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A Study on the Performance of the NCMRWF Analysis and Forecasting System During Asian Summer Monsoon: Thermodynamic Aspects

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Abstract—The thermodynamic characteristics of the Asian summer monsoon are examined with a global analysis-forecast system. In this study, we investigated the large-scale balances of heat and moisture by making use of operational analyses as well as forecast fields for June, July and August (JJA), 1994. Apart from elucidating systematic errors in the temperature and moisture fields, the study expounds the influence of these errors on the large-scale budgets of heat and moisture over the monsoon region. The temperature forecasts of the model delineate predominant cooling in the middle and lower tropospheres over the monsoon region. Similarly, the moisture forecasts evince a drying tendency in the lower troposphere. However, certain sectors of moderate moistening exist over the peninsular India and adjoining oceanic sectors of the Arabian Sea and Bay of Bengal.

The broad features of the large-scale heat and moisture budgets represented by the analysis/forecast fields indicate good agreement with the observed aspects of the summer monsoon circulation. The model forecasts fail to retain the analyzed atmospheric variability in terms of the mean circulation, which is indicated by underestimation of various terms of heat and moisture budgets with an increase in the forecast period. Further, the forecasts depict an anomalous diabatic cooling layer in the lower middle troposphere of the monsoon region which inhibits vertical transfer of heat and moisture from the mixed layer of the atmospheric boundary layer to the middle troposphere. In effect, the monsoon circulation is considerably weakened with an increase in the forecast period. The treatment of shallow convection and the use of interactive clouds in the model can reduce the cooling bias considerably.

Key words: Asian summer monsoon, systematic errors, temperature, moisture, heat budget, moisture budget.

1. Introduction

The Asian summer monsoon represents remarkable changes in the general circulation of the atmosphere characterized by periodic reversals of wind regimes,

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movements of jet streams and semi-permanent high/low pressure areas. The monsoon circulation is triggered by a sequence of events. The formation of heat low over northwest India, due to differential heating of land and ocean, precedes the transportation of moisture from the Arabian Sea to the Indian land mass (RAO *et al.* 1981). The convergence of moisture and heat (PEARCE and MOHANTY, 1984) in effect produces profound cumulus convection which in turn enhances diabatic heating. The persistent convergence of moisture and rise in diabatic heating enables generation of available potential energy (APE). The monsoon circulation culminates by a sudden and persistent rise in adiabatic generation of kinetic energy from APE (MOHANTY *et al.*, 1998), and a sharp rise in low-level kinetic energy (KRISHNAMURTI *et al.*, 1981; PEARCE and MOHANTY, 1984).

Although a large number of studies have been carried out on large-scale atmospheric energetics, only a few are related to the Asian summer monsoon (BUNKER, 1965; PISHAROTY, 1965; ANJANEYULU, 1969; RAO and RAJAMANI, 1972; SAHA and BAVADEKAR, 1973; CHOWDHURY and KARMARKAR, 1981 etc., through the analysis of heat and moisture budgets). By and large, these are either case studies using special data sets or studies restricted to only certain small regions and certain aspects of the large-scale budgets. The First GARP Global Experiment (FGGE) unravels a new epoch in the annals of meteorology by providing a comprehensive data set generated by state-of-the-art four-dimensional data assimilation systems and an opportunity to undertake detailed studies over the Asian summer monsoon region (MOHANTY *et al.*, 1982a,b, 1983; PEARCE and MOHANTY, 1984; GEORGE and MISHRA, 1993). Data are also abundantly available from operational centers (such as ECMWF, NCEP, JMA and BMRC, etc.). Recent studies making use of ECMWF data sets elucidate some interesting aspects of the Asian summer monsoon region (MOHANTY and RAMESH, 1994; RAMESH *et al.*, 1996).

It is well known that all numerical models systematically drift towards their preferred climatology. The presence of systematic errors in tropical forecasts of various numerical models may be mainly attributed to improper representation of various physical processes. Therefore, a comprehensive knowledge of physical processes which influence and are largely responsible for the maintenance of the summer monsoon, and the necessary parameterizations to represent them in the models, are vital. The physical processes are generally represented by the expressions of certain conceptual formulations of unresolved scales of motion in terms of resolvable scales of atmospheric circulation models. At the moment, a number of conceptual weaknesses exist in the representation of the physical processes which represent the functional relationships of the subgrid scale physical processes and the large-scale features of the prediction model. The dependence of systematic errors of the seasonal scale on the parameterization of physical processes was amply demonstrated (HOLLINGSWORTH *et al.*, 1980; TIEDKE *et al.*, 1988; SLINGO *et al.*, 1988). Further, the sensitivity of systematic errors to the initial conditions was analyzed in earlier studies (RABIER *et al*., 1996). It was also evinced that improvement in physical processes has reduced the errors considerably (MOHANTY *et al*., 1995a). Although, some of these studies revealed the error characteristics over the monsoon domain, none has dealt with the influence of these errors on the energetics of the monsoon, in particular, the large-scale balances which ought to be satisfied in various time scales.

In this study, the seasonal scale systematic errors related to temperature and moisture forecasts of a global spectral model, which is operational at the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi, over the Asian summer monsoon region, are examined in detail. In particular, their influence on the associated thermodynamical aspects is investigated through the comprehensive analysis of large-scale budgets of heat and moisture. In addition, the performance of the model is assessed, based on the fulfillment of these balances at different forecast ranges.

2. Methodology

The heat energy (total potential energy) and the moisture continuity equations are expressed in the flux form involving pressure coordinate in the vertical and represented below.

$$\overline{\frac{\partial(C_P T)}{\partial t}} + \nabla \cdot (C_P \bar{T} \bar{V}) + \frac{\partial(C_P \bar{T} \bar{\omega})}{\partial P} - \bar{\omega}\bar{\alpha} = \overline{Q_H}. \quad (1)$$

In equation (1) the first term on the left-hand side describes the mean rate of change of enthalpy. The second and third terms designate the mean horizontal and vertical fluxes of heat. Similarly, the fourth term represents the adiabatic conversion of available potential energy to kinetic energy. The right-hand side term describes the contributions from diabatic heating due to radiation, condensation, evaporation of falling rain drops and the turbulent transfer of sensible heat.

$$\overline{\frac{\partial(Lq)}{\partial t}} + \nabla \cdot L\bar{V}\bar{q} + \frac{\partial}{\partial p}(L\bar{\omega}\bar{q}) = \bar{Q}_L. \quad (2)$$

In equation (2) the first term on the left-hand side describes the mean rate of change of latent heat. The second and third terms represent the mean horizontal and vertical fluxes of latent heat, respectively. The right-hand side term represents the diabatic heating contributions from evaporation and condensation as well as the turbulent transfer of latent heat.

The overbar in the budget equations denotes the mean value of a quantity for a season. In this study the budgets are computed using operational daily analyses and forecasts for the summer monsoon season (JJA). Terms representing the local time rate of change of various processes over a period of 92 days make negligible contributions towards the respective budgets. The results at each regular grid points of 1.5° latitude/longitude resolution are averaged both in zonal and meridional directions over the summer monsoon region and integrated vertically from 1000 to 100 hPa. The right-hand side terms of the heat and moisture budget equations designate the contributions from the subgrid scale processes. These terms are evaluated as the residues of the remaining terms in the respective budget equations. The discussions in this paper are confined to those budget terms which contribute significantly to thermodynamic characteristics and are largely responsible for the maintenance of the summer monsoon circulation.

3. Data and Scheme of Analysis

The global data assimilation and forecasting system of the NCMRWF are adapted from the National Centers for Environmental Prediction (NCEP), Washington D.C., USA. The data assimilation system is based on a spectral statistical interpolation (SSI) scheme. The forecast model has a horizontal resolution of T-80 with 18 layers in the vertical. In the SSI scheme, observational residuals (observations—first guess at observation locations) are analyzed in spectral space. The analysis variables used in the SSI are the sigma level spectral coefficients of the amplitudes of empirical orthogonal functions of vorticity, unbalanced parts of divergence, temperature, log of surface pressure and the mixing ratio. The distinction of balanced and unbalanced variables is a way of implicitly including a linear balance relationship. The basic concept of the SSI is to minimize an objective function, defined in terms of deviations of the desired analysis from the first guess field, which is a six-hour forecast, and the observations, weighted by the inverse of forecast and observation errors, respectively. A remarkable feature of this scheme is that the analysis variables are closely related to the most commonly used variables in the operational models. Further, it makes use of forecast error covariance in spectral space. The analysis is carried out as a single global problem in the SSI, unlike local approximation in the case of multivariate optimal interpolation (OI). This has a major advantage of not producing discontinuities in the solution resulting from the data selection procedure required in the grid point by grid point approximation used in OI. It is known that there is no well-defined mass-wind relationship over the tropics unlike the geostrophic balance which determines the extra-tropical flow. The SSI incorporates the mass and wind balance in the analyzed fields by the appropriate choice of analysis variables. This balance is essentially achieved in two steps: firstly by an empirical approximation to the linear balance equation used implicitly in the definition of variables, and secondly through an explicit fitting of the full divergence tendency with that of the corresponding guess field tendency to refine the balance further. Since the analysis variables deal with the sigma levels and are closely related to the model variables, it reduces the scope of losing information between the final analysis output and the model input field. Furthermore, the analyzed increments in the SSI are smooth, and it supplies a better rms fit to the observations than OI. The details of the assimilation system are documented in earlier studies (PARRISH and DERBER, 1992).

The forecast model is based on the primitive equations for vorticity, divergence, virtual temperature, log of surface pressure, and specific humidity. These equations include forcing terms, which represent physical processes. The model uses the spectral method of horizontal representation of variables and a finite-difference representation in the vertical which has 18 unequally spaced levels cast on terrain following the sigma coordinate system. The horizontal resolution of the model is 80 waves represented in triangular truncation. In Gaussian grid representation there are 256 points in the east–west and 128 in the north–south, which corresponds to roughly 160 km. The model represents most of the commonly used physical parameterization schemes. A brief description of the model is provided in Table 1. The model uses a simple land-surface scheme which includes i) exchange coefficients computations based on Monin-Obukov similarity theory, ii) Penman-Monteith method of evapotranspiration over land which includes vegetation effects, iii) interactive bucket hydrology, iv) evaporation by bulk method over the ocean, and v) Charnock's roughness length computation over the ocean. The surface temperature is prescribed over the ocean. Further, a climatological albedo is used in the model. The comprehensive details of the model are provided in earlier studies (KANAMITSU, 1989).

The data base employed in this study comprises operational analyses (0000 UTC) and medium range forecasts (day 1 through day 5) of the NCMRWF for the monsoon season (JJA) of 1994. This year was chosen because it is a year of a normal monsoon season, and rainfall is well distributed throughout India. The basic meteorological fields considered for the study include wind, temperature and moisture over the summer monsoon region extending from 15°S to 45°N latitudes and 30°E to 120°E longitudes at ten pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100 hPa) at a horizontal resolution of 1.5° latitude/longitude. The mass and velocity fields are analyzed by a four-dimensional data assimilation scheme. In this scheme, the assimilation is carried out in two different steps: namely spectral statistical interpolation, and six-hour forecasts which provide the first guess for the subsequent analysis.

It is known that the assimilation-forecast system induces certain biases in the vertical motion fields. These biases can be avoided by deriving ω fields using horizontal wind components and a kinematic technique. Hence, instead of using ω field stored in the NCWRWF archives, the ω fields are derived from a kinematic technique suggested by O'BRIEN (1970), with the constraint that the vertical velocity vanishes at the bottom and top of the atmosphere (i.e., $\omega = 0$ at $P = 1000$ and 100 hPa). The various space derivatives are evaluated by centered difference scheme and time derivatives by a leap frog scheme. Further, the vertical integrations are computed making use of a trapezoidal rule. All the budget terms are computed at each regular latitude/longitude grid points and then integrated suitably over the domain of the atmosphere to obtain vertically integrated geographical distributions as well as spatial averaged vertical distributions of various thermodynamic budget parameters.

Table 1

Brief description of NCMRWF operational model

Grid	
Horizontal	T80 Spectral, Global
Vertical	18 Sigma layers (.995, .981, .960, .920, .856, .777, .688, .594, .497, .425, .375, .325, .275, .225, .175, .074, .021)
Dynamics	
Prognostic Variables	Relative vorticity, divergence, virtual temperature, log (surface pressure), specific humidity
Horizontal Transform	Orszag's technique
Vertical Differencing	Arakawa's energy conserving scheme
Time Integration	Semi-implicit (Robert)
Time Step	15 min
Time Filtering	Robert
Horizontal Diffusion	Second order over quasi-pressure surfaces, scale selective (Leith)
Physics	
Surface Fluxes	Monin and Obukhov similarity
Turbulent Diffusion	*K*-Theory
Radiation	Short wave—Lacis and Hansen Long-wave—Feles and Schwarzkopf
Deep Convection	Kuo scheme modified (Anthes)
Shallow Convection	Tiedtke scheme
Large-scale Condensation	Manabe-modified scheme based on saturation
Cloud Generation	Slingo scheme
Rainfall Evaporation	Kessler's scheme
Land Surface Processes	Pan scheme having three layer soil model for soil temperature and bucket hydrology of Manabe for soil moisture prediction
Air Sea Interaction	Roughness length over sea computed by Charnock's relation. Bulk formulae for sensible and latent heat fluxes
Gravity Wave Drag	Lindzen and Pierrehumbert scheme
Others	
SST	Prescribed
GDAS	Spectral Statistical Interpolation
Topography	Mean

4. Results and Discussion

All the semi-permanent circulation features associated with the establishment of the Asian summer monsoon are well depicted in the analyses and forecasts. However, a few anomalous features developed in the lower as well as upper levels, such as the weakening of the monsoon circulation with the increase in the forecast period up to day 5. Details of the systematic forecast errors in the flow fields are described in MOHANTY *et al*. (1995b) and RAO *et al*. (1998).

In the course of model integration, flow features at 850 hPa in the forecasts are dominated by the generation of anomalous circulation features and lead to i) the weakening of the southeasterly trades and the cross-equatorial flow (2–4 ms^{-1}) into the Northern Hemisphere; ii) intensification of the westerly flow (2 ms^{-1}) over the Arabian Sea to the north of 10°N during day 1; iii) weakening of the westerly flow over the North Indian Ocean and southern parts of the Indian peninsula and iv) intensification of flow (2–4 ms^{-1}) over the Bay of Bengal. Furthermore, these anomalous flow characteristics displace the mean position of the shear line associated with the monsoon trough.

Similarly, analysis of the upper level flow at 200 hPa reveals that forecast errors are responsible for the development of several anomalous circulation features. These anomalous circulation features are reflected in i) weakening of the easterly flow over the northern sectors of the Bay of Bengal and Arabian Sea; ii) intensification of an easterly core over the North Indian Ocean (5–7 ms^{-1} by day 5); iii) amplification of easterly flow (5–10 ms^{-1} by day 5) over the equatorial African continent; iv) weakening of the Tibetan anti-cyclone and v) reduction of return flow into the Southern Hemisphere.

4.1 Systematic Error Characteristics of Thermodynamic Fields

The geographical distributions of temperature and moisture forecast errors in the lower troposphere at 850 hPa are illustrated in Figures 1 and 2, respectively. Analysis of temperature forecasts reveal that the entire monsoon region is dominated by cooling in the lower levels. However, over the parts of Africa, Arabia, Afghanistan, Pakistan, NW India and the Gangetic plains of north India, anomalous warming is taking place. The established temperature gradient also demonstrates that the monsoon westerlies weaken with height and all these trends are found to increase with the increase in the forecast period from day 1 to day 5. Though the moisture forecasts (Fig. 2) show a drying of the model atmosphere over the monsoon region dominating in the lower levels, sectors of moderate moistening are delineated, particularly over the Arabian Sea, peninsular India and the central Bay of Bengal. By day 3 the moistening tendency develops dominantly over the Arabian Sea and peninsular India (Figs. 2b and c).

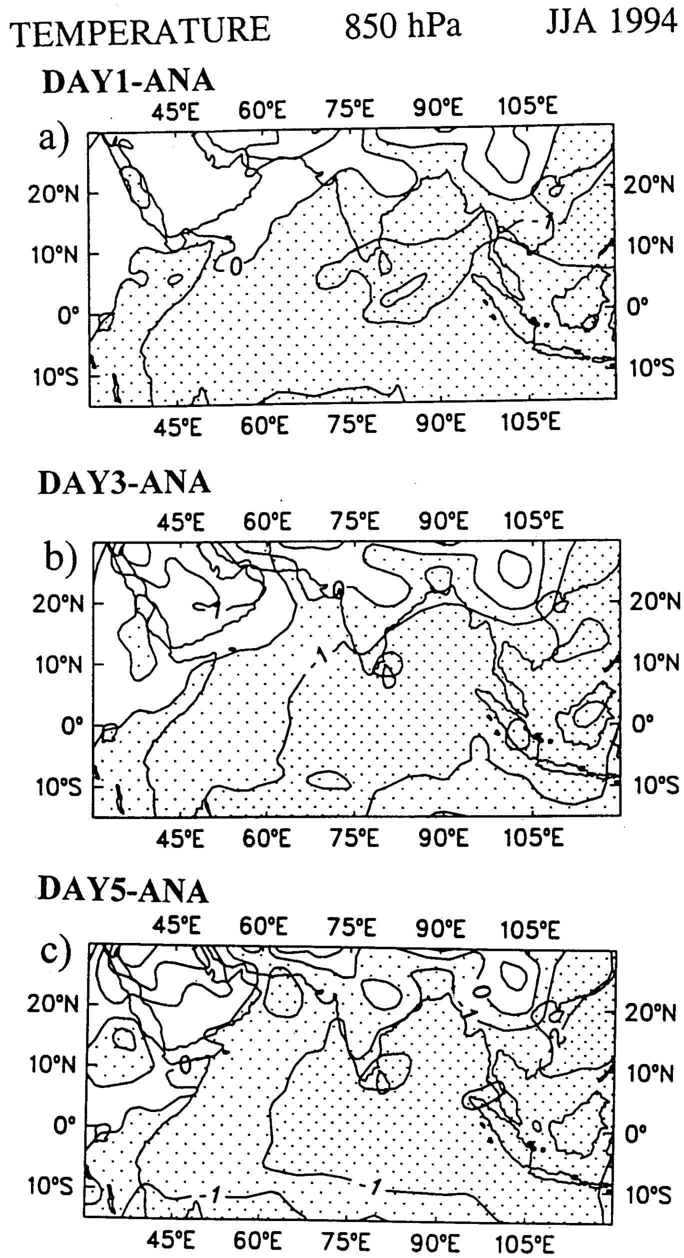

Figure 1
Geographical distribution of temperature forecast errors at 850 hPa for JJA 1994 [units: °K]. (a) Day 1 forecast error, (b) Day 3 forecast error, (c) Day 5 forecast error [contour interval: 1, negative values are shaded].

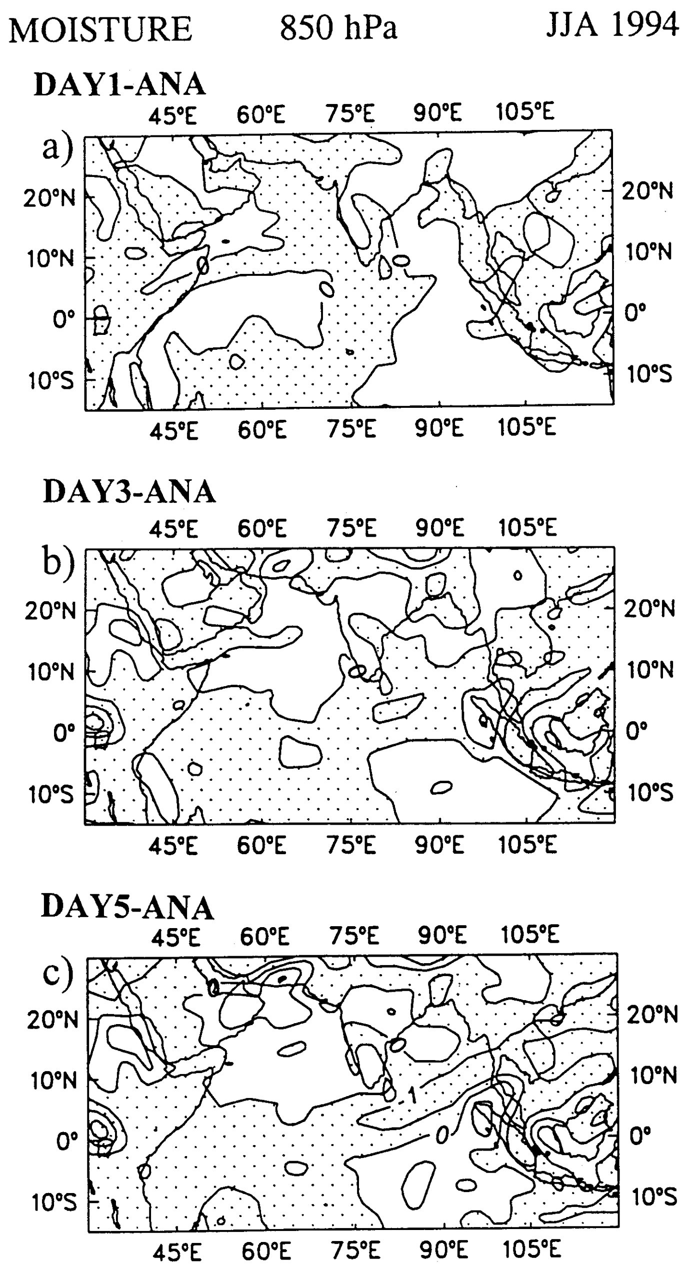

Figure 2
Same as Figure 1, but for moisture.

The general characteristics of the temperature and moisture forecast errors are further analyzed through their corresponding sectorial (30°E–120°E) mean vertical cross sections. The model forecasts of temperature (Fig. 3) exhibit cooling in the entire troposphere except in the lower troposphere of the Northern Hemisphere where predominant warming is observed. It is apparent that temperature errors in the forecasts are reasonable (1–2°K) up to day 5. The general cooling of middle and upper troposphere layers is explained by the long wave radiation parameterization, nevertheless lower troposphere cooling (900–700 hPa) demands considerable attention. This problem may be ascribed to the treatment of shallow convection which is expected to offset the radiational cooling in the lower troposphere and is presumably not so effective in minimizing the radiational effects. The sectorial (30°E–120°E) mean moisture forecast errors (Fig. 4) display general drying of the model atmosphere in lower and middle tropospheres.

The seasonal mean (JJA) precipitation forecasts are depicted in Figure 5 for day 1, day 3 and day 5. All forecasts depict two rainfall maxima, i.e., over the western coast of India and the head of the Bay of Bengal and the Myanmar region. It is discerned that the day 1 forecast underpredicts the westcoast and Bay of Bengal maxima. However, day 3 and day 5 forecasts realistically represent these maxima. The rainfall forecasts are further analyzed through the latitudinal variation (Fig. 5d). In the monsoon domain, maximum rainfall is noticed around 10°N and minimum around 40°N. This is in confirmation with the climatological rainfall over the summer monsoon region.

4.2 Heat and Moisture Budgets

The thermodynamic characteristic features of the monsoon circulation represented by seasonal mean analysis and forecasts are examined through heat and moisture budgets. The spatially (15°S–45°N, 30°E–120°E) averaged vertical profile of heat budget terms is depicted in Figure 6. The horizontal flux of heat (Fig. 6a) shows two maxima over the monsoon region with a flux convergence maximum in the lower troposphere and a flux divergence maximum in the upper troposphere. On the contrary, the vertical flux of heat (Fig. 6b) indicates strong flux divergence in the lower troposphere and flux convergence in the upper troposphere. Thus, the horizontal flux of heat to a large extent balances the vertical flux in the heat budget. The forecasts fairly stimulate the horizontal and vertical fluxes of heat. However, day 3 and day 5 forecasts exhibit underestimation of heat flux convergence in the lower, and flux divergence in the upper levels (Fig. 6a). This underestimation may possibly be accounted by the general cooling of the monsoon atmosphere supported by the weak monsoon current with the increase in the forecast period (Figs. 1 and 3). Similarly, the vertical flux of heat also shows the identical tendencies of weakening of the vertical flux divergence in the lower levels and flux convergence in the upper levels. Earlier studies (Mohanty *et al.*, 1983) reveal that the magnitudes

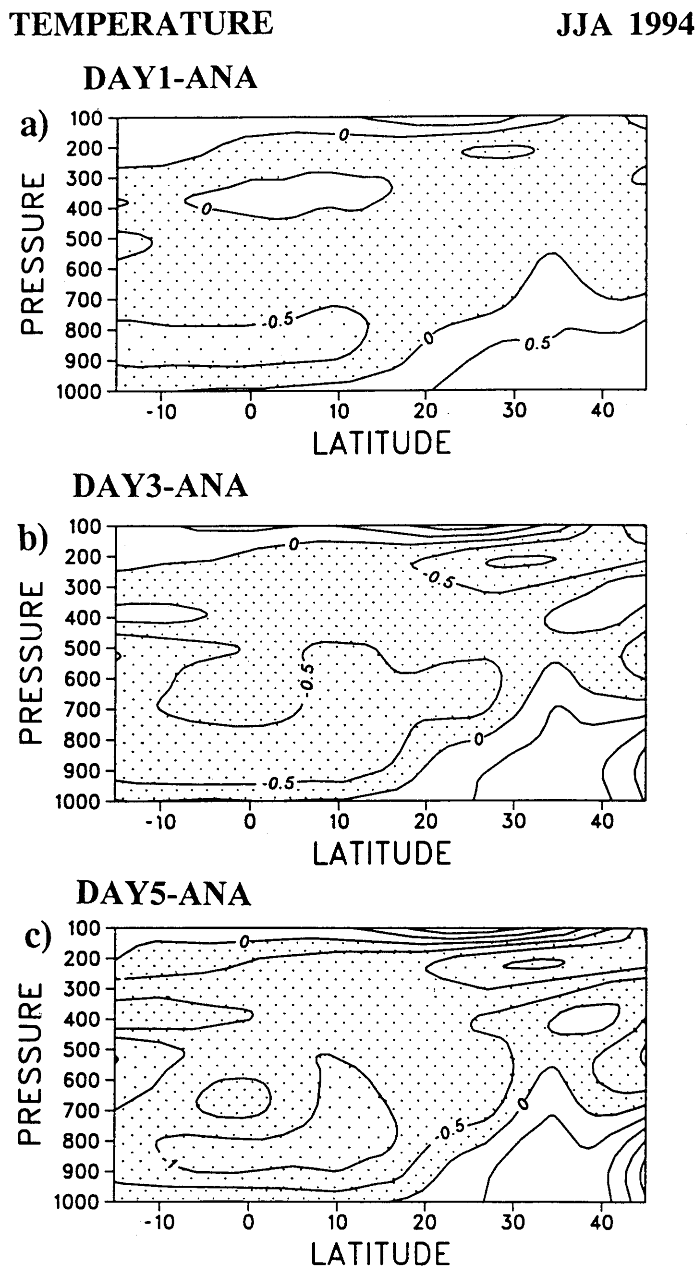

Figure 3

Sectorial (30°E–120°E) mean pressure-latitude cross sections of temperature forecast errors for JJA 1994 [units: °K]. (a) Day 1 forecast error, (b) Day 3 forecast error, (c) Day 5 forecast error [contour interval: 0.5, negative values are shaded].

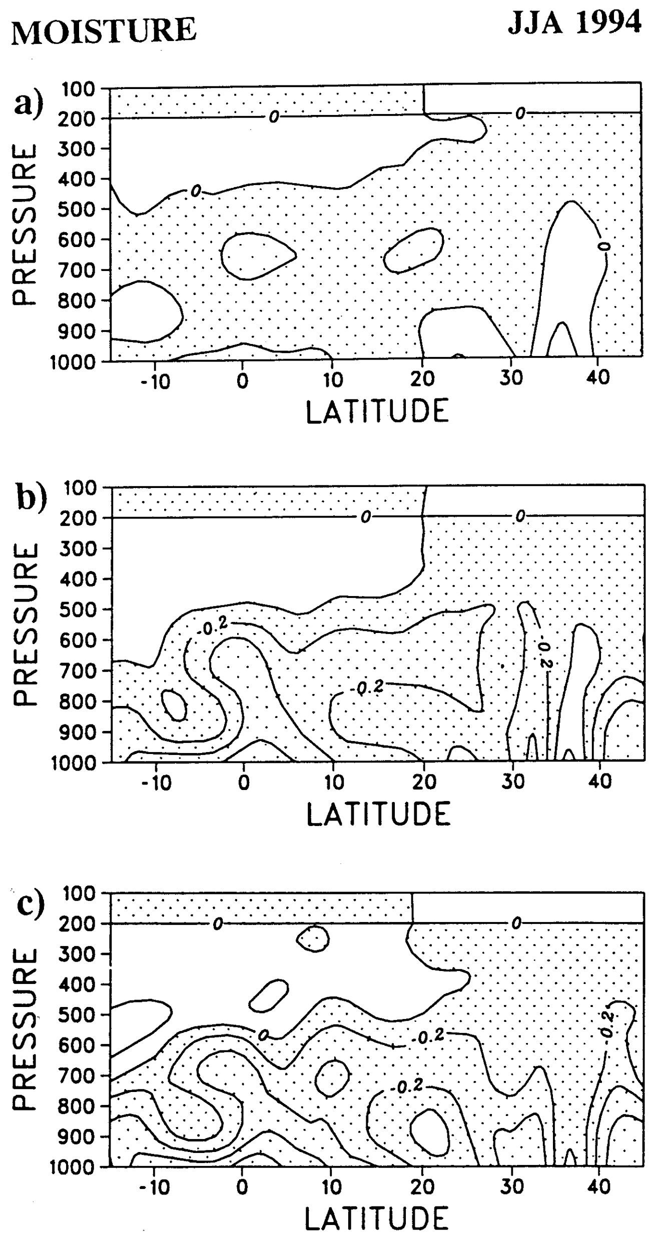

Figure 4

Sectorial (30°E–120°E) mean pressure-latitude cross sections of moisture forecast errors for JJA 1994 [units: gm/kg]. (a) Day 1 forecast error, (b) Day 3 forecast error, (c) Day 5 forecast error [contour interval: 0.2, negative values are shaded].

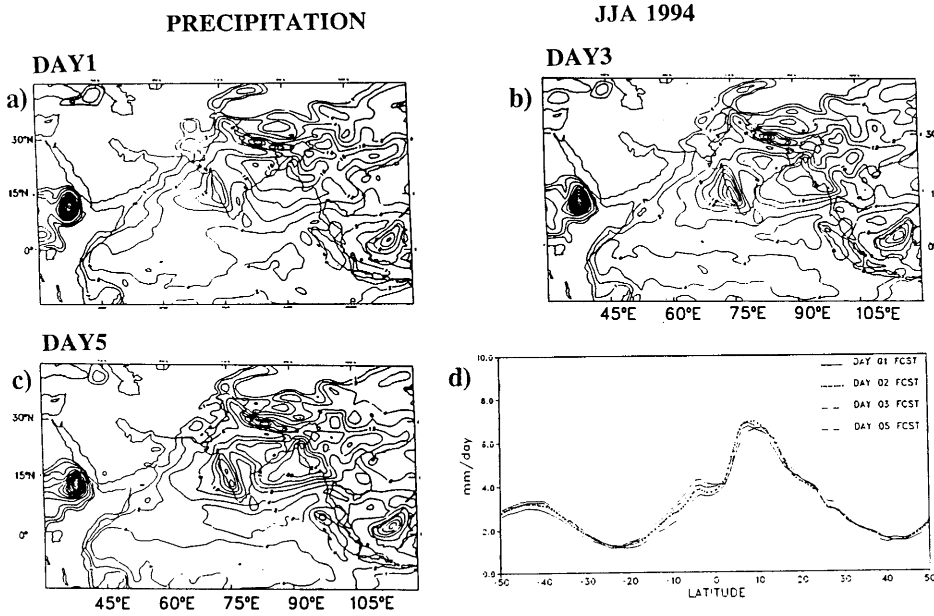

Figure 5
Precipitation forecasts for JJA 1994. (a) Day 1 forecast, (b) Day 3 forecast, (c) Day 5 forecast, (d) zonal variation of vertically integrated precipitation.

of horizontal and vertical heat flux divergences are very large and counter balance each other. In the summer monsoon domain, horizontal flux divergence is dominant at higher levels and vertical flux divergence in the lower levels. The consistency of the characteristic features of the flux parameters in the heat budget is further adduced by earlier studies (SAVIJARVI, 1980, 1981).

The vertical variation of adiabatic conversion of kinetic energy from the available potential energy (Fig. 6c) shows maximum generation of kinetic energy in the 500–300 hPa layer. This is supported by an intense vertical rising motion around 500 hPa level. Although the forecasts captured this zone of generation reasonably well, they depict a weaker zone of generation with the increase in the forecast period. This is presumably due to weak low level convergence of the monsoon flow and the moderate cooling of the model atmosphere in the forecasts. The adiabatic generation confirms the presence of a thermally driven (direct) circulation over the monsoon region. Profound vertical motions, which are characteristic of the monsoon region, give rise to generation of abundant available potential energy which in turn becomes transformed to kinetic energy. Moreover, the level of maximum in the upper troposphere is in good agreement with earlier findings (NITTA, 1970).

The vertical profile of diabatic heating (Fig. 6d) signifies heating in the lower troposphere and cooling in the upper troposphere. The forecasts represent these features reasonably well. As noticed in other heat budget parameters, the forecasts produce comparatively weaker heating and cooling patterns. Nevertheless, the diabatic heating depicts a steep reduction in the lower troposphere (800–650 hPa), which impedes the vertical transfer of heat flux from the boundary layer to middle layers of the atmosphere. This may influence the monsoon circulation and associated rainfall considerably. Earlier studies (MOHANTY *et al.*, 1983) reveal that the

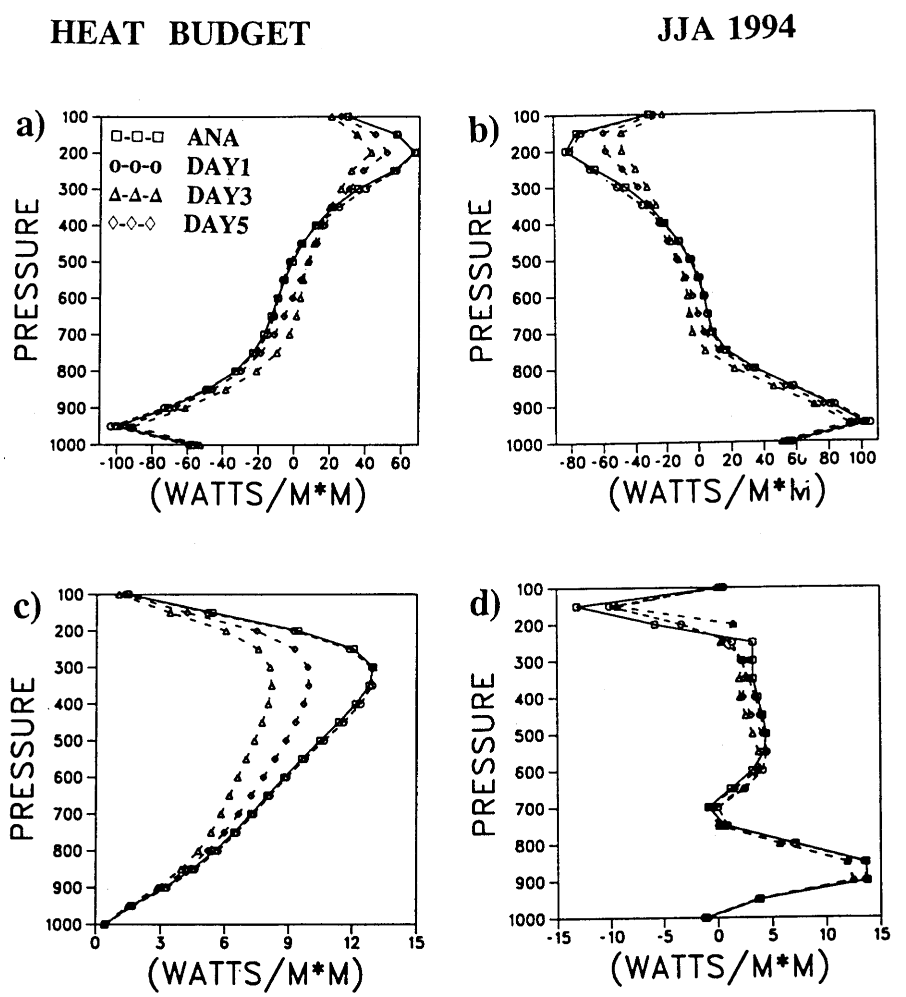

Figure 6
Vertical profile of heat budget terms for JJA 1994. (a) Horizontal flux of heat, (b) vertical flux of heat, (c) adiabatic conversion of available potential energy to kinetic energy, (d) diabatic heating.

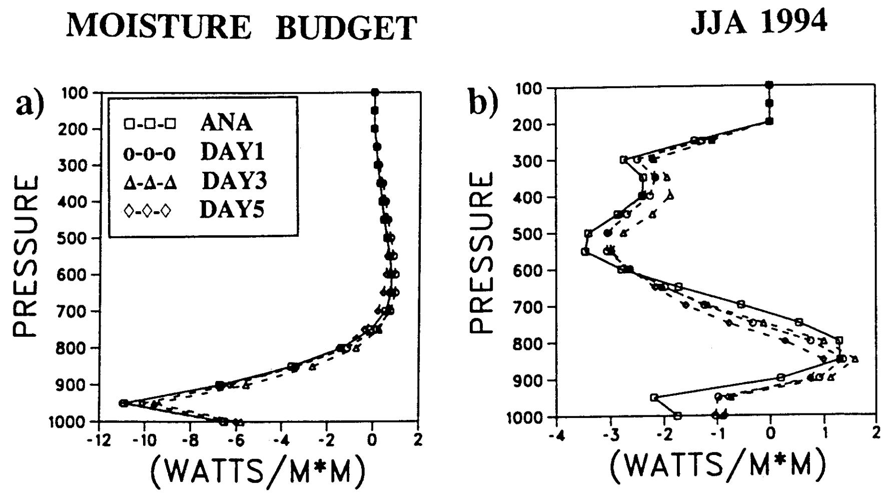

Figure 7
Vertical profile of moisture budget terms for JJA 1994. (a) Horizontal flux of moisture, (b) moisture source/sink.

vertical variation of diabatic heating distribution shows a boundary layer maximum in the tropical latitudes. This heating is accounted by the turbulent heat transfer from the relatively warm ocean and land surfaces.

All forecasts slightly underestimate the budget parameters. Earlier studies (MOHANTY *et al.*, 1982a, 1983) carried out over the summer monsoon indicate diabatic heating over the monsoon region during its active phase. As explained earlier, the diabatic heating in the lower troposphere is due to the turbulent exchange of sensible and latent heat fluxes between surface and overlying upper layers. The reduction in diabatic heating in the lower middle troposphere hinders the vertical transfer of heat and moisture from the mixed layer to the middle levels. Apart from the problems associated with the treatment of shallow convection, the use of zonal mean climatological clouds in the model can produce abundant radiational cooling. This appears to stabilize the model's mid-troposphere and is also responsible for the cold bias near 700 hPa. However, experiments performed at NCEP (WHITE, 1988) reveal the improvement in the lower and middle troposphere cooling by introducing the interactive clouds. The diabatic heating in the upper levels due to the release of latent heat by condensation is also not represented properly in the model.

The vertical profile of moisture budget parameters for the monsoon season of 1994 is illustrated in Figure 7. The horizontal flux convergence of moisture indicates maximum in the boundary layer, minimum around 700 hPa and thereafter it depicts weaker flux divergence up to 300 hPa. Similar to the heat flux, the influx of moisture is found to be weaker in the forecasts as compared to the corresponding analyses. The influx of moisture to the monsoon region leads to excessive condensation which in turn enhances diabatic heating which eventually governs the monsoon circulation. The diabatic moisture source indicates excessive evaporation compared to condensation while the moisture sink signifies *vice versa*. The moisture source/sink is represented in Figure 7b. It shows a characteristic moisture sink in the lowest and upper tropospheres (up to 300 hPa) except between 900–700 hPa layer where moisture source is dominant. The model forecasts simulate the characteristics fairly well, though with slight underestimation of magnitudes. Earlier studies (MOHANTY *et al.*, 1983) reveal that the monsoon domain serves as a moisture sink region. The analysis and forecasts show a moisture sink in the lower part of the boundary layer and the upper troposphere due to excess condensation compared to evaporation. However, in the lower tropospheric layer around 900–700 hPa, a moisture source is found, indicating the availability of excess moisture due to evaporation dominating over the condensation.

The distribution of vertically integrated horizontal heat flux is depicted in Figure 8. The entire monsoon region is dominated by heat-flux convergence with maxima over the Bay of Bengal and the Arabian Sea, respectively. However, divergence maxima is noticed along the east African coast and the west coast of India. The above findings are consistent with earlier studies carried out using the

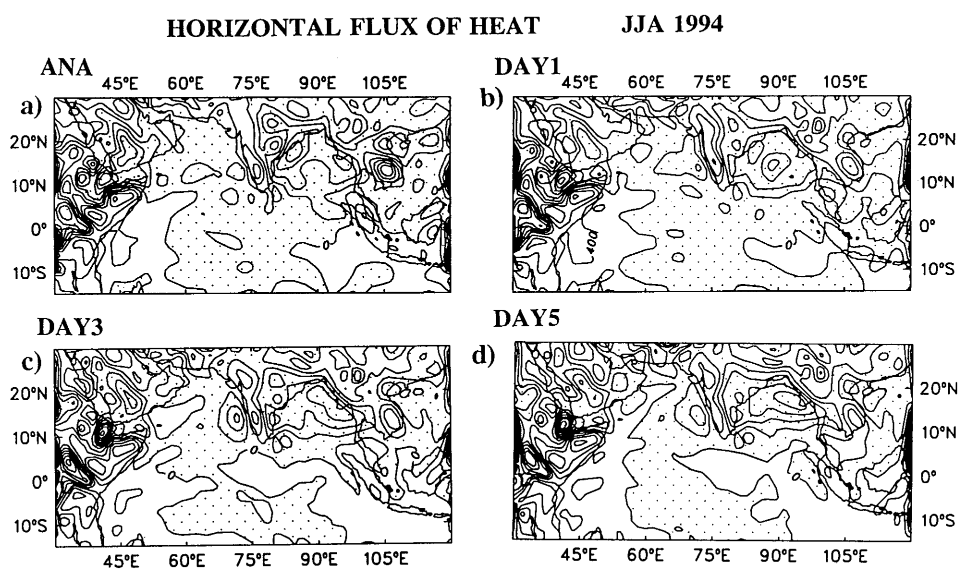

Figure 8
Geographical distribution of vertically integrated horizontal flux of heat for JJA 1994 [units: watts m^{-2}]. (a) Analysis, (b) Day 1 forecast, (c) Day 3 forecast, (d) Day 5 forecast [contour interval: 400, negative values are shaded].

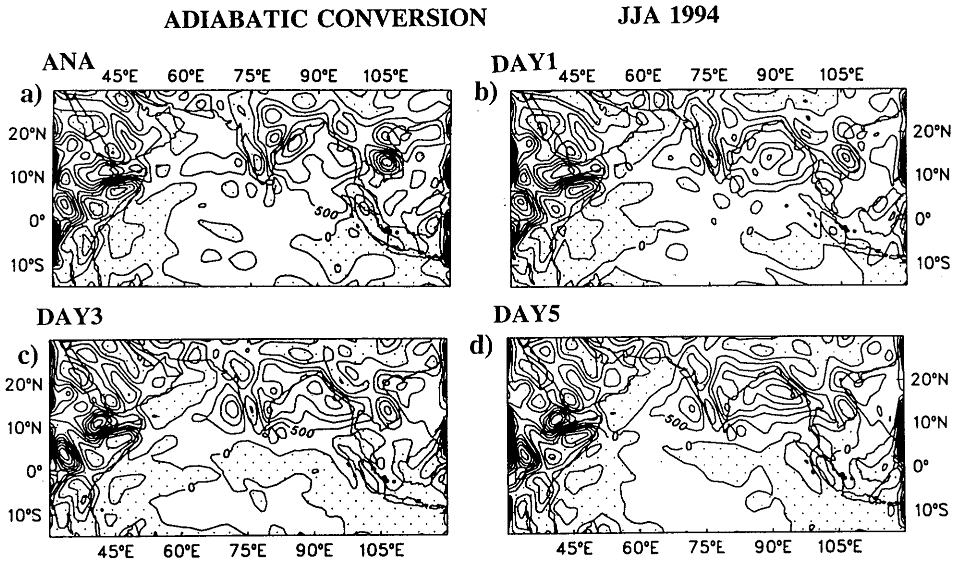

Figure 9
Same as Figure 8, but for adiabatic conversion of available potential energy to kinetic energy [contour interval: 500, negative values are shaded].

ECMWF operational analyses (MOHANTY and RAMESH, 1994). The forecasts evince an increasing tendency in the Arabian Sea maximum.

The conversion of available potential energy to kinetic energy (Fig. 9) illustrates two maxima, over the Bay of Bengal, and eastern Arabian Sea. The positive magnitudes in the entire monsoon region confirm the predominant rising motion over the monsoon region. This is adequately represented in the analysis and forecasts as well. These are in good agreement with the observations made in the earlier studies (MOHANTY and RAMESH, 1994; RAMESH *et al.*, 1996). A zone of strong dissipation is observed all along the east African coast. The day 1 forecast underestimates the maximum of the Bay of Bengal. On the contrary, the Arabian Sea maximum shows increasing tendency by day 3. This may be due to the modulations of ω field and also partly due to the easterly bias in the upper levels over the Arabian Sea.

The vertically integrated geographical distribution of the horizontal moisture flux is illustrated in Figure 10. The analysis reveals that the monsoon region is dominated by moisture flux convergence with a maximum over the Bay of Bengal and another over the Arabian Sea. A strong zone of flux divergence seen all along the east African coast. The model forecasts up to 5 days simulate these features reasonably well. Further, the Arabian Sea maximum exhibits intensification in day 3 forecasts and thus produces more quantum of seasonal rainfall over the west coast of India in day 3 forecasts (Fig. 5b). As stated before, the moisture flux convergence provides the necessary net moisture availability over the monsoon region to sustain the high levels of condensation usually observed over southeast Asia. Owing to the modulations of net moisture flux in the forecasts, the rainfall predictions show corresponding variations. It appears that the moisture convergence plays a dominant role in determining the diabatic heating patterns which in turn maintain the monsoon circulation. The heat and moisture budgets are further analyzed through the vertically integrated sectorial mean variations in order to examine the model performance at different latitude sectors. The latitudinal variation of heat and moisture budget parameters is represented in Figure 11. It shows a maximum horizontal influx of heat (Fig. 11a) around 10°N and this influx regime extends to 30°N or so. Though the forecasts simulate these features fairly well, marginal variations are depicted by and large. The forecasts in general underestimate the heat-flux convergence over the monsoon region. Also the slight overprediction of around 12°N–20°N in the day 5 forecasts may be due to intensification of low-level westerlies over the Bay and the upper tropospheric easterly bias of the model. The adiabatic conversion of kinetic energy from available potential energy (Fig. 11b) demonstrates maximum generation around 10°N and a zone of generation is found up to 30°N over the monsoon region. As noticed in the horizontal flux convergence of heat, the forecasts depict fluctuations in the generation of kinetic energy as well. Similarly, the diabatic heating (Fig. 11c) shows maximum around 10°N and cooling around 35°N. The maximum and minimum locations are in

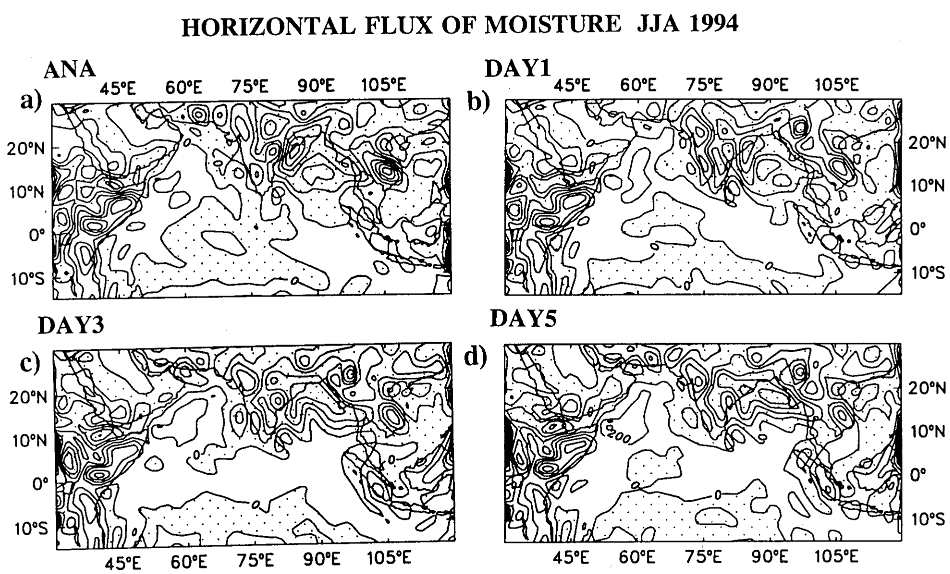

Figure 10
Same as Figure 8, but for horizontal flux of moisture [contour interval: 200; negative values are shaded].

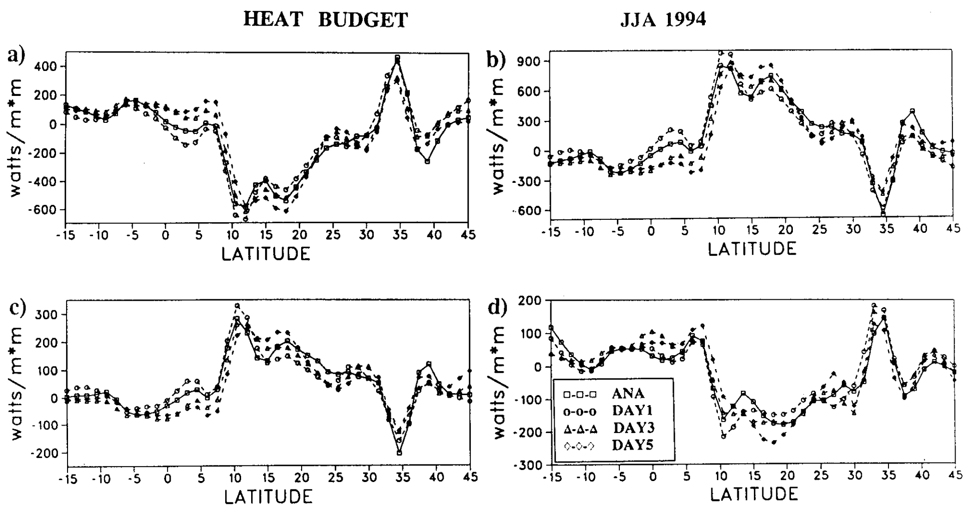

Figure 11
Zonal variation of vertically integrated heat and moisture budget terms, (a) horizontal flux of heat, (b) adiabatic conversion of available potential energy to kinetic energy, (c) diabatic heating, (d) horizontal flux of moisture.

conformity with the horizontal flux of heat and adiabatic conversion of kinetic energy. The forecasts simulate these features reasonably well. In general, as depicted in other heat budget terms, they underestimate the diabatic heating. However, day 1 and day 5 forecasts represent slight overestimation between the regions 0–7°N and 12°N–20°N, respectively. This confirms the consistency of all the heat budget terms over the monsoon region. The horizontal flux of moisture (Fig. 11d) shows maximum influx regime of moisture over the monsoon region with convergence around 10°N and minimum around 35°N. This is in conformity with the sectorial variation of rainfall which also shows maxima and minima around the same locations. Further, the diabatic heating (Fig. 11c) maxima and minima are also in conformity with the rainfall. Hence, all the variations in these budget terms are interrelated and consistent. Though the forecasts fairly simulate the moisture flux convergence over the monsoon, weaker convergence is predicted over the monsoon region with an increase in the forecast period at different latitudes.

5. Conclusions

Based on these discussions, the results of the study may be summarized as follows: The characteristics of temperature forecasts errors indicate that the entire monsoon region is dominated by a systematic tropospheric cooling in the lower and middle atmospheric levels. Although the moisture forecasts largely indicate a general characteristic drying tendency within the troposphere, certain pockets of moderate moistening exist over the sectors surrounding the Indian subcontinent particularly at 850 hPa.

The detailed examination of large-scale heat and moisture budgets which use the seasonal mean analyses and medium range forecasts (day 1–day 5) suggests that both the magnitude and nature of the vertical variation of various budget terms are well consistent with the earlier studies. However, some degree of underestimation is noted in respect to the low-level influx of heat and moisture, adiabatic conversion, etc. Such reduction in the magnitudes of heat-flux convergence and adiabatic conversion may ensue from the development of cold bias in the forecasts of the summer monsoon.

Further, the model atmosphere is found to generate a diabatic cooling layer characterized by a moisture source (excess evaporation compared to condensation) in the lower troposphere above the diabatic heating maximum of the atmospheric boundary layer (ABL). It is believed that the development of a diabatic cooling layer inhibits the vertical transfer of heat and moisture from the ABL to the middle atmospheric levels which is expected to be explained by the treatment of shallow convection in the forecast model. Furthermore, the usage of interactive clouds representation as opposite the existing zonal mean prescription of clouds, may also lead to the reduction of a systematic cooling tendency of the model atmosphere.

The distribution of vertically integrated influx of heat and moisture as well as adiabatic conversion in the forecast fields of the summer monsoon are found to be in good correspondence with the predicted rainfall distributions. The moderate moistening of the lower troposphere over the Arabian Sea, peninsular India and Bay of Bengal suggests that more moisture may be allowed to be transported to the free atmosphere for heating the troposphere in the treatment of deep cumulus convection with an increase in the quantum of rainfall forecasts.

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