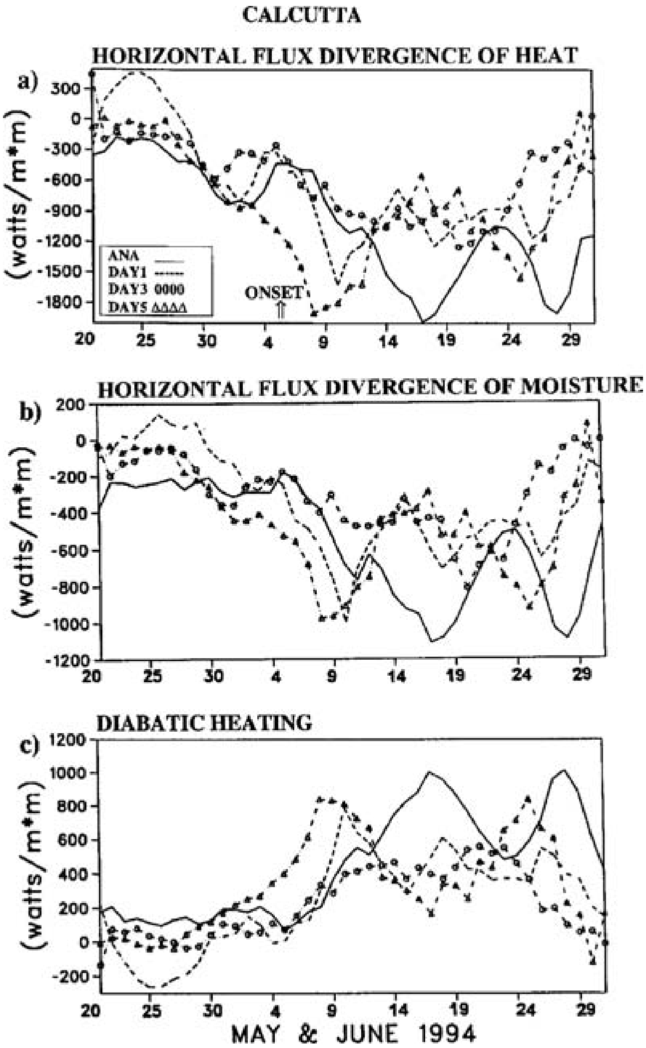

Figure 8. *As Figure 7, but for Calcutta.*

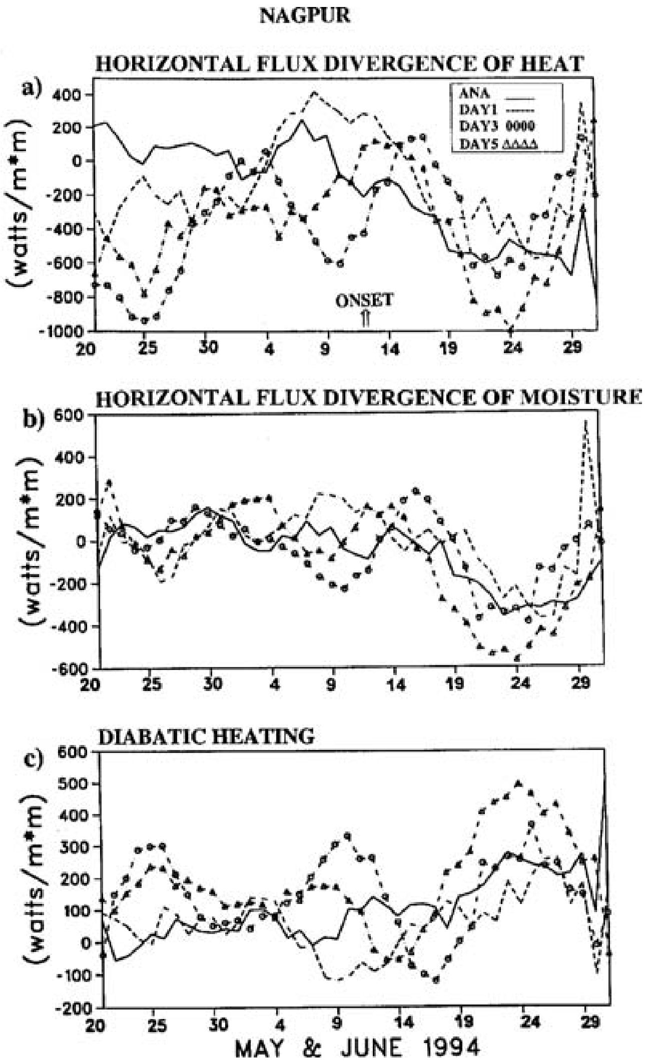

Figure 9. *As Figure 7, but for Nagpur.*

shown) are not observed. The model forecasts show the changes accurately. Similar temporal variations of tropospheric energetics at Calcutta are illustrated in Figure 8. The horizontal flux divergences of heat and moisture connote a convergence regime as early as the third week of May. The convergence regime prevails before the onset at Calcutta. The arrival of the monsoon at Calcutta was declared on 5 June, when significant rises in the influxes of heat and moisture are apparent. In tandem with these changes, the diabatic heating also indicates a persistent rise. The forecasts predicted the signature of the onset reasonably well at Calcutta. Further, the intensity of monsoon circulation at Calcutta is much larger compared to Bombay and Nagpur and the influx regime starts well in advance. The influx regime of moisture and heat at Calcutta is in agreement with pre-monsoon thunderstorm activities as explained earlier.

The net tropospheric energetics at Nagpur are indicated in Figure 9. Corresponding to the onset on 12 June, the flux divergences of heat and moisture indicate convergence. They change from divergence to convergence during the onset. Similarly, diabatic cooling before the arrival of the monsoon changes to a heating regime during the onset. The model forecasts also indicate these changes with some differences, which are attributed to the systematic biases. Further, the changes associated with the arrival of the monsoon over Nagpur and Bombay may be regarded as similar to those over the Arabian Sea, albeit with less intensity. However, the characteristics at Calcutta are identical to those of the Bay of Bengal. The energetics indicate multifarious fluctuations before the onset at these locations, which are due to the presence of any localised atmospheric system. These should not be misconstrued as the monsoon. The broad monsoon signal is persistent. The corresponding forecasts indicate these changes fairly well despite differences with respect to the analyses. The summer monsoon is preceded by an influx of moisture over the Bay of Bengal. The monitored changes in the net tropospheric moisture are supported by the persistent influx of moisture during the northward progress of the monsoon. On the other hand, the role of advective processes in an influx of moisture over the Arabian Sea is found to be limited until the monsoon sets in over Kerala. It is evident that the moisture build-up, which occurs from early May over the Arabian

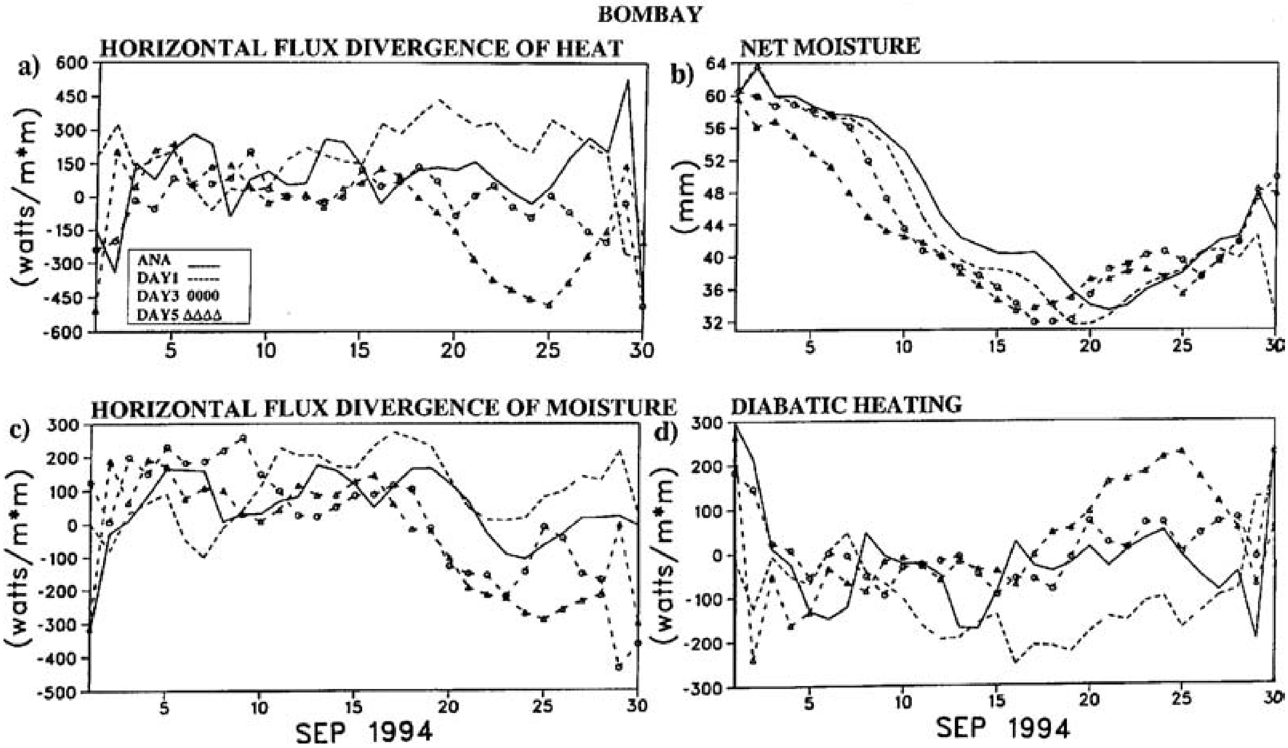

Figure 10. *Time series of energetics at Bombay for September 1994. (a) horizontal flux divergence of heat; (b) net moisture; (c) horizontal flux divergence of moisture; (d) diabatic heating.*

Sea, is entirely due to convective processes coupled with a positive moisture feedback mechanism (Pearce & Mohanty 1984).

The rainfall is the end product of the forcing mechanism. In accordance with changes in moisture, and other budget terms of heat and moisture, the rainfall also displays corresponding changes in response to changes in atmospheric circulation. In this vein, a remarkable increase in rainfall amounts occurs with the progress of the monsoon over the respective locations (Figure 6). Further, a clear decline in diabatic heating is noticed around 14 June, almost simultaneously over the Arabian Sea (Figure 3c), Bombay (Figure 7c) and Calcutta (Figure 8c) in view of the stagnation of the monsoon over the Gangetic plains in the period 13–22 June. This is also reflected in weekly accumulated rainfall totals.

3.4. The retreat of the monsoon

Detailed isochronal description of the retreat of monsoon is depicted in Figure 1b. Retreat is an important phase, which begins around the second week of September. It is generally preceded by a change in the upper level (200 hPa) Tibetan anticyclone, which starts moving southwards with the formation of an anticyclonic circulation over northwest India at 850 hPa (Rao 1976). In order to comprehend the retreat process of the monsoon, the temporal variations of net tropospheric moisture, diabatic heating and horizontal fluxes of heat and moisture corresponding to September 1994 are examined at Bombay (Figure 10), Calcutta (Figure 11), Nagpur (Figure 12), and over the Arabian Sea (Figure 13).

Normally, the withdrawal of the monsoon starts from west Rajasthan around the middle of September and is completed by the second week in October. During 1994, the retreat of the monsoon started on 19 September (Figure 1b). However, the monsoon withdrew from west Uttar Pradesh, west Madhya Pradesh and Gujarat on 23 September, which was one week earlier than the normal date. The subsequent withdrawal of the monsoon was rather slow and it withdrew as far as 20°N by 15 October, and then retreated rapidly from the rest of the country by 17 October.

The low-level (850 hPa) anticyclone was observed on 13 September. This was persistent and was also responsible for triggering the retreat of the monsoon. But the southward movement of the upper level (200 hPa) anticyclone did not start till 15 September. Both these large-scale changes resulted in the initiation of the monsoon's retreat from northwestern sectors of Rajasthan. According to IMD, the monsoon retreated from Bombay and Nagpur on 23 and 25 September respectively, followed by Calcutta on 1 October. The time series of net tropospheric energetics and moisture at Bombay are delineated in Figure 10. The horizontal flux divergence of heat (transport of enthalpy) is indicated in Figure 10a. Positive magnitudes correspond to divergence and negative magnitudes to convergence. The horizontal transport of heat shows convergence up to 3 September and depicts divergence thereafter. The

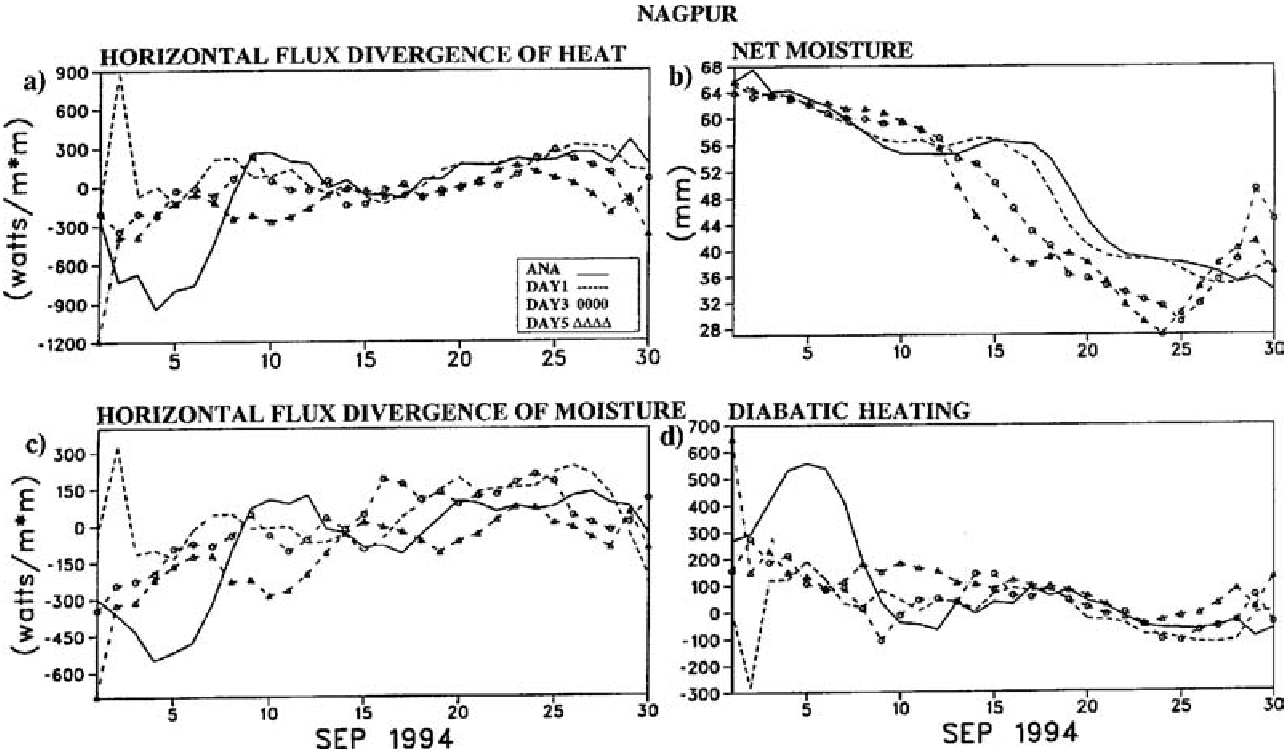

Figure 11. *As Figure 10, but for Nagpur.*

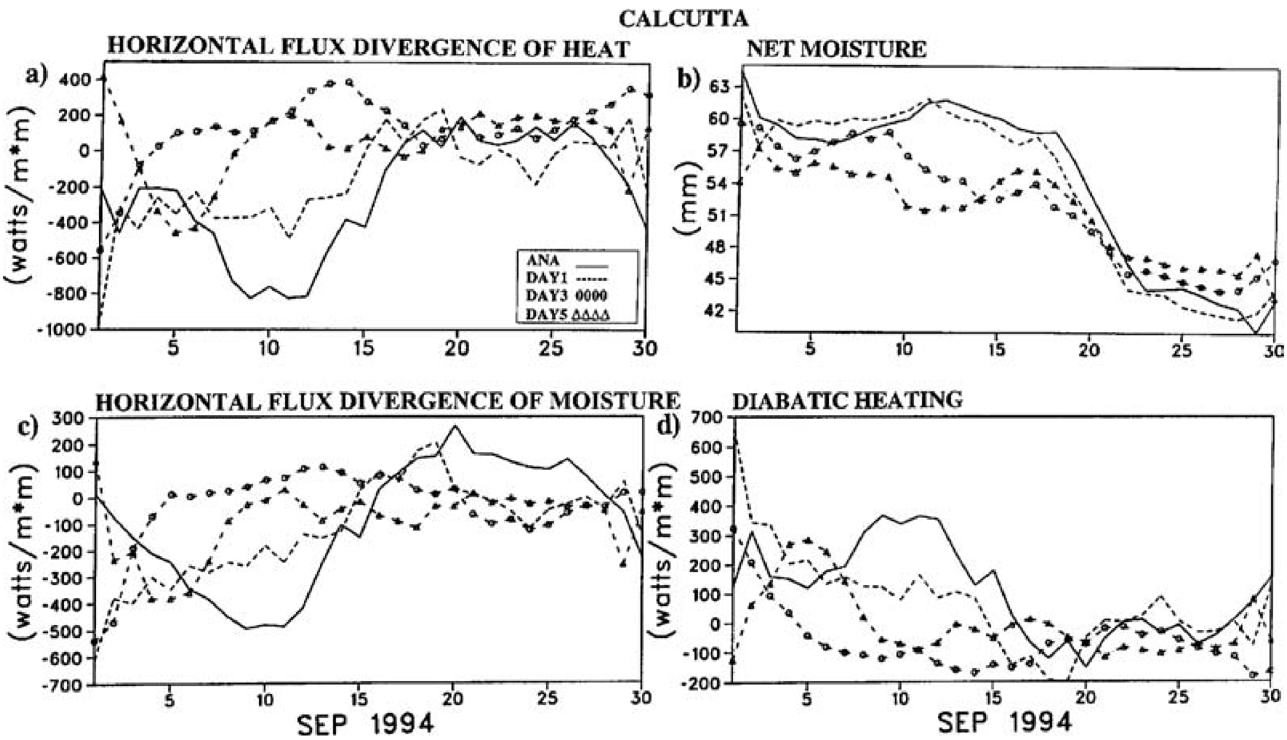

Figure 12. *As Figure 10, but for Calcutta.*

forecasts follow this trend till the middle of September and thereafter day3 and day5 forecasts show little convergence. One of the important changes associated with the retreat of the monsoon is a decrease in net tropospheric moisture (or total precipitable water content). The net tropospheric moisture (Figure 10b) shows a decreasing trend from the beginning of September. Apparently, the forecasts indicate the same trend, despite underestimating the moisture. This is consistent with the model bias of systematic drying over the monsoon domain at various forecast ranges. In association with the reduction of moisture, the horizontal flux divergence of moisture also indicates a decreasing trend from 3 September. The forecasts indicate this trend despite underestimating the horizontal transport of moisture. The persistent reduction in the horizontal

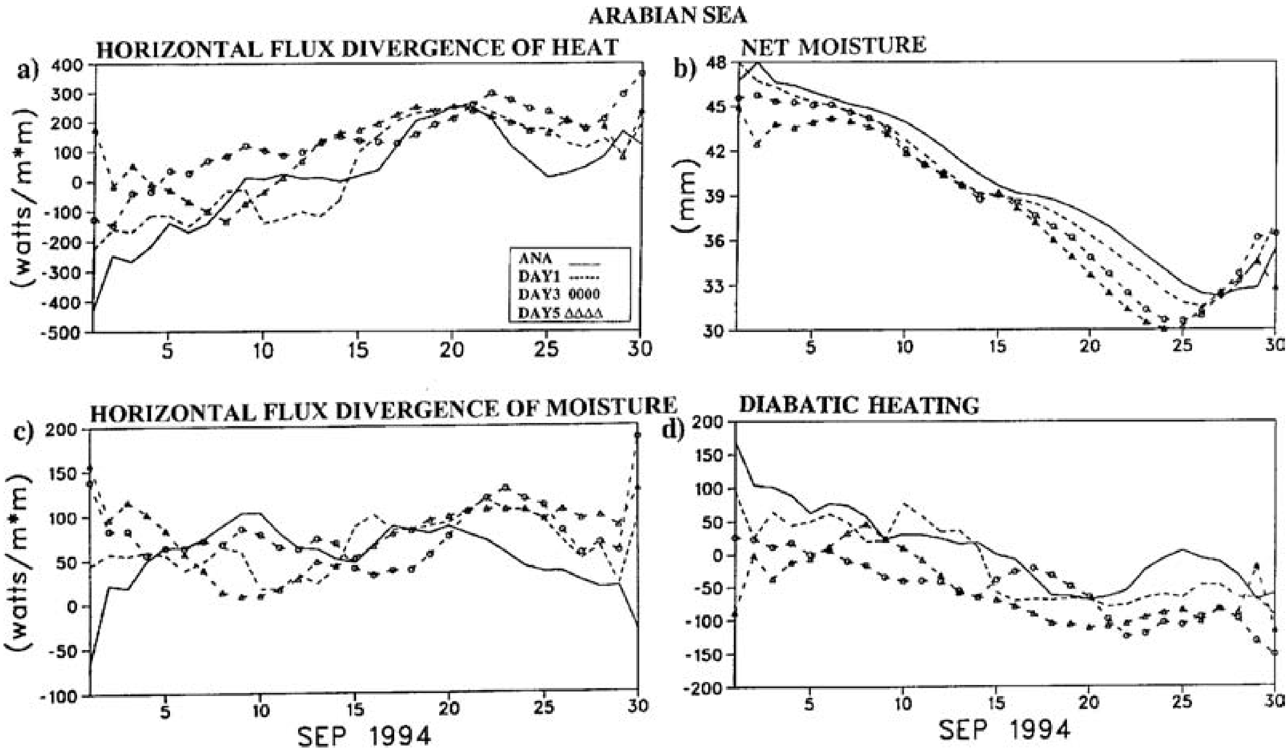

Figure 13. *As Figure 10, but for the Arabian Sea.*

transport of heat and moisture inhibits vertical motion and subsequently hinders convection. The reduction in convective activity is denoted by diabatic heating (Figure 10d). Positive values indicate heating and negative values connote cooling. The diabatic heating denotes a transition from a heating to a cooling regime from 3 September. It actually consists of various diabatic effects in the atmosphere, which include radiation, evaporation, condensation and turbulent transfer. The forecasts maintained the trend up to first week of the September and differed from the analysis later. Only the day3 forecast followed the trend to some extent. Figure 11 illustrates the retreat characteristics of the summer monsoon at Nagpur. The features are similar here also. The horizontal flux divergence of heat changes from convergence to divergence around 9 September and persists thereafter. The forecasts, barring day1, show the convergence during the first week. However, they indicated divergence from 12 September, which is in agreement with the analysis. The net tropospheric moisture also shows a similar trend as we noticed for Bombay. The moisture reduces to half of its previous level from 68 to 34 mm during the third week. The horizontal flux divergence of moisture also shows a transition around 9 September from a strong convergence regime to a divergence regime and it persists until the retreat. The diabatic heating (Figure 11d), which denotes heating during the active phase of the monsoon, starts decreasing from 9 September. This cooling trend persists until the monsoon's retreat.

The retreat characteristics at Calcutta are shown in Figure 12. Essentially, the signature of retreat in terms of transition from convergence to divergence for horizontal transports of heat and moisture is also reflected at Calcutta. In addition, diabatic heating changes to a cooling regime here. Nevertheless, the difference is that these changes are initially reflected at Bombay followed by Nagpur and subsequently at Calcutta. Further, the changes are identical, except for the intense circulation at Calcutta, which is indicated by the magnitude of the energetics. Corresponding to the retreat of the monsoon, the tropospheric moisture level was around 42 mm, which is higher than that at Bombay and Nagpur. The horizontal flux divergences of heat and moisture indicate transition from convergence to divergence around 17 September. Similarly, the diabatic heating also changes from a heating to a cooling regime from 17 September, in agreement with the horizontal transport of heat and moisture. The retreat features over the Arabian Sea are shown in Figure 13. Although the signature is the same, there are remarkable differences compared with other locations. The horizontal flux divergence of moisture changes to a divergence regime from 2 September. This is the most significant change corresponding to the retreat of the summer monsoon over India. In terms of circulation changes, the retreat occurs around the second week of September over northwest India. However, the precursor to circulation changes is indicated in terms of the horizontal transport of moisture. It is very interesting to note that the retreat signature of the summer monsoon emanates from the Arabian Sea in terms of transition to a divergence regime. This is indicated further by net tropospheric moisture, which reduces drastically from 2 September. Unlike the horizontal flux divergence of moisture, the heat flux indicates convergence up to 10 September and change to a divergence regime thereafter and this trend persists till the end of the monsoon. The reduction in the transport of moisture and heat results in a reduction in convection, and in turn in a reduction in diabatic heating. The diabatic heating denotes the transition around 10 September similar to the heat flux transport. The retreat characteristics of the summer monsoon may be summarised as follows. The signature of retreat emerges from the Arabian Sea in the form of a horizontal flux divergence of moisture by 2 September. This is followed by the change from convergence to divergence of horizontal transport of heat and moisture at Bombay, followed by Nagpur and Calcutta, with a time lag of approximately a week. However, the changes in terms of transition of convergence to divergence in the case of heat flux transport and diabatic heating to cooling over the Arabian Sea occurs around the second week of September. The persistent reduction in the moisture is apparent at various locations from the first week of September. All these characteristic features are also fairly consistent in the forecast fields. The sharp decrease in the influx of moisture as well as heat leads to the reduction of diabatic heating. Hence, the retreat of the monsoon at these locations is characterised by diabatic cooling. The forecasts indicate these changes fairly well, despite underestimation. It clearly indicates that the withdrawal features of the monsoon are developed rather abruptly and rapidly at these two locations. These changes take place both over the Indian subcontinent and the Arabian Sea (which is the major source of moisture for the monsoon circulation) almost simultaneously. With the establishment of the low-level anticyclonic circulation over northwest India, the cold air incursion inhibits influx of moisture from the Arabian Sea. As a consequence of these large-scale changes, the diabatic heating is reduced and it exhibits a cooling trend, which in turn leads to a weakening of convective activity. This then leads to a fall in tropospheric warming, which reduces the land and sea temperature contrast over the monsoon regime. Following the formation of the low-level anticyclonic circulation/ridge over northwest India, the monsoon air mass, characterised by the warm and humid air, is gradually replaced by cold and dry air from the north. This leads to a decrease in the moisture content of the atmosphere. As a consequence, mean tropospheric convective heating also decreases considerably. The cold and dry air mass impedes the influx of heat and moisture into the monsoon region due to the prevalence of anticyclone type circulation at 850 hPa. Since heat and moisture fluxes are the main contributors of the diabatic heating and associated convection, a decrease is also observed in the diabatic heating along with replacement of flux convergence of heat and moisture by the divergence regime. The overall activity, including stagnation phases, is accurately indicated by various budget parameters. However, some minor differences do exist, which may be attributed to the systematic errors and the coarse resolution of the GDAFS. These differences may be reduced considerably by ameliorating the initial state with improvements in the physical processes and quality of the non-conventional data. Further, the use of high-resolution models is essential to capture the myriad features of the monsoon. In order to do this, the horizontal resolution of model (T80) is not adequate to represent the terrain of the Western Ghats as well as the Himalayan massif. Studies by Chen et al. (1996) reveal that the flux divergence of moisture is determined inaccurately in the models. Increased temporal resolution and continuous accumulations can provide some solution to this problem. It is essential that more than four synoptic samplings are required to represent the realistic flux divergence of moisture, though one time analysis is sufficient to capture the variations associated with the onset of the summer monsoon. It is also known that the monsoon is sensitive to sea surface temperature (Ju & Slingo 1995). Although the climatological monthly mean SST is used in this study, the interactive SST would influence the simulations of energetics in various ranges of forecasts. Nevertheless, the broad characteristics remain the same.

4. Conclusions

The study has produced the following conclusions.

The characteristic features associated with the arrival of the monsoon are location dependent and their sequences are dissimilar. Changes associated with the onset of the monsoon over the Arabian Sea are sudden and steep. The influxes of heat and moisture are insignificant until the onset of the monsoon. The adiabatic production of kinetic energy from the available potential energy displays a remarkable increase synchronous with low-level kinetic energy. This is a useful parameter in the prognosis of the onset of the monsoon. The increase in heat and moisture flux convergence and the diabatic heating over the Arabian Sea confirm the advance of the monsoon.

The onset features of the monsoon over the Bay of Bengal are gradual and increase slowly. The arrival of the summer monsoon is preceded by influxes of heat and moisture. The study indicates that in addition to a sufficient level of net tropospheric moisture (above 40 mm) a minimum strength of low-level flow (around 20–25 m^2s^{-2}) is needed to trigger convective activity over the Bay of Bengal. Further, diabatic heating increases with the progress of the monsoon.

The advance of the monsoon at various locations is depicted by an increase in net tropospheric energetics. Broadly, the onset features at various locations can be dichotomised in terms of the features over as the Arabian Sea and the Bay of Bengal. Locations over the west coast (Bombay) and central India (Nagpur) denote features similar to those over the Arabian Sea, albeit with different intensity. In the same manner, east-coast locations (Calcutta) indicate characteristics identical to those over the Bay of Bengal. The principal variations in the net tropospheric moisture are supported by the persistent influx of moisture and the enhancement of diabatic heating during the progress of the monsoon. Interestingly, a good correspondence between the temporal variation of diabatic heating and the observed rainfall at these locations is apparent. Similarly, during the retreat process of the monsoon, the convergence of moisture and heat changes to a divergence regime at these locations. The monotonic decrease in the energetics starts about three weeks before the withdrawal of the monsoon. It is very interesting to note that these locations show identical trends during the retreat. The model underestimates various energetics, which is consistent with the systematic biases of the model. Despite this trend, the forecasts captured the essential signature of the onset and retreat phases of the monsoon accurately. The study demonstrates that with static boundary forcings, the location-dependent subseasonal variability can be captured.

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