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The Influence of Systematic Errors on the Asian Summer Monsoon Circulation

P. L. S. Rao

IBM India Research Laboratory, Indian Institute of Technology, Hauz Khas, New Delhi–110016, India

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ABSTRACT

The systematic errors of wind field associated with the prediction of Asian summer monsoon and their impact on the monsoon circulation have been studied in this paper. The daily operational analyses and forecasts (up to day–5) of the National Centre for Medium Range Weather Forecasting (NCMRWF), India, over the Asian summer monsoon domain for the period June, July and August of 1995 are made use for the purpose.

The systematic errors associated with the low level flow delineate, reduction in the strength of trade winds leading to weakening of cross equatorial flow as well as westerly flow over Indian Ocean. The upper level errors connote weakening of Tibetan anticyclone and reduction in the strength of return flow into the Southern Hemisphere. Further, these errors evince growing tendency with increase in the forecast period. Apart from the general underestimation of kinetic energy budget terms, the model forecasts fail to represent the transient eddies. The forecasts show increasing trend in the conversion of eddy to mean kinetic energy. These errors enfeeble Asian summer monsoon circulation with increase in the forecast period.

Key words: Monsoon, Systematic errors, Kinetic energy budget

1. Introduction

The Asian summer monsoon circulation is a thermally driven circulation, which arises primarily from the temperature differences between the warmer continental areas of the Northern Hemisphere and the oceans of the Southern Hemisphere. The complex feedback between the flow field and the heating, especially through the interaction between the large–scale flow and moist convection, is yet to be well understood. Nevertheless, this facet ensures the prominence of the summer monsoon circulation. The peculiar orography of the Indian subcontinent also modifies the circulation considerably. The result is that the monsoon in particular is a complex weather system. The mechanism of monsoon circulation may be expounded as follows.

Formation of a heat low over Northwest India takes place as a response to increase in seasonal insolation. The convergence of moist air at low levels in the heating region will lead to convection and release of latent heat, thus giving a positive feedback, which reinforces the summer monsoon circulation. In accordance with the thermal wind balance, a strong anticyclone prevails over the heat low. The mountain barrier across the equator off East Africa, leads to the concentration of flow in a low level jet along the foot of the orography. The low level jet facilitates the transport of flux of mass and moisture across the equator in summer season. The strong low–level winds are also effective at evaporating water from the Arabian Sea and strengthening the convection over the northern continent. This provides yet another positive feed back which amplifies the monsoon circulation. The Tibetan plateau and the Himalayan Mountains also provide an important element in the observed monsoon, in the form of total barrier to low level meridional winds. The ascent and rainfall caused as the low level flow encounters the mountain barrier both increase the strength of the heating and confine it to the region south of the Tibetan plateau. Further, the sensible heating, caused as the elevated Tibetan plateau absorbs solar radiation, strengthens the upper level anticyclone. The persistent influx of heat and moisture along with diabatic heat sources maintain the summer monsoon circulation.

The identification and diagnosis of the source of errors associated with the simulation and prediction of the atmospheric circulation is an integral component of the continual efforts in model refinement. A substantial component of the errors of simulation is described as systematic, i.e. it is the error that is manifested in an ensemble of many forecasts or in long term drift of a model simulation from the observed climate. Systematic errors in medium and extended range predictions, as well as in climate simulation, are a substantial component of the prediction errors apparent in atmospheric circulation models. It is known that all the numerical models drift towards their preferred climatology as the forecast period advances. The forecast errors are dominated by such tendencies in general. Asian summer monsoon region is no exception to these errors. The major part of these systematic errors in the numerical models could be attributed to improper representation of sub–grid scale physical processes such as planetary boundary layer, cumulus convection, radiation and land surface processes and their complex interactions. Therefore, comprehensive knowledge of physical processes which influence and largely control the maintenance of the summer monsoon and the necessary improvements to various parameterization schemes to represent them suitably in the general circulation models are imperative to improve the forecast skill. 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. Weaknesses still exist in the representation of functional relationships of sub–grid scale physical processes, in these models.

Several attempts were made to analyze the nature, characteristic features, and isolate the tropical systematic errors of European Centre for Medium Range Weather Forecast (ECMWF) model. Kanamitsu (1985) demonstrated that the predictability in the tropics is about 2 days for the mass and wind fields. It was shown that the forecast errors essentially caused by the failure of cumulus parameterization to produce the climatological distribution of rainfall associated with the ITCZ. Heckley (1985) studied the tropical errors of the ECMWF model. The temperature forecasts exhibit warming around the tropopause and cooling in the mid and lower troposphere. The moisture forecasts depict a general drying of the model atmosphere. Precipitation and evaporation are too weak and a new balance within the model is slowly established with reduced total energy. Further, the associated wind errors are found to have a highly baroclinic structure. Tiedtke et al., (1988) studied the improvement in tropical forecasts of ECMWF after the introduction of a new convection scheme and increase in horizontal resolution. The forecasts improved significantly through the reduction of systematic errors in response to a more realistic tropical diabatic forcing. The impact of these changes is substantial for the thermal state of the observed as well as model atmosphere. White (1988) studied the performance of NCEP medium range forecast model in mid latitudes. It was observed that the forecasts fail to maintain the analyzed transient eddy activity.

Experiments suggest that the enhanced orography decreases transient activity. Further, gravity wave drag also dampens the atmospheric variability. All these studies evince the requirement of a new approach to the problem of parameterization of the physical processes particularly, convection, radiation, boundary layer and their interactions for further reduction of the tropical forecast errors.

Despite many studies which elucidate the systematic errors, very few explained the effect of these errors on the atmospheric circulation in various time scales. In this regard, we made an endeavor to examine the errors asociated with the flow field and the impact of these errors on the Asian summer monsoon circulation.

2. Data and analysis procedure

The NCMRWF was set up to provide agro–advisory to the farming community of India. The global data assimilation and forecast system is adapted from the NCEP, USA. The operational model currently runs at T80 horizontal resolution with 18 layers in the vertical. The details of the data assimilation system and model are provided in the studies of Parrish and Derber (1992) and Kanamitsu (1989) respectively. The data employed in this study consist of daily analyses (00Z) and forecasts (day–1 through day–5) of the NCMRWF for summer season comprising June, July and August of 1995. The basic meteorological fields considered for the study include wind and geopotential 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) having horizontal resolution of 1.5° latitude / longitude. The mass and velocity fields are analyzed by three–dimensional data assimilation scheme in which, the assimilation is carried out in two different steps, viz–spectral statistical interpolation, and six hour forecast which provides the first guess in order to carry out the subsequent analysis. The impact of the systematic errors associated with the wind field is assessed through the study of kinetic energy budget in the analyzed as well as model atmosphere.

The kinetic energy budget equation is obtained from the equation of motion, which the atmosphere obeys and represented in the flux form with pressure as the vertical coordinate. It is well known that any time mean atmospheric circulation can be bifurcated into mean and eddy parts. Since tropical circulations are dominated by the mean component of the flow, we have elucidated the mean budget. The mean kinetic energy equation is expressed as

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

where

$K_{\mathrm{M}} = \frac{1}{2}\overline{V}^2$ kinetic energy of the mean flow, $K_{\mathrm{T}} = \frac{1}{2}V'^2$ kinetic energy of the eddy flow, Various notations used in the equation are given below.

$$H_0 = K_{\mathrm{M}}\overline{V},$$

$$H_1 = \overline{(\overline{V} \cdot V')V'},$$

$$C(K_{\mathrm{M}}, K_{\mathrm{T}}) = C_H(K_{\mathrm{M}}, K_{\mathrm{T}}) + C_v(K_{\mathrm{M}}, K_{\mathrm{T}}),$$

$$C_H(K_{\mathrm{M}}, K_{\mathrm{T}}) = -\frac{\overline{u'u'}}{a\cos\varphi}\frac{\partial\overline{u}}{\partial\lambda} - \frac{\overline{u'v'}\cos\varphi}{a}\frac{\partial}{\partial\varphi}\left(\frac{\overline{u}}{a\cos\varphi}\right)$$

$$- \frac{\overline{u'v'}}{a\cos\varphi}\frac{\partial \overline{v}}{\partial \lambda} - \frac{\overline{v'v'}}{a}\frac{\partial \overline{v}}{\partial \varphi} + \overline{u'u'}\frac{\overline{v}\tan\varphi}{a}.$$

and

$$C_{V}(K_{M}, K_{T}) = - \overline{u'\omega'}\frac{\partial \overline{u}}{\partial P} - \overline{v'\omega'}\frac{\partial \overline{v}}{\partial P}.$$

Further, the term $\frac{\partial}{\partial P}\overline{(K_M + VV')\omega}$ can be bifurcated as follows:

$\frac{\partial}{\partial P}(\overline{K_M}\,\overline{\omega})$ mean component and $\frac{\partial}{\partial P}\overline{(VV')\omega'}$ eddy component.

The first term on the left of Eq. (1) designates the local rate of change of the kinetic energy. The second and third terms describe the horizonal and vertical divergence fluxes of kinetic energy respectively. Similarly, the first term on the right denotes the conversion of available potential energy to kinetic energy through the action of pressure forces (adiabatic generation of kinetic energy). The second term evinces the exchange of K_M to K_T and vice versa which arises basically from the large scale horizontal and vertical Reynold's stresses. The last term signifies the dissipation of kinetic energy by the turbulent frictional processes.

Further, the volume integral of any variable $F(\lambda,\Phi,P)$ 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

$$\overline{F} = \frac{1}{g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{P_1}^{P_2} Fa^2\cos\varphi\, d\lambda\, d\varphi\, dP. \tag{2}$$

Instead of using ω field stored in the NCWRWF archives, ω field is derived employing kinematic technique using the uninitialized wind fields in this study with a constraint that the vertical velocity ($\omega = dP/dt$) vanishes at the bottom and top of the atmosphere (i.e., $\omega = 0$ at $P = 1000$ and 100 hPa levels). In the kinematic method, the main problem is that of the accumulated biased errors involved in the computation of divergence from the wind components. A technique suggested by O'Brien (1970) has been used in the study to adjust the divergence in such a way that its vertically integrated valuein any particular column of the atmosphere becomes zero. Albeit, we have analyzed mean as well as eddy components of kinetic energy budget, the discussion invariably pertains to the mean component as the contribution of transient eddies to the time mean is one order less than the mean component. Further, the terms representing local rate of change and the vertical flux have negligible contribution towards the kinetic energy budget. Hence, the discussion is restricted to significant terms such as horizontal flux, adiabatic generation and dissipation, whose contribution governs the kinetic energy budget. The various space derivatives are evaluated by centered difference scheme and vertical integrations by trapezoidal rule in this study.

3. Results and discussion

The distribution of vector wind fields in respect of mean analysis and forecast errors at day–1, day–3 and day–5 for 850 hPa and 200 hPa pressure levels have been examined. Further, the large–scale budget terms of kinetic energy are also examined to comprehend the characteristic monsoon circulation depicted by the analyses and forecasts of the model.

The semi–permanent circulation features associated with the establishment of Asian

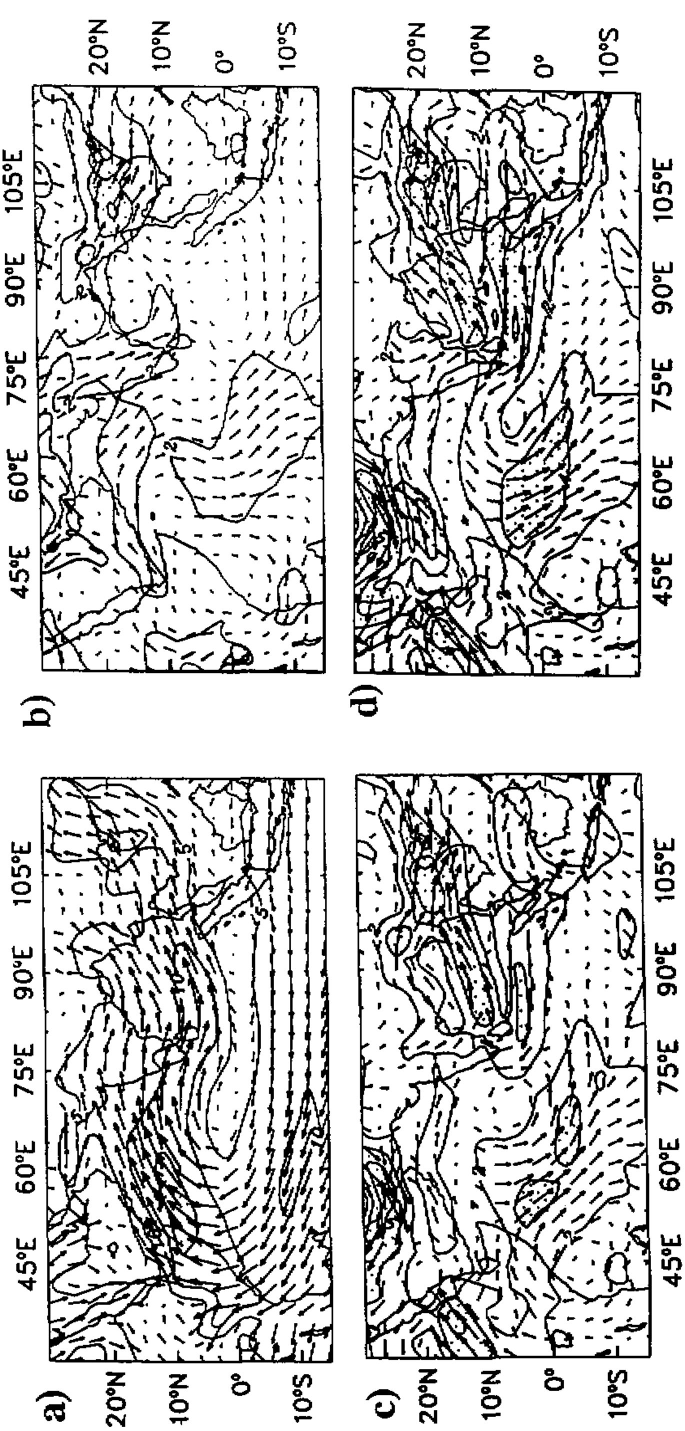

Fig. 1. Wind field at 850 hPa for JJA 1995. (a) Analysis (b) Day 1 error (c) Day 3 error (d) (Day 5 error [Contour interval for (a): 5 ms^{-1}; for (b), (c) & (d): 2 ms^{-1}. Isotaches more than 15 ms^{-1} and errors larger than 4 ms^{-1} are shaded].

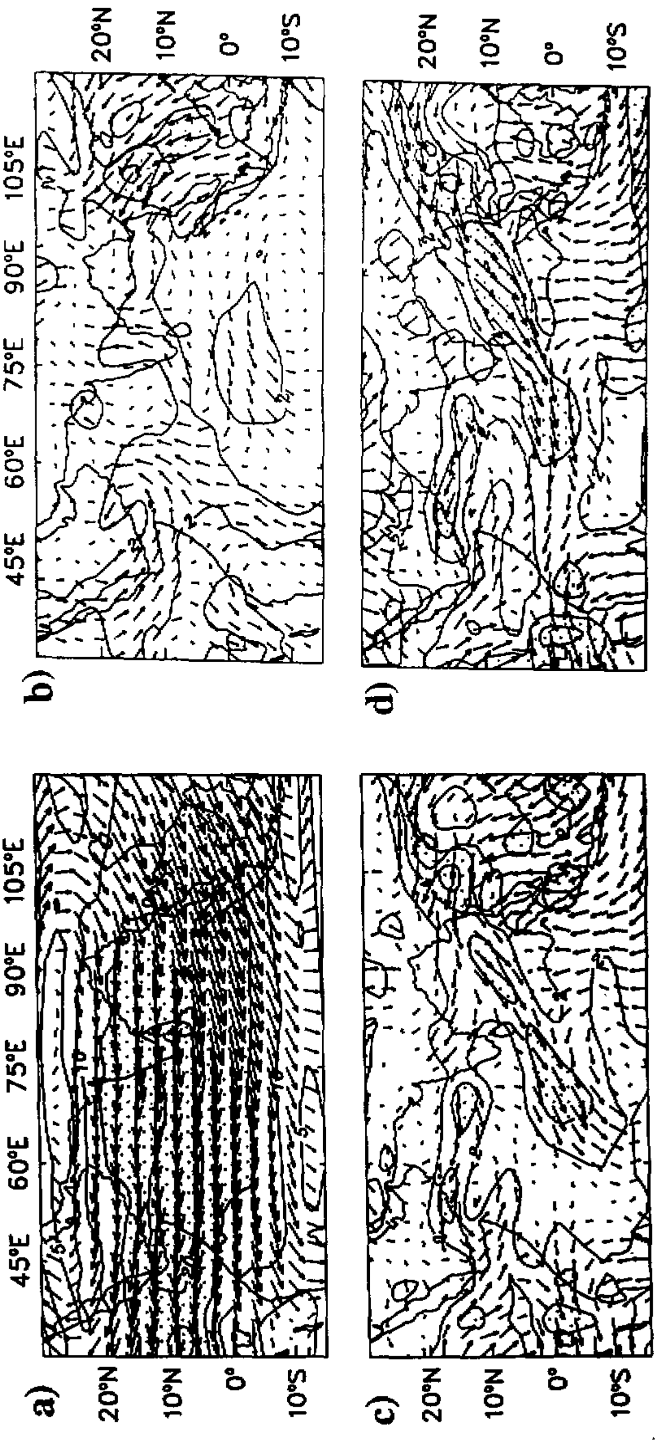

Fig. 2. As in Fig. 1, but for 200 hPa.

summer monsoon are well depicted in the mean analysis and forecasts. The mean analyzed wind fields at 850 hPa and 200 hPa levels are presented in Figs. 1a and 2a respectively. The prominent monsoon circulation features of these two levels namely the low level namely the low level Somali jet and the upper level Tropical Easterly Jet (TEJ) are in good agreement with their respective climatological features (Newell et al., 1972; Rao, 1976). The wind field distribution at 850 hPa also depicts the existence of strong Southern Hemispheric trades having a speed of about 10 ms^{-1}, strong cross–equatorial flow into the Northern Hemisphere off the Somali coast and a strong zone of westerlies (10–15 ms^{-1}) over the Arabian Sea and Bay of Bengal.

Wind field distribution at 200 hPa (Fig. 2a) is charaterized by a strong and elongated anti–cyclone centered over Tibet (30°N) in the Northern Hemisphere. Two contrasting wind regimes present on either side of the Tibetan anti–cyclone, i.e. westerly wind regime (Sub–Tropical Jet) towards the north, (not shown in Fig. 2a) and easterly regime (TEJ) to the south, are the significant circulation features of the Asian summer monsoon. Fig. 2a depicts a strong zone of easterlies which extends over Indonesia, Bay of Bengal, Arabian Sea and Africa with a core of maximum (20 ms^{-1}) around 5–12°N over the south Indian peninsula and adjoining Arabian Sea.

In the course of model integration, error characteristics at 850 hPa in the forecasts are dominated by the generation of anomalous circulation features viz. cyclonic circulation over the Bay of Bengal and adjoining Orissa region, and a vortex is noticed over the Somali coast which transforms into a cyclonic circulation and gradually shifts to southeastward with increase in the forecast period. Further, the intensity of these anomalous features is found to grow with the forecast length (day–1 through day–5) and thus, leading to i) the weakening of the south easterly trades and the cross–equatorial flow (2–4 ms^{-1}) into the Northern Hemisphere; ii) intensification of 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. Other significant low level flow characteristics of the forecasts include rapid intensificaiton of westerly flow 2–4 ms^{-1}) over equatorial Africa (0–15°N), weak westerlies over the equatorial western Pacific and adjoining Indian Ocean (10°S–10°N) during day–1, however, in the subsequent forecasts these winds change over to strong easterlies. These anomalous flow characteristics displace the mean position of shear line associated with the monsoon trough. The significant aspect to be noted is that the model produces weaker cross–equatorial flow as the forecast period increases.

Analysis of the upper level flow characteristics in the forecasts of the NCMRWF reveals that forecast errors are largely generated due to the development of several anomalous circulation features (three anti–cyclones respectively over the Bay of Bengal, Arabian Sea and central regions 80°E–100°E) of Indian Ocean which shifts westwards and strengthens with forecast period) in the course of model integration. Further, circulation features at 200 hPa also indicate a cyclonic circulation over Tibetan region particularly in day–3 and day–5 forecasts. These anomalous circulation features are responsible for (i) weakening of easterly flow over the northern sectors of Bay of Bengal and Arabian Sea; (ii) intensification of easterly core over the North Indian Ocean (4 ms^{-1} by day–5); (iii) weakening of Tibetan anti–cyclone; (iv) amplification of flow (6 ms^{-1} by day–5) over the equatorial Africa; and (v) reduction of return flow into the Southern Hemisphere. These errors have considerable influence on the summer monsoon circulation. The large–scale balance of kinetic energy provides an insight into this aspect.

The kinetic energy of the atmosphere is created through the conversion of the available potential energy and eventually dissipated through the irreversible frictional processes. The maintenance and intensity of the general circulation depend on the balance between generation and dissipation of kinetic energy. In order to comprehend the large–scale atmospheric dynamics, the kinetic energy generation and dissipation are vitally important. The vertical profile of area averaged (15°S–45°N, 30°–120°E) kinetic energy budget terms is presented in Fig. 3 for the monsoon season (JJA) of 1995. The vertical profile of the horizontal flux due to mean and eddy flows is prepresented in Figs. 3a & b. In the lower and middle troposphere, the forecasts represent the horizontal flux components of kinetic energy reasonably well. The mean component of the horizontal flux depicts weak convergence in the lower levels and strong divergence in the upper levels. However, the forecasts underestimate the divergence and depict strong convergence in the upper troposphere between 400–200 hPa levels. This is possibly due to the shrinking of zone of easterlies depicted by the model in the troposphere between 500–300 hPa. In the case of eddy component also the forecasts underestimate the eddy flux divergence in the upper troposphere. However, by day–5 the model retains most of the analyzed divergence. The horizontal flux patterns depicted for the monsoon region is in agreement with the earlier studies (Kung, 1966; Savijarvi, 1981; Ding and Reiter, 1983). They found that the source regions of kinetic energy are characterized by the strong flux divergence in the upper levels and convergence in the lower levels. The vertical profile of horizontal flux of kinetic energy shows that the monsoon region is characterized as the source region of kinetic energy and transported horizontally across. The adiabatic generation of kinetic energy (Fig. 3c) shows two maxima, the primary one in the bondary layer and the other in the upper troposphere (jet level). Several earlier studies (Kung, 1966; Savijarv, 1981; Ding and Reiter, 1983) also confirm this fact. The zone of kinetic energy production in the planetary boundary layer over the Northern Hemisphere is confined to tropics indicating the presence of strong ageostrophic flow. Since, Kung and Savijarvi carried out the budget calculations over the North American region the one–to–one correspondence may not be possible. However, Ding and Reiter (1983) carried out their study over tropical West–Pacific, which adduces the monsoon features. The forecasts fairly represent the generation of kinetic energy in the lower troposphere, but underestimate in the upper troposphere at the jet level. The residue of kinetic energy balances the production (Fig. 3d) through parameterization of turbulent momentum fluxes in terms of surface similarity and mixing length theories in the NCMRWF model. It also shows two maxima, the primary one in the boundary layer and the secondary in the free atmosphere in the upper levels associated with tropical easterly jet and subtropical jet. Although the adiabatic generation is the resultant of zonal and meridional ageostrophic components, the contribution from the meridional component is significant (the zonal component is one order less than that of meridional component). The zonal and meridional components of the adiabatic generation of kinetic energy are represented in Figs. 3e and 3f respectively. The zonal adiabatic generation is underestimated in the lower as well as higher levels with the forecast period. This may be due to weak monsoon westerlies in the lower level and weak easterlies in the upper level flow. However, the meridional component depicts generation in the upper levels. The strong weaker generation in the lower levels is enabled through meridional ageostrophic component. Due to weak return flow, the generation in the upper

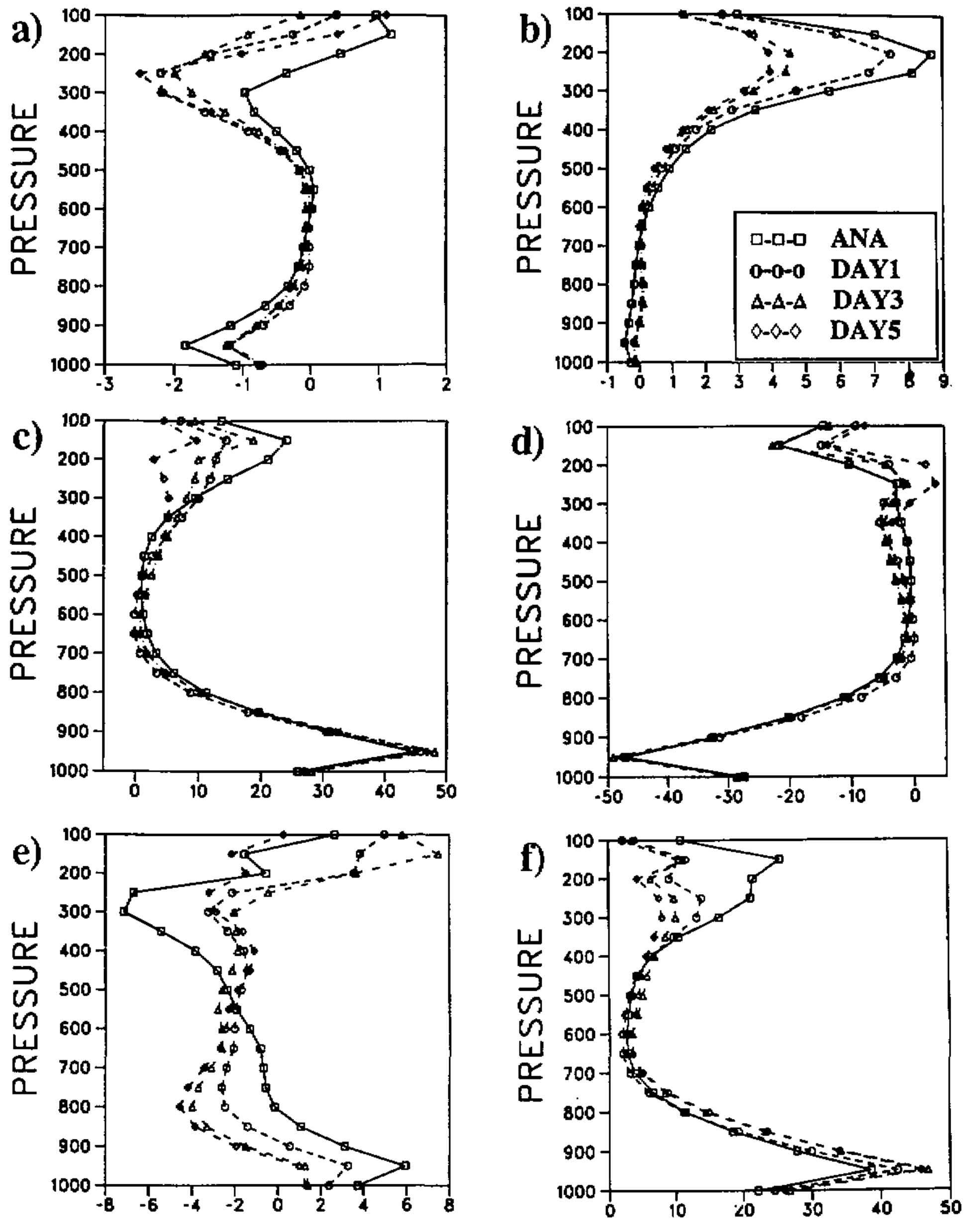

Fig. 3. Vertical profile of kinetic energy budget terms for JJA 1995. (a) Horizontal flux due to mean flow (b) Horizontal flux due to eddy flow (c) Adiabatic generation (d) Dissipation (e) Zonal generation (f) Meridional generation.

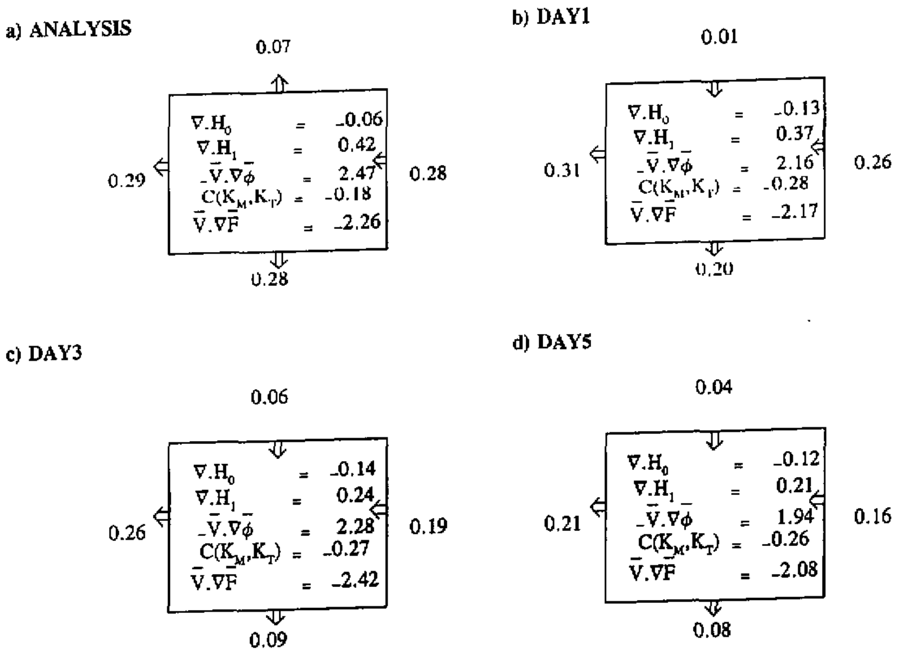

Fig. 4. Volume integrated kinetic energy budget terms for JJA 1995. (Units: Watts m^{-2}).

levels is underestimated. It is evident from kinetic energy budget terms that the forecasts fail to maintain the analyzed atmospheric variability. This is presumably explained by underestimation of eddy kinetic energy in all ranges of forecasts. It appears to affect both kind of eddies with periods associated with baroclinic activity and eddies of lower frequencies. Because of this fact, the horizontal flux, which consists of transient eddy components, is improperly represented by all forecasts.

The volume integrated kinetic energy budget for the analysis and forecasts is represented in Fig. 4. The balance requirements maintained in the forecasts are in good agreement with the analysis. Nevertheless, all ranges of forecasts underestimate the budget terms. The significant aspects depicted by kinetic energy budget include increase in the convergence of horizontal flux of KE due to mean component of flow in the forecasts. The convergence of kinetic energy hinders the adiabatic generation, in turn the monsoon circulation gets weakened considerably. Further, the conversion term shows increase in the conversion of eddy to mean kinetic energy with the increase in forecast period. The boundary fluxes depicted by the analysis and forecasts, evince the monsoon domain as the source of kinetic energy with maximum outflow through western boundary.

4. Conclusions

The following conclusions can be drawn from the study.

The systematic errors in the low level flow delineate weak trade winds, in turn weak cross–equatorial flow. They also show weak surface westerlies over the monsoon domain. In upper levels, they indicate reduction in the strength of return flow as well as Tibetan anticyclone. These errors in the flow field increase with increase in the forecast period. Although, the kinetic energy balance is well represented, the budget terms are underestimated in all ranges of forecasts. The significant aspects found in this study include increase in the convergence depicted by horizontal flux of kinetic energy due to mean component of flow by the model forecasts. Further, the conversion term shows increase in the eddy to mean conversion of kinetic energy, which increases with increase in forecast period. Normally, the monsoon domain is characterized as the source region of kinetic energy, as it is generated with in the domain and transported horizontally across. Consequently, the horizontal flux of kinetic energy indicates, predominant divergence over the monsoon region. Nevertheless, the model forecasts show convergence. Which connotes that the monsoon circulation produced by the model is quite feeble. Moreover, the increase in eddy to mean conversion indicates underestimation of transients by the model. Since the transient systems draw their energy from the mean circulation, which leads to underestimation of the mean circulation as well. The epitome of the study is that the model forecasts produce feeble monsoon circulation, which weakens further with increase in forecast period.

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