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Systematic errors in the medium range prediction of the Asian summer monsoon circulation

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Abstract. The present study describes an analysis of Asian summer monsoon forecasts with an operational general circulation model (GCM) of the European Centre for Medium Range Weather Forecasts (ECMWF), U.K. An attempt is made to examine the influence of improved treatment of physical processes on the reduction of systematic errors. As some of the major changes in the parameterization of physical processes, such as modification to the infrared radiation scheme, deep cumulus convection scheme, introduction of the shallow convection scheme etc., were introduced during 1985–88, a thorough systematic error analysis of the ECMWF monsoon forecasts is carried out for a period prior to the incorporation of such changes i.e. summer monsoon season (June-August) of 1984, and for the corresponding period after relevant changes were implemented (summer monsoon season of 1988).

Monsoon forecasts of the ECMWF demonstrate an increasing trend of forecast skill after the implementation of the major changes in parameterizations of radiation, convection and land-surface processes. Further, the upper level flow is found to be more predictable than that of the lower level and wind forecasts display a better skill than temperature. Apart from this, a notable increase in the magnitudes of persistence error statistics indicates that the monsoon circulation in the analysed fields became more intense with the introduction of changes in the operational forecasting system.

Although, considerable reduction in systematic errors of the Asian summer monsoon forecasts is observed (up to day-5) with the introduction of major changes in the treatment of physical processes, the nature of errors remain unchanged (by day-10). The forecast errors of temperature and moisture in the middle troposphere are also reduced due to the changes in treatment of longwave radiation. Moreover, the introduction of shallow convection helped it further by enhancing the vertical transports of heat and moisture from the lower troposphere. Though, the hydrological cycle in the operational forecasts appears to have enhanced with the major modifications and improvements to the physical parameterization schemes, certain regional peculiarities have developed in the simulated rainfall distribution over the monsoon region. Hence, this study suggests further attempts to improve the formulations of physical processes for further reduction of systematic forecast errors.

Keywords. Summer monsoon; parameterization of physical processes; systematic errors; general circulation model; forecast skill.

1. Introduction

The Asian summer monsoon is a spectacular manifestation of large scale atmospheric circulation anomalies arising out of the differential heating of land and sea, and also by the orographic features of Asia. The Asian summer monsoon is known to be a very complex circulation involving several feed-back mechanisms and physical processes which control its maintenance. As the rainfall during the summer monsoon accounts for nearly 80% of the annual rainfall of India, the simulation and prediction of the summer monsoon is an important task before Indian meteorologists. To accomplish the desired level of predictive skill by numerical models, it is necessary to understand the influence of different physical processes, and to parameterize them appropriately. In general, all physical processes are represented by expressions of conceptual formulations of unresolved processes in terms of resolvable quantities in large scale circulation models. Unfortunately, there are several conceptual weaknesses pertaining to the functional relationships of sub-grid scale physical processes and the large-scale features of the model. These limitations are mainly responsible for the development of simulation/prediction errors i.e. systematic errors in the large scale atmospheric models.

Most of the models tend to drift rapidly towards a preferred climatology, and this tendency dominates the forecast errors over the tropics. The nature and associated features of systematic errors of earlier versions of the ECMWF forecasting system have been extensively documented in several earlier studies (Heckley 1985a, b; Kanamitsu 1985; Mohanty *et al* 1984 and others). These errors were found to be resilient to changes in model and the associated forecasting system. A dramatic reduction of systematic errors in the prediction, together with a change in their characteristics, was observed when few major changes were introduced in physical parameterization schemes during May 1985 (Mohanty *et al* 1995). Due to several continuous changes introduced in different components of the ECMWF forecasting system during 1984–88, a marked improvement in the quality of the ECMWF forecasts was observed. But, the credit goes to those crucial modifications that were introduced in the formulations of physical parameterization schemes. Details of these changes and their effect on forecasts in general and monsoon circulations in particular, are described by Slingo *et al* (1988) and Tiedtke *et al* (1988). The latter describes several sets of forecast experiments involving both the old and new forecasting systems spread over a period of 20 days. A recent study by Mohanty *et al* (1995), which was made with the daily operational forecast products of the ECMWF for a longer period, demonstrated the dependence of systematic errors on seasonal scales. They are related to the parameterization of physical processes.

In this study, the performance of the ECMWF operational model, a state of the art GCM for medium range weather prediction over the entire globe is examined. The nature and other specific features associated with systematic forecast errors of the model are investigated by utilizing the archived daily operational forecasts of the summer monsoon seasons (June-August) [JJA] of 1984 and 1988. The main aim of this study is to analyse and illustrate the role of improved representation of physical processes in a forecast model. The significant model and analysis changes introduced during the period 1984–88 are briefly summarized below:

- A modified radiation scheme and stratospheric drag was introduced (Ritter 1985; Slingo and Ritter 1985) from December 1984. A more economical procedure for considering interactions between scattering and highly non-linear band absorption and emission patterns in the radiation parameterization scheme of the ECMWF model was a major improvement. This is achieved by a technique called Exponential Sum Fitting of Transmission (ESFT) proposed by Wiscombe and Evans (1977). It treats the gaseous absorption in an improved manner for infrared flux calculations. By virtue of this, the effect of gases is included directly in the flux calculations.

- A new T-106 model, with the introduction of a shallow convection scheme, a modified Kuo scheme and a new representation of cloudiness (Slingo *et al* 1988; Tiedtke *et al* 1988) from May 1985. The role of shallow convection is to increase the moisture flux out of the sub-tropical boundary layer, which allows the model to maintain a realistic trade wind inversion with a typical layered structure – boundary layer; cloud layer and an inversion. The increased moisture supplied to the boundary layer is transported into the tropics by trade winds. This increases the moisture source for deep cumulus convection and enhancement of the tropical hydrological cycle (Tiedtke *et al* 1979; Mohanty *et al* 1984).
- Atmospheric tides are thermally excited by the absorption of solar radiation by ozone and water vapour. The initialization condition of setting initial time tendencies of the gravity mode coefficients to zero is not appropriate for atmospheric tides. It is required to allow the gravity modes to propagate westward with the movement of sun instead of making stationary for the gravity mode projection of the tidal signal. Also, for diabatic initialization, the Mechenhauer condition is only appropriate if the forcing is quasi-stationary and is not clearly the case if the radiation scheme simulates the diurnal cycle of the sun. In addition, observational data reflect the presence of tidal activity in the analysis and thus imply transient tidal components in the model tendencies.

  Due to vertical distribution of ozone and water vapour, the diurnal zonal wave number 1 pressure wave is largely trapped where as the semi-diurnal wave can propagate vertically (Chapman and Lintzen 1970). Therefore, the semi-diurnal wave dominates the surface pressure field and amplitudes of 1·22 hpa and 0·22 hpa are found for the dominant first two gravest symmetric spherical harmonics of the semidiurnal surface pressure oscillation. The corresponding harmonics of the diurnal wave are 0·46 and 0·21 hpa respectively. Hence, it is necessary to exclude the tidal signal from the initialization following procedures implemented in the studies of Wergen (1987).
- Satellite derived precipitable water content (PWC), and modified (reduced) SYNOP data were used for humidity analysis (Illari 1989) from March 1988. In this procedure, an attempt is made to evaluate the quality of TIROS-N PWC mositure data provided by the National Environmental Satellite Data Information Service (NESDIS) through a statistical retrieval method for its subsequent use in humidity analysis. Appropriate collocation studies with these data have indicated that PWC data from satellites are comparable to radiosonde, and to the first guess data fields. Further, it is found that satellite data can describe total moisture in a column without a large bias, except in dry situations and upper tropospheric levels, where the PWC is low with an unacceptable large bias. The estimated error that can be ascribed to satellite PWC data varies from 15% in the tropics rising to 35% in the extra tropics.
- Model levels were increased to 19 (Simmons *et al* 1989) from 16 levels with threeadditional levels in the stratosphere above 50 hpa (10, 20, 30 hpa) from May 1986.
- Gravity wave drag parameterization was introduced (Miller and Palmer 1987) from July 1986.
- The parameterization of surface processes was revised (Blondin and Böttger 1987) from April 1987.

As most of the significant changes in the ECMWF forecasting system have taken place during 1985–87, the role of improved representation of physical processes for simulating the monsoon is analyzed by comparing the operational forecast errors of JJA 1988 with those of JJA 1984, prior to the introduction of major changes described above.

2. Assessment of the forecast skill

An objective assessment of the forecast fields is made by verifying them against the respective fields of initialized analyses which are used as initial values for the forecast model integration. A positively oriented skill score (s) for the forecasts over the monsoon region may be expressed by

$$s = \left[1 - \frac{RF^2}{RP^2}\right] 100$$

where RF represents the root mean square(rms) forecast error and RP represents the rms persistence error. This evaluation of the forecast skill has the advantage of measuring the skill over persistence.

The average skill scores of day-1, day-3 and day-5 forecasts over the monsoon region (5°N–32°N; 75°E–102·5°E) for vector winds and temperature at 200 hpa and 850 hpa are depicted in figure 1. In general, the monsoon forecasts display an increasing trend of forecast, and the predictive skill was found to have improved further after the introduction of major changes. The short range skill scores up to day-3 have a clear edge over the medium range scores except for 200 hpa vector winds where the day-3/5 scores are better than the day-1 scores. Further, the skill scores demonstrate that the summer monsoon is less predictive than the winter flow characteristics over the Indian region. Overall observations suggest that the upper level flow is more predictable than the lower level and wind forecasts have a better skill than temperatures. It is interesting to note that temperature forecasts have a better skill over the monsoon region compared to corresponding scores over the tropics (Mohanty *et al* 1995). Another important aspect of forecast skill is that the skill increases with the forecast period (day-1 to day-5) in the lower troposphere, and a reverse feature with a decrease in forecast skill with forecast period is found in the upper troposphere.

It is to be noted that dramatic dips in the forecast skill that were observed in wind scores of 1982 and temperature scores of 1983–1984 may be attributed to diverse factors, such as, the introduction of analyzed SST from the National Meteorological Centre (NMC), Washington D.C., USA in the model; the introduction of a spectral model and the introduction of a new radiation scheme (Heckley 1985). However, the 1982 dip in the wind score is weakly reflected in temperature scores, while the 1983–84 dips in the temperature scores are weakly reflected in the wind scores.

To analyse the impact of major changes in the operational forecasting system of the ECMWF more closely, the rms vector wind errors of the model and persistence forecasts, are examined as a function of forecast period for the summer (JJA) of 1984 and 1988. They were averaged over India and adjoining Southeast Asia (5°N–32°N; 70°E–102·5°E). We find that 1985 changes have contributed significantly towards an improvement of wind forecasts at 850 hpa after day-3 (figure 2). The forecast skill has improved considerably in the medium range (3–7 days). The impact of 1985 changes was not so significant at 200 hpa. In view of the increased spin-up problem in the forecasts of JJA-1988, the day-1 forecasts do not display any skill improvement. Due to

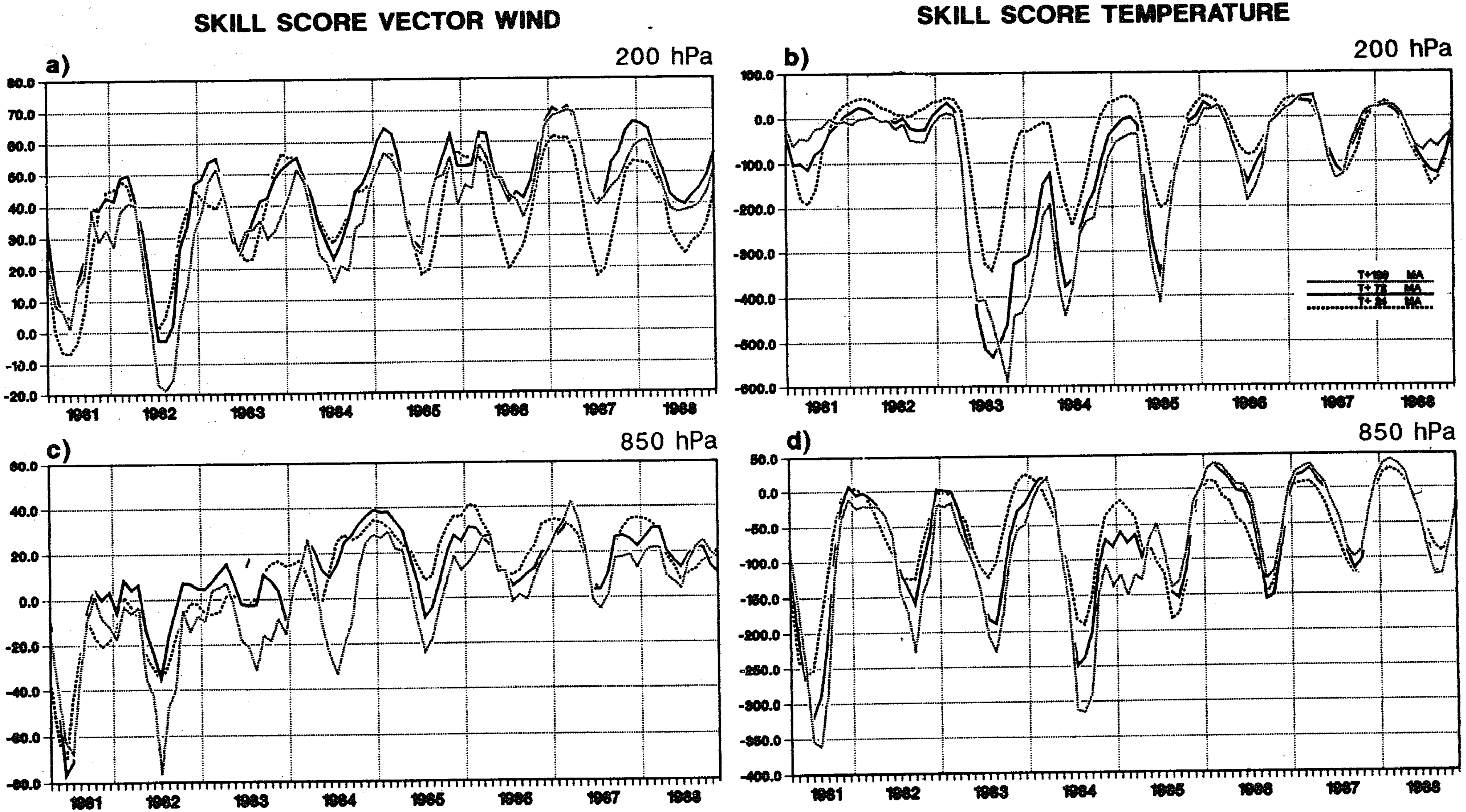
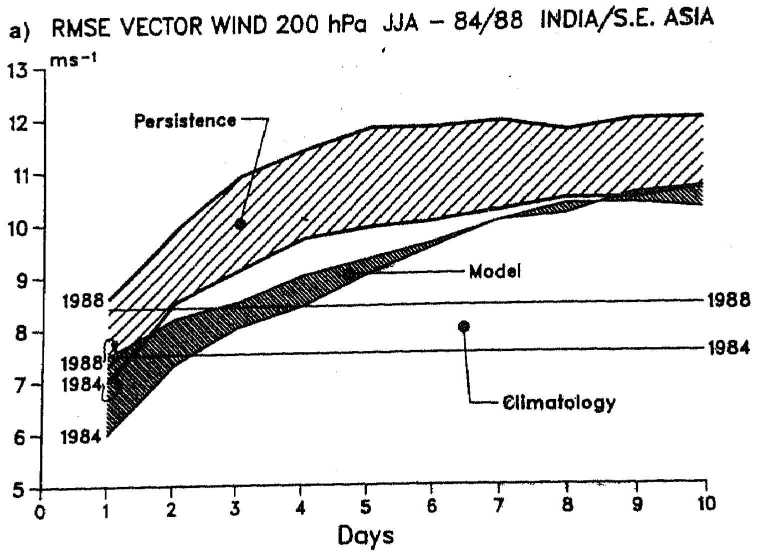
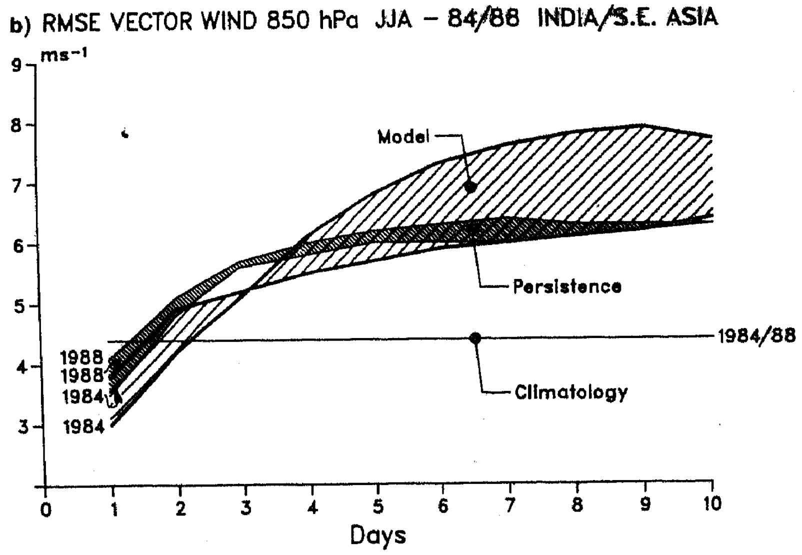


Figure 1a–d. Positively orientated skill score (3 month moving average) in percentage for day-1, day-3 and day-5 forecasts for India/S. East Asia (5°N–32°N and 75°E–102·5°E). **a**) vector wind at 200 hpa; **b**) temperature at 200 hpa; **c**) vector wind at 850 hpa; **d**) temperature at 850 hpa.



a) RMSE VECTOR WIND 200 hPa JJA – 84/88 INDIA/S.E. ASIA



b) RMSE VECTOR WIND 850 hPa JJA – 84/88 INDIA/S.E. ASIA

Figure 2a and **b.** Seasonal (JJA) mean of RMS vector wind error for India/S. East Asia vs forecast length for the years 1984 and 1988 [Units: $m s^{-1}$]. **a)** 200 hpa; **b)** 850 hpa.

an increase in horizontal resolution and the introduction of more accurate physical parameterization led to an enhancement of the hydrological cycle closer to reality (Slingo *et al* 1988; Tiedtke *et al* 1988). By such procedures, the spin up problem became more intense (figure 9) in the early stages of the forecast, and this could be responsible for the poor skill in day-1 forecasts of JJA-1988. An increase in the rms errors of persistence indicates that the circulation in the analyzed fields became more and more intense with the introduction of different changes in the operational forecasting system. When compared to the climatological variance, useful predictability was little reduced in 1988 compared to 1984. To achieve useful predictability, when measured against climatological variance over the monsoon region, it is desirable to have a model climatology which is more faithful to the real atmosphere (i.e., a rms value of $< 4\,\mathrm{ms}^{-1}$ 850 hpa and $< 9\,\mathrm{ms}^{-1}$ at 200 hpa). We believe that further improvements in the mechanics of parameterization are needed to achieve this objective.

3. Flow characteristics

A detailed examination of the flow characteristics in the ECMWF analyses and forecasts is made with the help of seasonal (JJA) mean fields of wind and the corresponding day-5 and day-10 forecasts. The impact of the changes that were introduced to the forecasting system during the period 1984–88 on the evolution of flow characteristics in the medium range scales is studied using the operational archives of JJA-1984 and JJA-1988.

The distribution of vector wind fields for analyses and, forecast errors at day-5 and day-10 for 850 hpa and 200 hpa are presented in figures 3–6. A comparison of the 850 hpa wind analyses of JJA-1988 (figure 3a) with that of JJA-1984 (figure 4a) shows that both are by and large similar, except over the Bay of Bengal where the flow is found

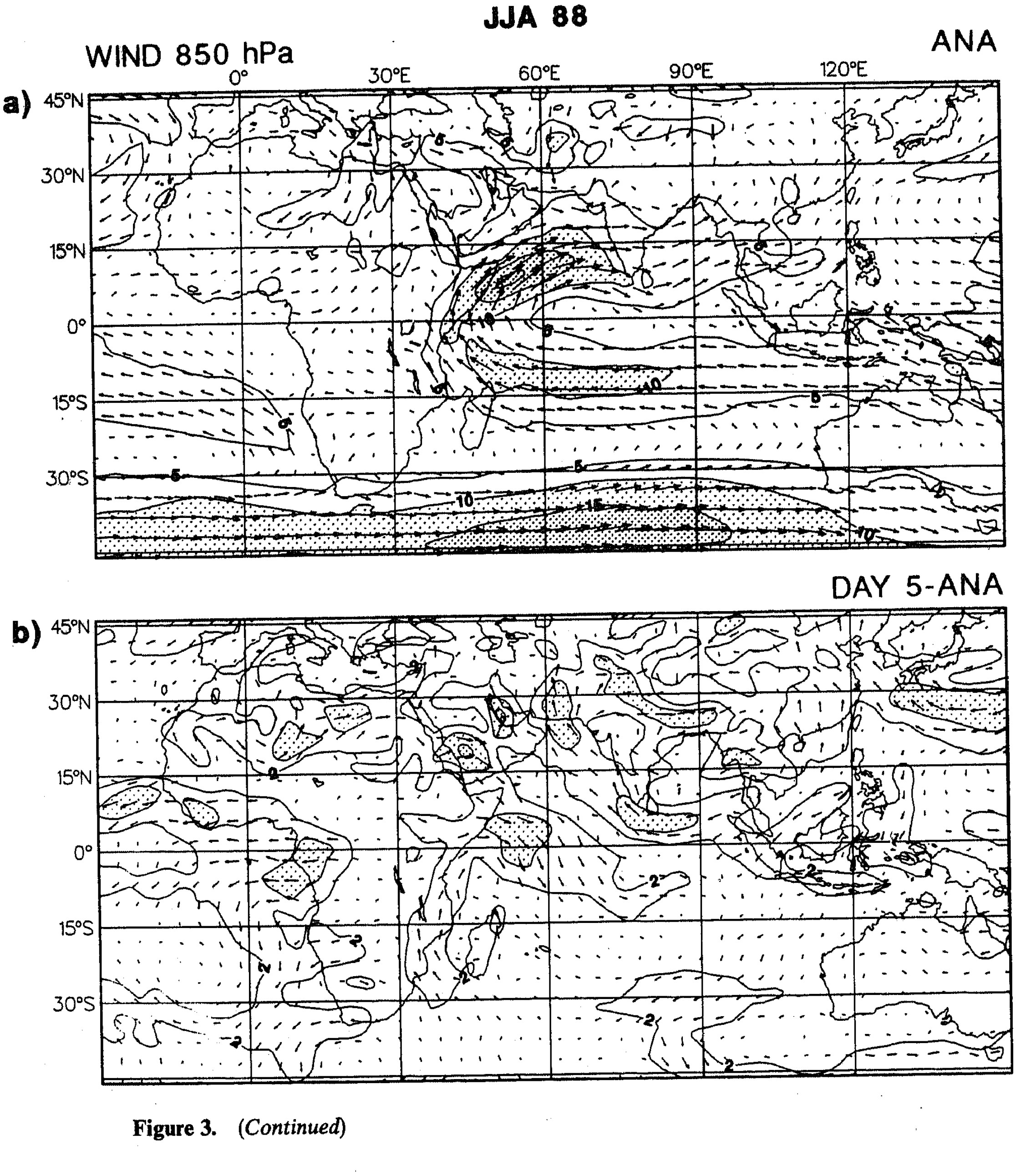


Figure 3. *(Continued)*

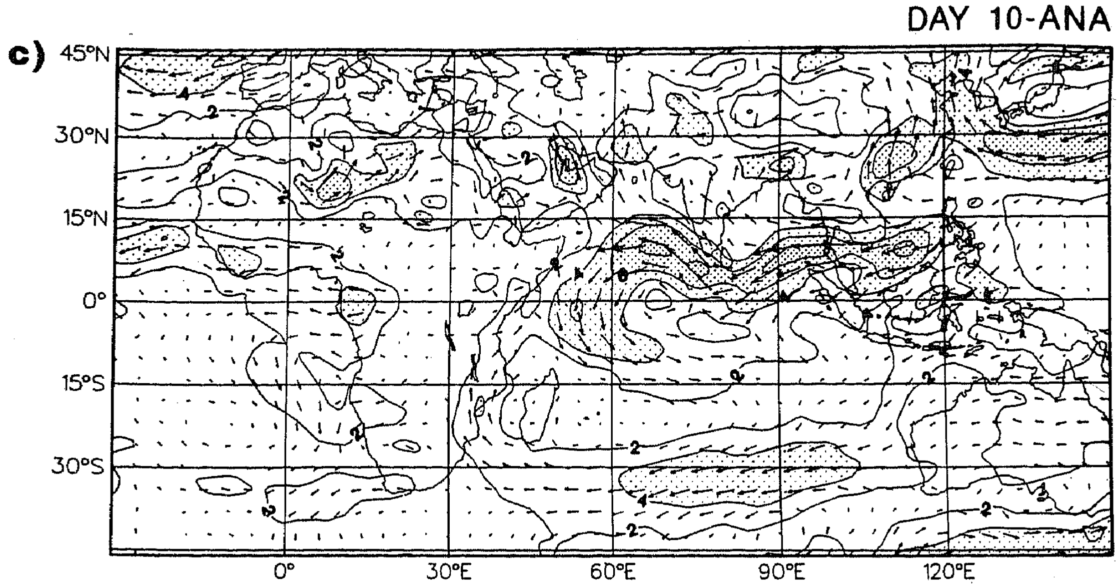


Figure 3a–c. Vector wind during JJA 1988 at 850 hpa. **a**) analysis, contour interval: 5 ms^{-1}; values over 10 ms^{-1} are shaded; **b**) day 5 forecast errors, contour interval: 2 ms^{-1}; errors greater than 4 ms^{-1} are shaded, **c**) day 10 forecast errors, contour interval: same as **b**).

to be weaker (by about 5 ms^{-1}) in 1988. On the other hand, the forecast error shows a remarkable improvement in the medium range flow forecasts of JJA-1988 with a reduction in the magnitude of forecast errors over India and its adjoining oceanic sectors. Some features of the ECMWF wind forecast errors, which are common to JJA-1988 and JJA-1984 forecasts are: ■ weak anticyclonic flow over the sub-tropical high at 0°E and 45°E and stronger anticyclonic flow over the southeast Indian Ocean (105°E); ■ weakening of cross-equatorial flow into the northern hemisphere to the

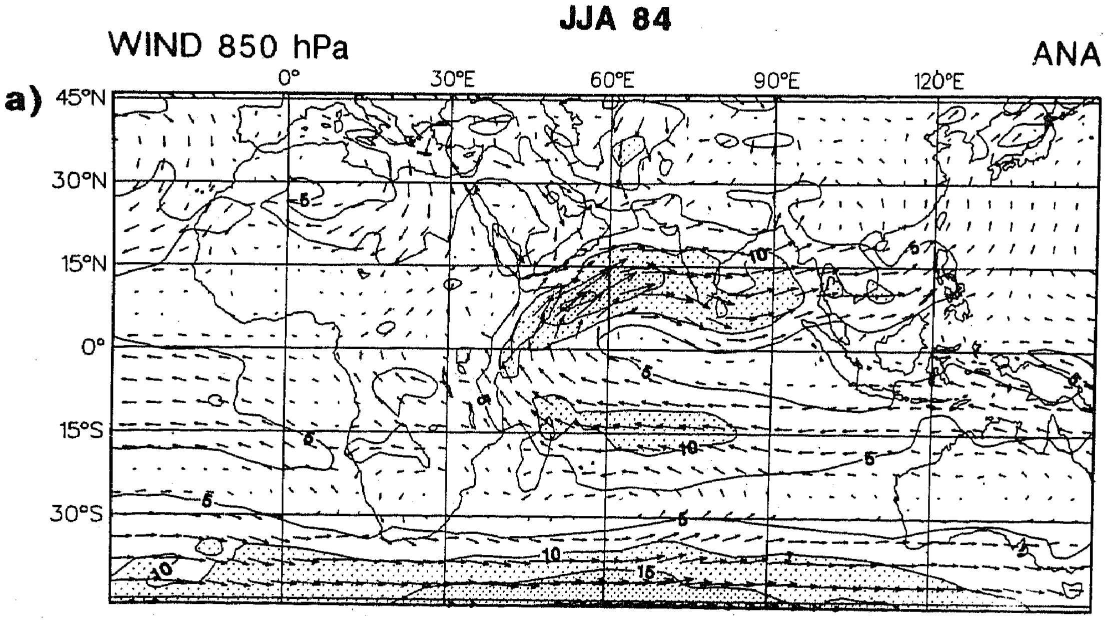


Figure 4. (*Continued*)

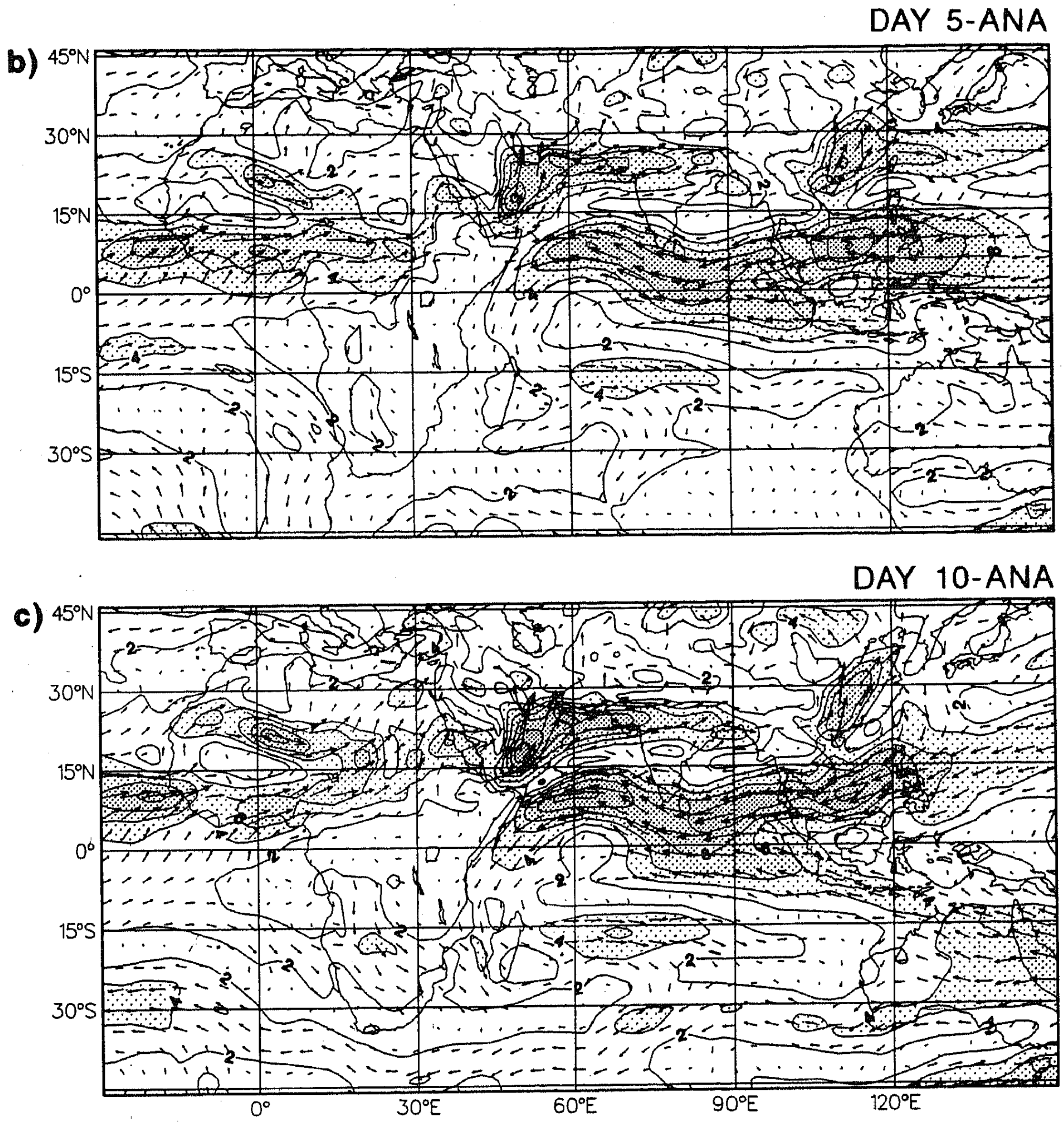


Figure 4a–c. Same as figure 3, but for JJA 1984.

north of Madagascar; ■ weakening of monsoon westerlies over the Arabian Sea, peninsular India and the Bay of Bengal. It may be noted in the day-5 forecast errors, a dramatic reduction is observed during JJA-1988 when compared at JJA-1984. We find that the forecast errors over the monsoon region continue to grow from day-5 to day-10. The nature of forecast errors at day-10 remain similar though the magnitude of errors of JJA-1984 are almost twice that of the corresponding errors of JJA-1988.

The upper level flow characteristics show that JJA-1988 had a strong core of easterlies (tropical easterly jet[TEJ]) over the Arabian Sea in contrast to a more elongated easterly core during JJA-1984. The distribution of forecast errors during JJA-1988 (figures 5b,c) show a net reduction compared to JJA-1984 (figures 6b,c), particularly over the Bay of Bengal and the Arabian Sea. A major change in day-5 forecast errors is found during 1988 over the Indonesian region, where a very large westerly error during JJA-1984 was transformed into an easterly error. Interestingly, by day-10, the Indonesian region is dominated by a westerly error, which is almost similar to 1984. Similarly, the introduction of major changes contributed to a weakening of the easterly flow(westerly error) over the equatorial Atlantic and strengthening of the easterly flow (easterly error) over the equatorial west Indian Ocean off the east coast of Africa in day-5/10 forecasts.

The sectoral mean (40°E–100°E) cross-sections of the zonal wind for analyses and day-5 forecast errors are presented in figure 7. The improved analyses during JJA-1988 (figures 7a, b) show that the TEJ over the monsoon region and sub-tropical westerly jets (STJ) are better represented. However, the low level Somali Jet at 850 hpa is weaker in the 1988 analyses when compared to 1984. Day-5 forecast errors of zonal wind during

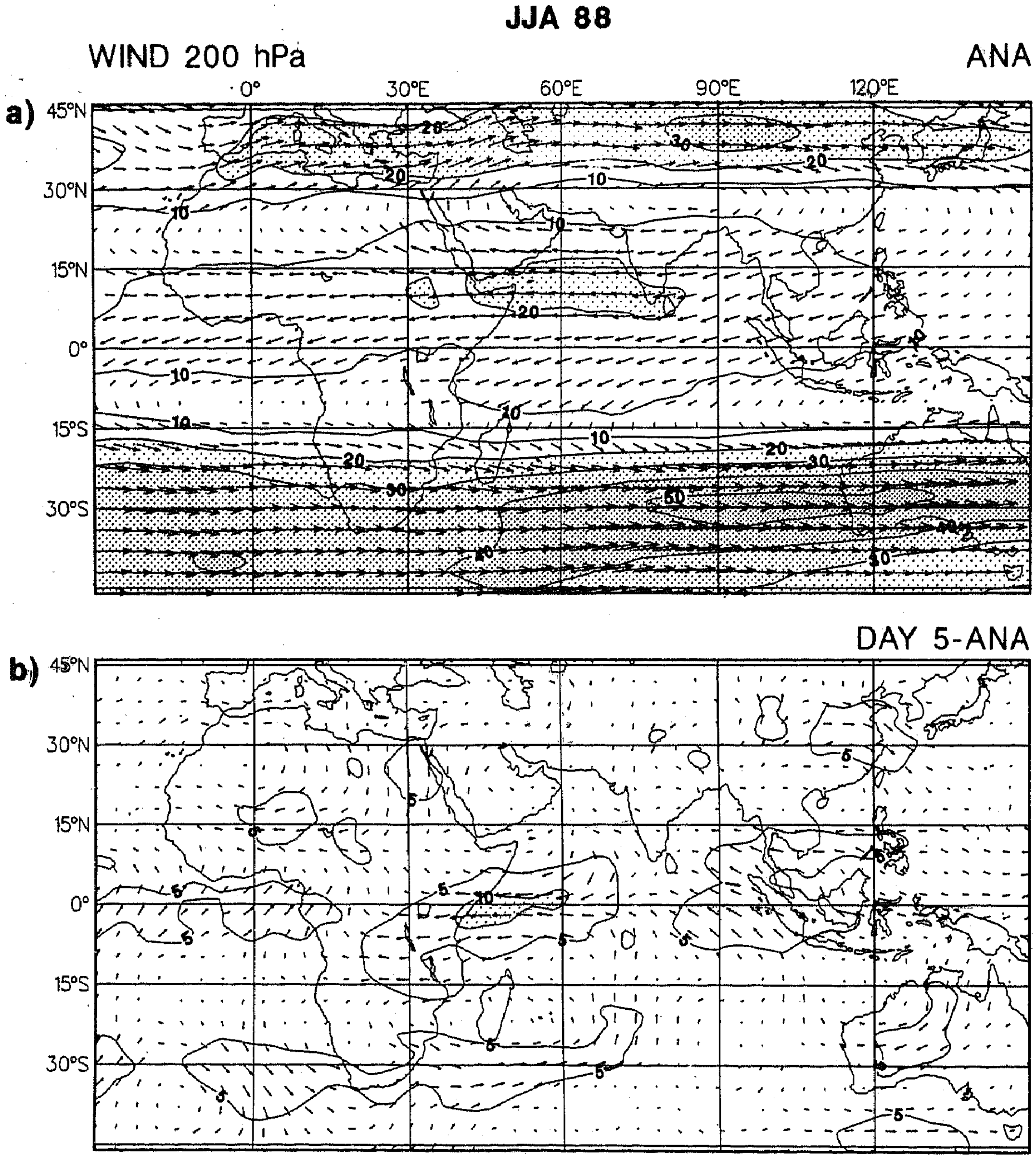


Figure 5. *(Continued)*

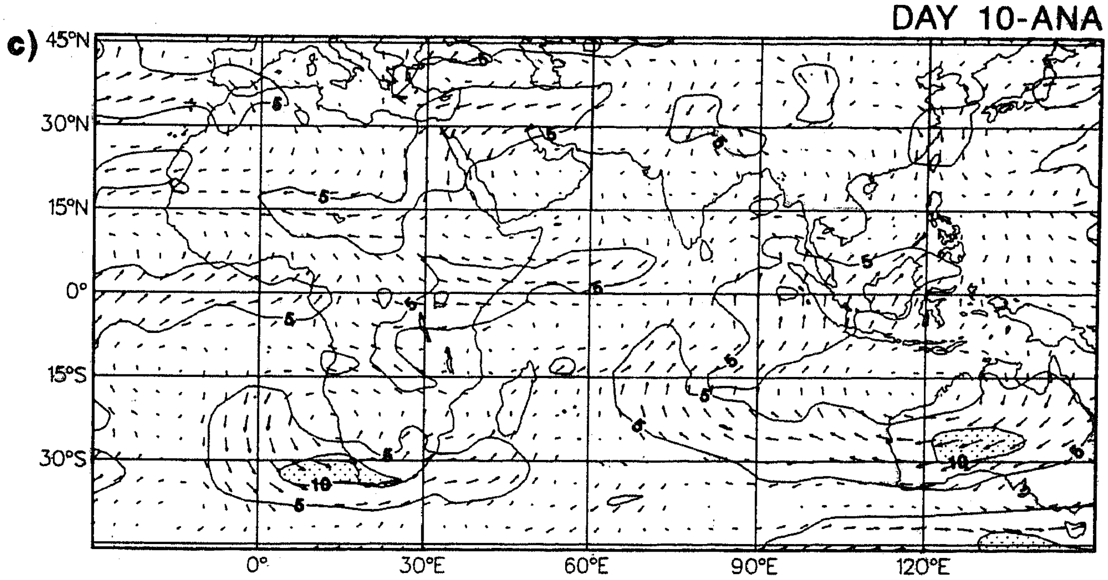


Figure 5a–c. Same as figure 4 but at 200 hpa and **a**) contour interval: 10 ms^{-1}; values over 20 ms^{-1} are shaded; **b**) and c) contour interval: 5 ms^{-1}; errors greater than 10 ms^{-1} are shaded.

1988 show a remarkable improvement with considerable reduction of easterly error (from about 5 ms^{-1} to 1 ms^{-1}) in the lower tropospheric regime and a westerly bias in the upper tropospheric easterly regime. Further, the maximum errors in the day-5 zonal wind forecasts are confined to the equatorial troposphere. In contrast to the major improvements observed in the day-5 forecasts in JJA-1988, the day-10 errors display similar errors as in JJA-1984, but with a reduction of error magnitudes (figures not shown). This particular feature of forecast errors suggest that the improvements

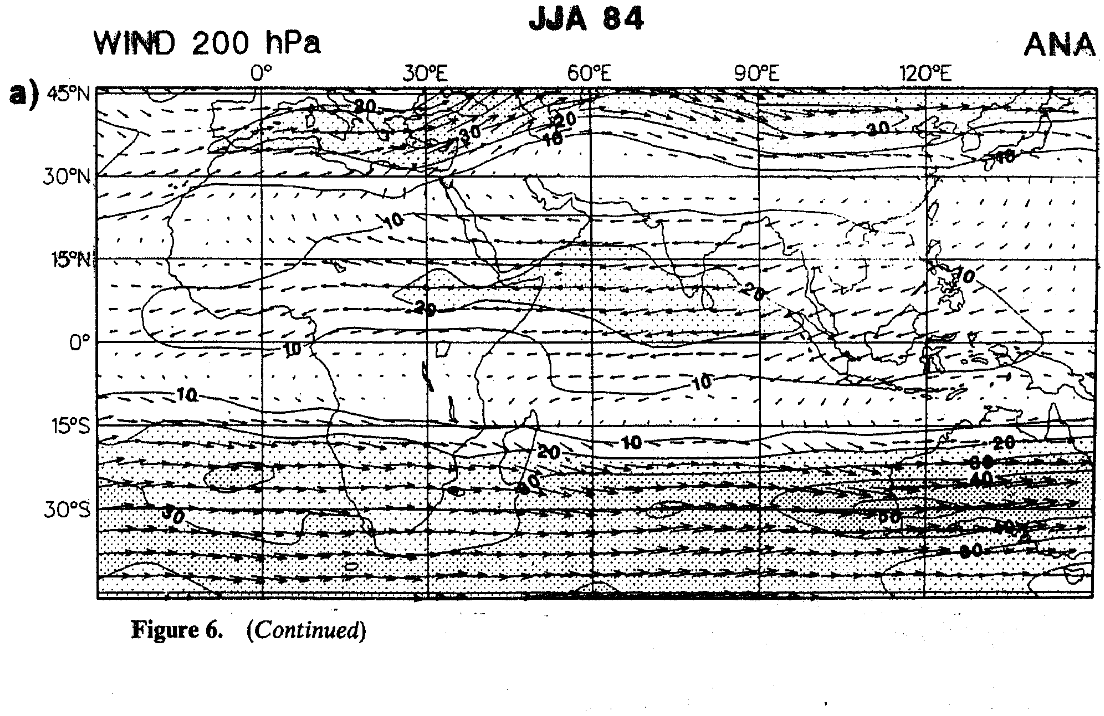


Figure 6. (*Continued*)

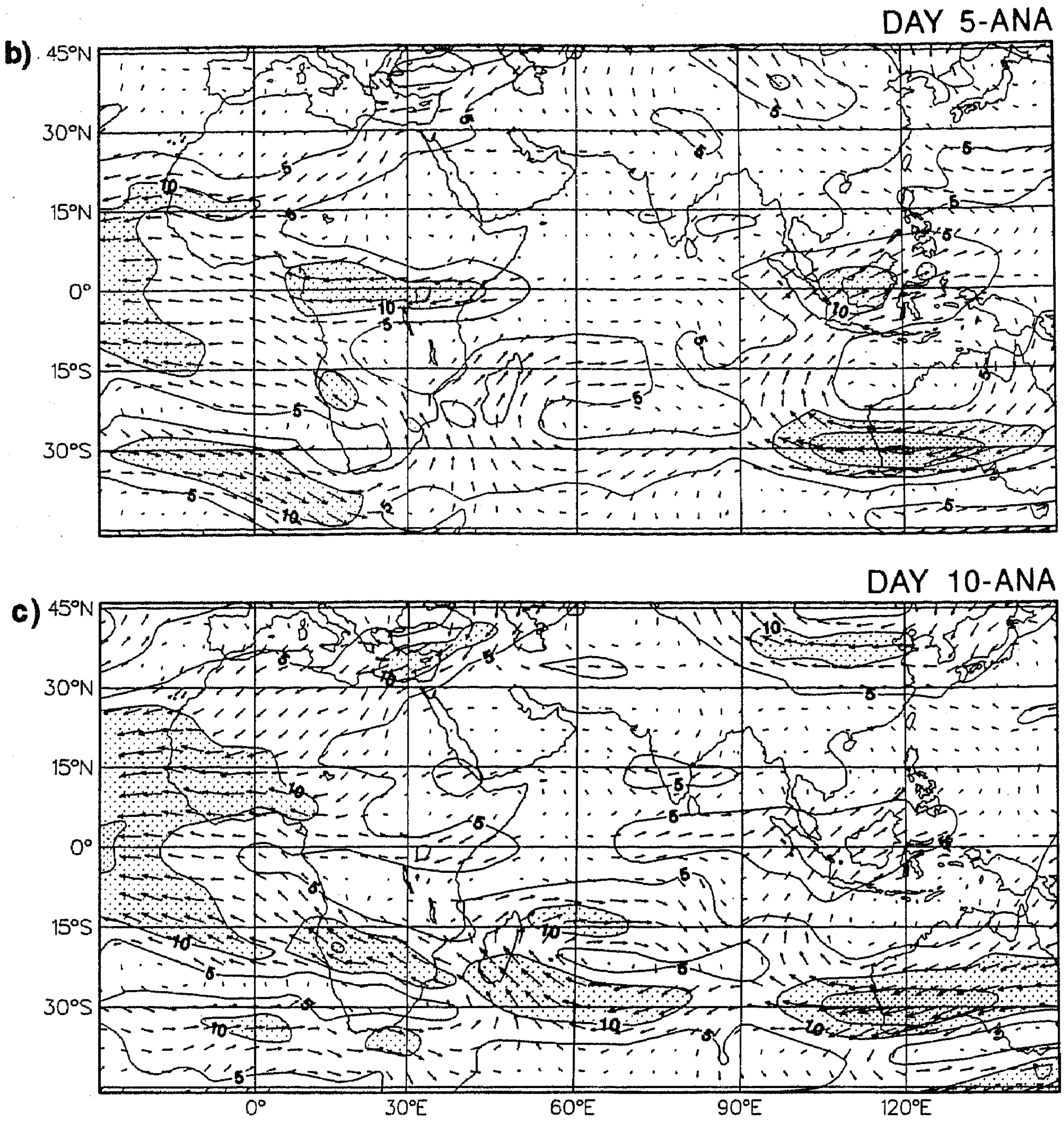


Figure 6a–c. Same as figure 5, but for JJA 1984.

introduced by way of physical parameterization schemes have contributed significantly to an improvement in prediction up to 5 days. Beyond that period, the model starts drifting towards its preferred climatology; consequently, the nature of the error remains almost similar to that of 1984.

The distribution of mean analyses and day-5 forecasts meridional wind in the form of sectoral mean vertical cross-sections are presented in figure 8. The meridional circulation over the monsoon is characterized by strong cross-equatorial flows with southerly flow into the northern hemisphere in the lower levels, and northerly flow back into the southern hemisphere in the upper levels. The upper level meridional circulation is found to be very intense during JJA-1988 compared to that of JJA-1984, though the intensity of the lower level southerly flow is maintained at the same level. With the introduction of major changes in the parameterization of physical processes,

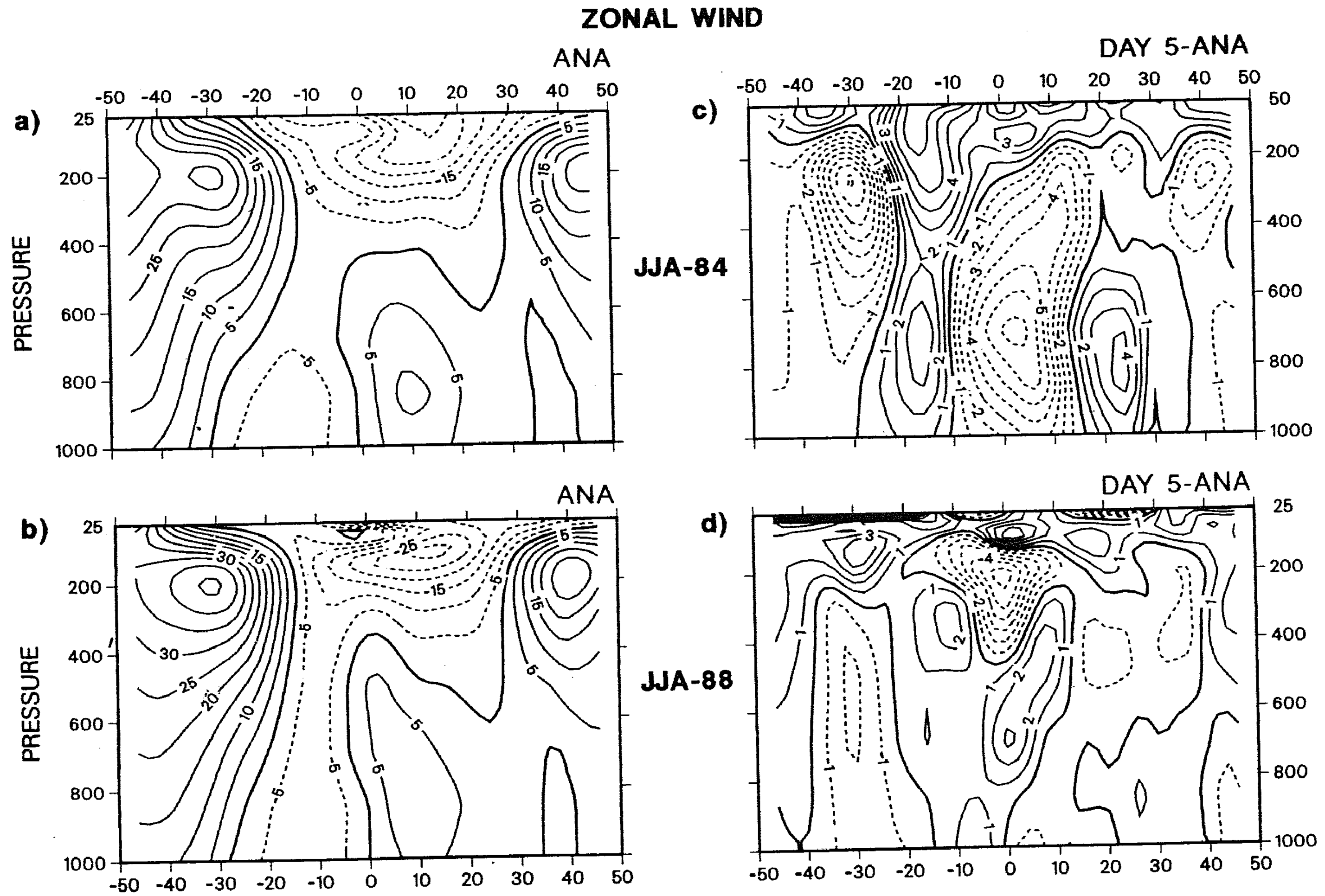


Figure 7a–d. Sectorial mean (45°E–100°E) cross sections of zonal wind [Units: ms^{-1}]. **a)** analysis for JJA 1984; **b)** forecast errors at day 5 for JJA 1984; **c)** analysis for JJA 1988; **d)** forecast errors at day 5 for JJA 1988.

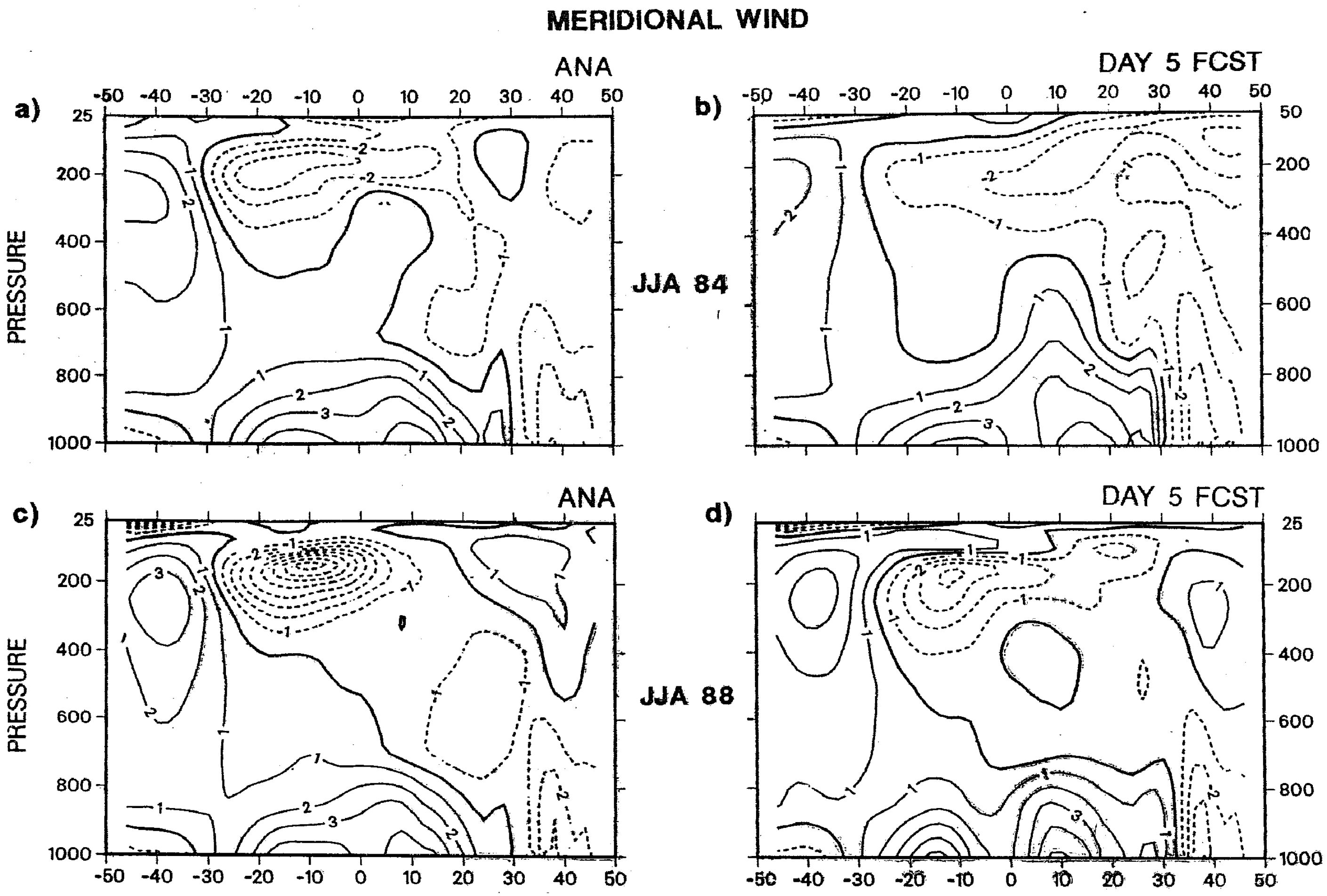


Figure 8a–d. Same as figure 7, but for meridional wind.

it is found that the prediction of meridional circulation has improved considerably. The strong narrow core of northerly flow into the southern hemisphere, which was weaker and elongated in JJA-1984, is better represented during JJA-1988, Further, a weak southerly bias in the lower troposphere and a weak northerly bias in the upper troposphere are the important features of the meridional wind forecasts.

4. Precipitation and evaporation

The notable changes in parameterization of deep cumulus convection were made during 1985. It was found that before shallow convection was introduced, the planetary boundary layer (PBL) was too shallow and too moist. It was surmounted by an excessive dry inversion. As a consequence the moisture supply (evaporation) from the oceans was too weak as the lower part of the PBL was almost saturated. On some occasions, this was even responsible for unrealistic and excessive large scale precipitation in the forecast fields. This suppresses the growth of deep cumulus convection and affects the diabatic heat distribution in the mid-tropospheric layers. More effective treatment of shallow convection increased the vertical moisture transports from the PBL into the cloud layer above. This supports the growth of deep convective activity, which further intensifies the moisture supply through evaporation from the sea. Thus, the increased moisture source together with a revision of the parameterization of deep cumulus convection generates greater rainfall.

The evolution of precipitation and evaporation, which are the main components of the hydrological budget in the seasonal mean operational forecasts, are averaged over the region (30°E–100°E; 30°N–30°S) for JJA-1984 and JJA-1988. This is depicted in figure 9. The introduction of shallow convection has enhanced the predicted rainfall and corresponding evaporation considerably, but we find that the operational forecasts still suffer from the spin-up problem which is worse during JJA-1988. The day-1, day-3, day-5 and day-10 forecasts of total precipitation in JJA-1988 and JJA-1984 are presented in figures 10 and 11. The precipitation patterns are presented as accumulated values for a period of past 24 hrs of the model's integration. We find that the rainfall is intensified over the landmass of the monsoon region during JJA-1988 compared to the corresponding period in JJA-1984. Interestingly, the day-1 precipitation of JJA-1988 is found to be very similar to seasonal climatology, and to the derived estimates from the outgoing longwave radiation (figure 12). During JJA-1988, however, precipitation magnitudes over the equatorial tropics are found to decrease considerably with the increase in forecast period. This leads to a split in the rain belt and the development of two rainfall maxima on either side of the equatorial tropics over the Indian Ocean. The rainfall during JJA-1984 is generally weak and differs considerably from mean seasonal climatology, but it has no split in the rainfall belt.

The geographical distribution of predicted evaporation (mm day^{-1}) for JJA-1984 and JJA-1988 are shown in figure 13 and presented in the same manner as that of precipitation estimates in the form of accumulated figures for the past 24 hrs of the model integration. An enhancement of evaporation is observed in the forecasts of JJA-1988 when compared with those of JJA-1984. We also note that the predicted evaporation patterns of JJA-1988 compare well with the seasonal climatology (figure 12). On the other hand, evaporation was reducing considerably over the tropical south Indian Ocean from day-1 to day-5 during JJA-1984 by not allowing the moisture to go

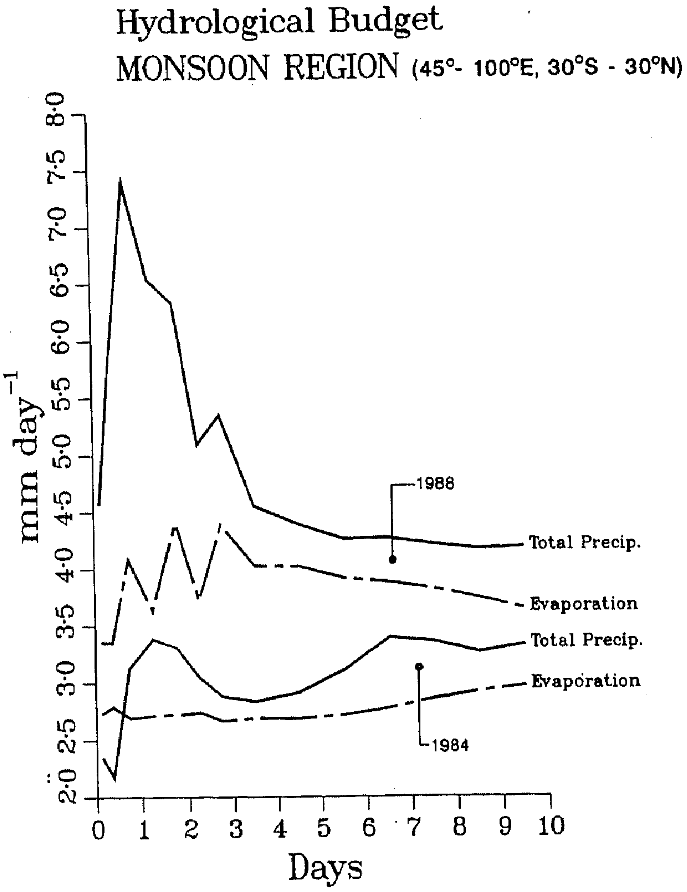


Figure 9. Mean precipitation and evaporation for the Indian summer monsoon region (45°E–100°E and 30°N–30°S) during the course of the forecasts in JJA 1984 and JJA 1988. Solid line – precipitation; dashed line – evaporation [Units: mm day^{-1}].

up. This discrepancy was removed with the introduction of the shallow convection which has enhanced the evaporation all over the oceanic regions. The most significant enhancement in evaporation occur over the Arabian Sea and the Bay of Bengal. The increase is above 40% in day-1 and above 30% in day-5 forecasts. It may be noted that the enhancement of evaporation over the tropical south Indian Ocean and Bay of Bengal is unrealistic to a certain extent and this may be responsible for a split in the rain belt in the JJA-1988 forecasts (figure 10).

The hydrological cycle of the model appears to have enhanced in general during JJA-1988 with modifications and improvements in parameterization of deep cumulus convection, radiation and the introduction of shallow convection. But, certain regional peculiarities have developed in the course of model integration over the monsoon region.

5. Temperature and moisture

The discussion of the results so far indicate that the thermal state of the model atmosphere would change considerably with the introduction of a shallow convection scheme in the model, particularly due to its impact on the model's hydrological cycle

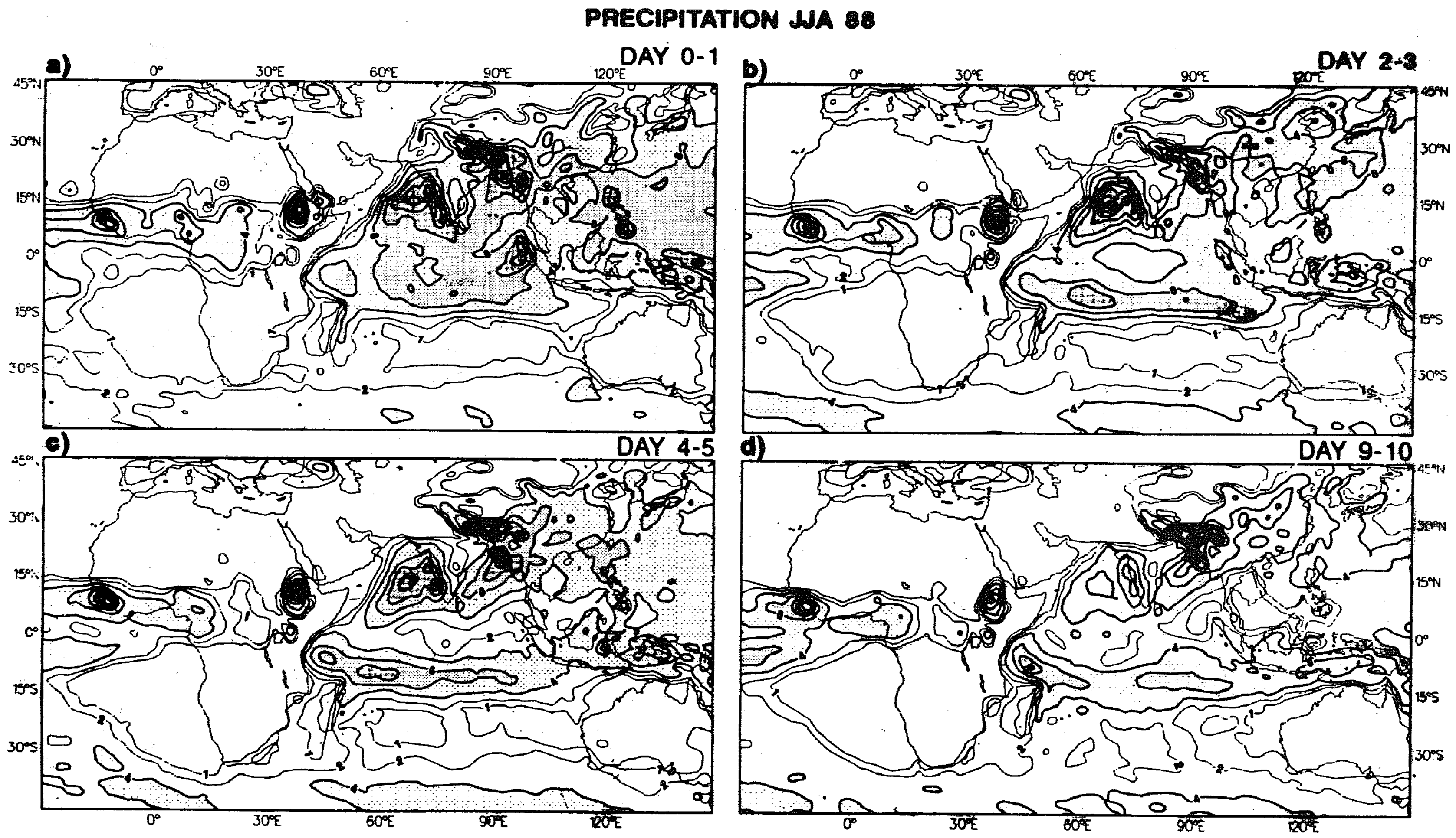


Figure 10a–d. Total precipitation during the course of the forecast in JJA 1988 [Units: mm day^{-1}]. **a)** day 0–1; **b)** day 2–3; **c)** day 4–5; **d)** day 9–10. Contours at 1, 2, 4, 8, 12, 16 and 20 mm day^{-1}, areas with more than 4 mm day^{-1} are shaded.

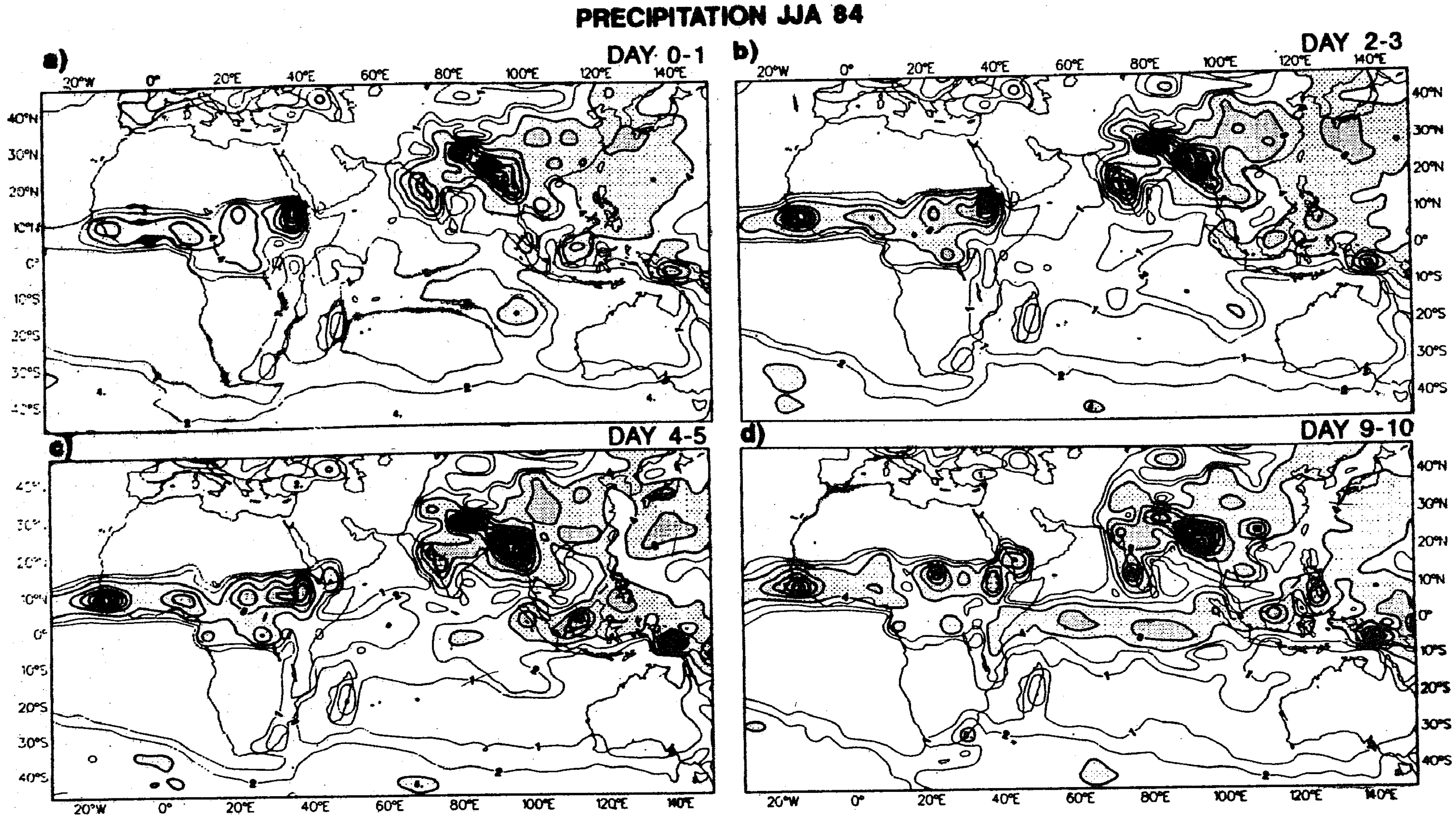


Figure 11a–d. Same as figure 10, but for JJA 1984.

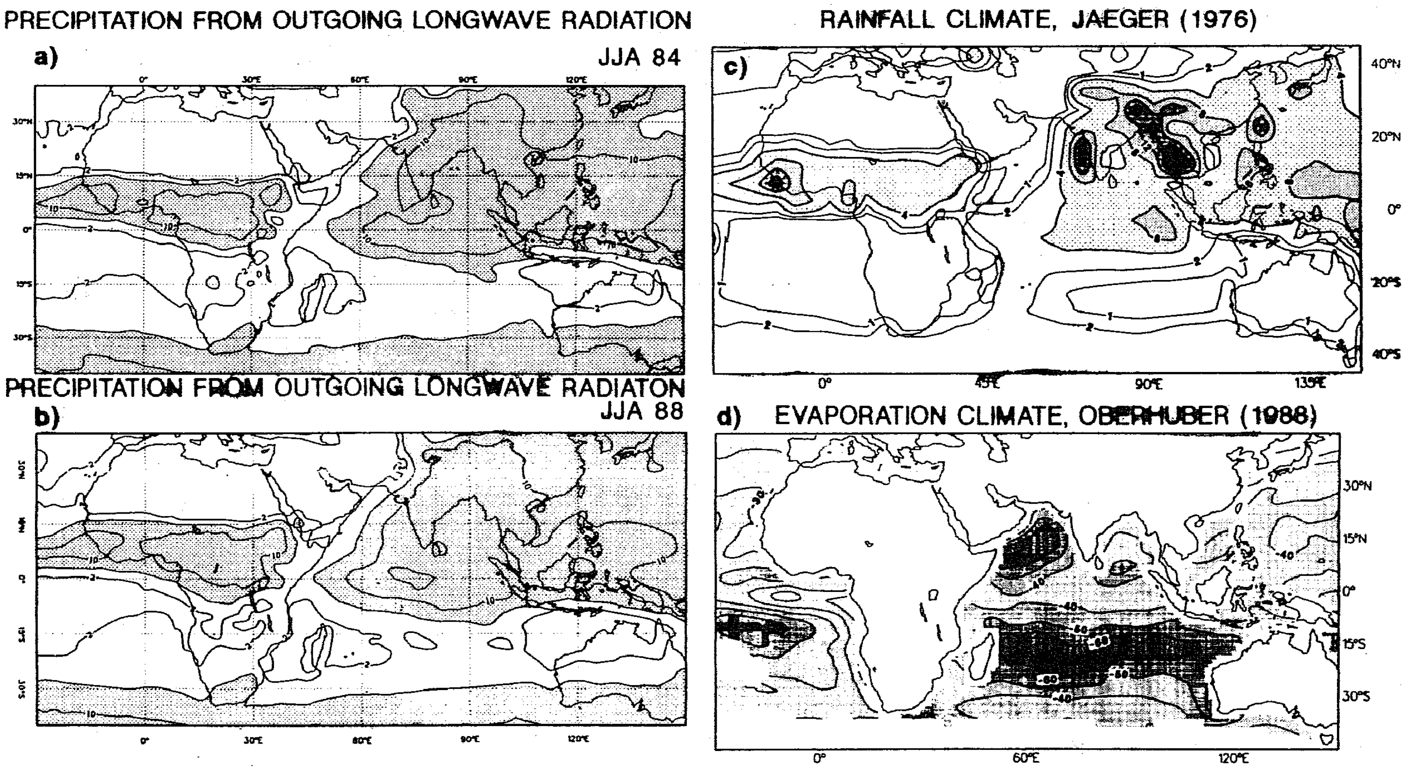


Figure 12a–d. Climatological values of precipitation and evaporation and OLR estimates of total precipitation. [Units: precipitation in mm day^{-1}; evaporation in 10^{-1} mm day^{-1}]; **a)** precipitation for JJA 1984 derived from OLR as observed by satellite; contours at 2, 5, 10 and 20 mm day^{-1}; areas with more than 5 mm day^{-1} are shaded; **b)** same as a) but for JJA 1988; **c)** JJA precipitation climatology from Jaeger (1976) contours at 1, 2, 4, 8, 12, 16 and 20 mm day^{-1}; areas with more than 4 mm day^{-1} are shaded; **d)** JJA evaporation climatology over the ocean from Oberhuber (1988), contour interval: 1 mm day^{-1}; values over 1 mm day^{-1} are shaded.

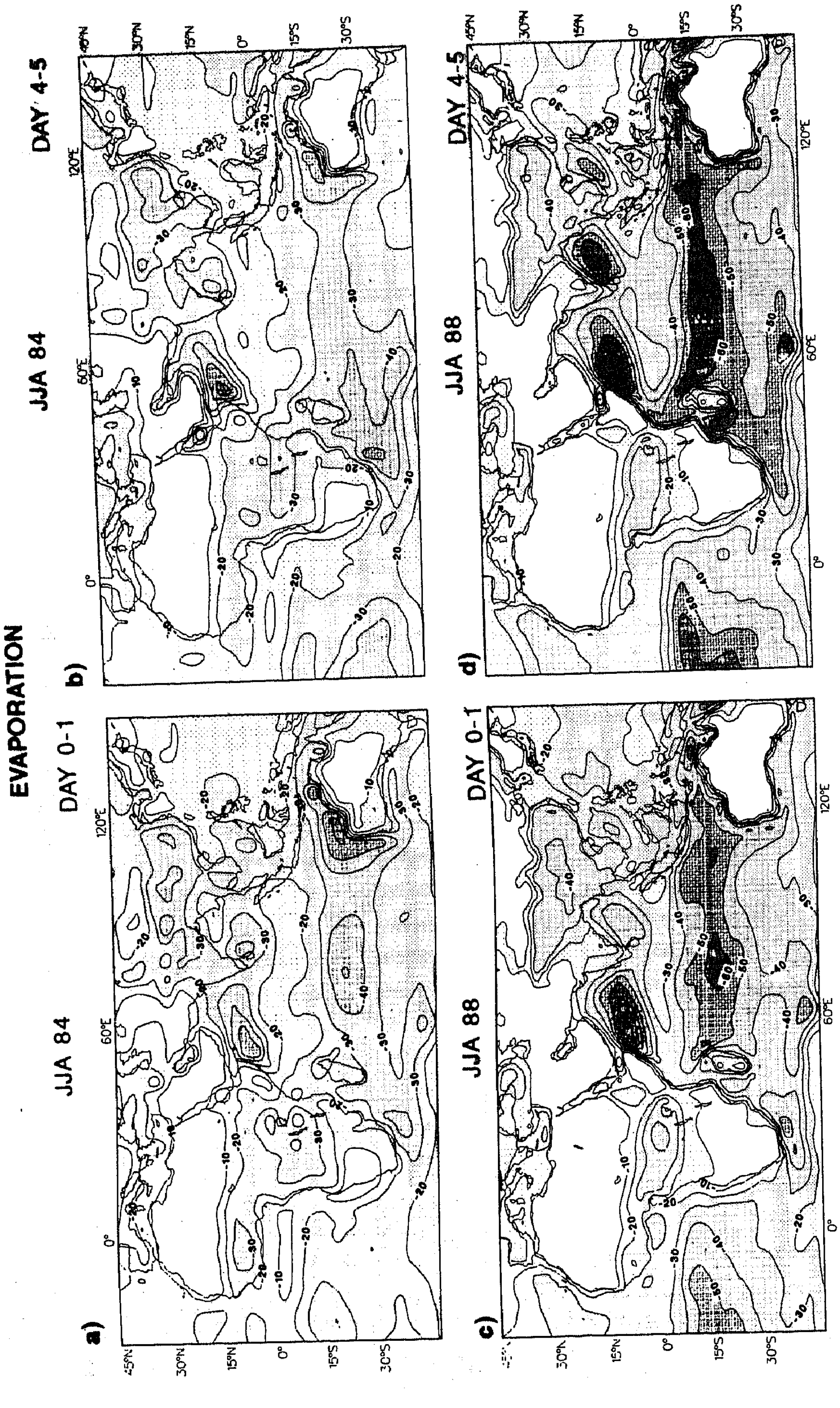


Figure 13a–d. Evaporation [Units: 10^{-1} mm day^{-1}]. **a)** day 0–1 for JJA 1984; **b)** day 4–5 for JJA 1984; **c)** day 0–1 for JJA 1988; **d)** day 4–5 for JJA 1988. Contour interval: 1 mm day^{-1}; values over 1 mm day^{-1} are shaded.

and increased vertical transports of heat and moisture from the lower troposphere. Moreover, the revised radiation parameterization schemes can contribute to the energy balance of the model. The extent to which these changes have contributed to the temperature and moisture forecasts is an interesting aspect for study.

The general structure of the temperature and moisture forecast errors at day-5 are analyzed through their corresponding sectorial mean vertical cross-sections shown in figure 14. We note that the temperature errors have been considerably reduced in JJA-1988 forecasts as compared to those of JJA-1984. This reduction in forecast errors is largely accounted for by the changes incorporated in the treatment of long-wave radiation. This has contributed to the reduction of errors in the monsoon tropospheric layers. Also, the introduction of shallow convection lead to the reduction of tropospheric cooling in the middle troposphere in view of the enhanced diabatic heating due to condensation mechanism thus offsetting the radiative cooling of the atmosphere. However, the lower tropospheric cooling below 800 hpa still persists in the JJA-1988 forecasts.

As far as the moisture forecasts are concerned, the modifications in the parameterization of cumulus convection have resulted into the drying up of the model atmosphere (figures 14c, d). The impact of the above changes were such that more of the available moisture in a vertical column went into heating, and less was available for moistening the environment. This leads to the drying up of the troposphere.

6. Divergent circulation

The summer monsoon circulation represents a large scale convergence of mass and moisture surrounding the Indian sub-continent and adjoining parts in the lower levels, and a strong upper level divergence aloft. A strong divergent center is located around South Africa and Madagascar at 850 hpa which controls the strength of the cross-equatorial flow and moisture transport from the Southern Hemisphere to the monsoon region. Another major center of low level convergence is located over northeast India, Burma and the adjoining land mass. It is an active zone of copious rainfall during the monsoon season. An exactly opposite circulation is observed in the upper troposphere (200 hpa) with a strong center of divergence over the southeast Asia and the West Pacific, with a strong convergence regime over the Indian Ocean to the south of equator. The above mentioned active zones of divergence/convergence drive the north-south/and east-west divergent circulations, which are crucial for the monsoon.

An analysis of the divergent circulation as seen in the operational products of JJA-1988 and JJA-1984 are shown in figures 15-16. We find that the model is tending to weaken the dominant centers of action over the summer monsoon region. The weakening of the upper level divergent center during JJA-1988 is due to the appearance of a strong anomalous divergent center in the forecasts over the Indonesian region, whereas similar weakening in JJA-1984 forecasts is due to the presence of an elongated anomalous zone of divergence at 200 hpa. Similarly, certain anomalous zones of divergence are produced in the forecasts of JJA-1984 and JJA-1988 at 850 hpa.

7. Vertical circulations

It is interesting to study the vertical motion which indicate the large scale ascent/descent in the troposphere. The vertical motion of JJA-1988 are found to be generally intense

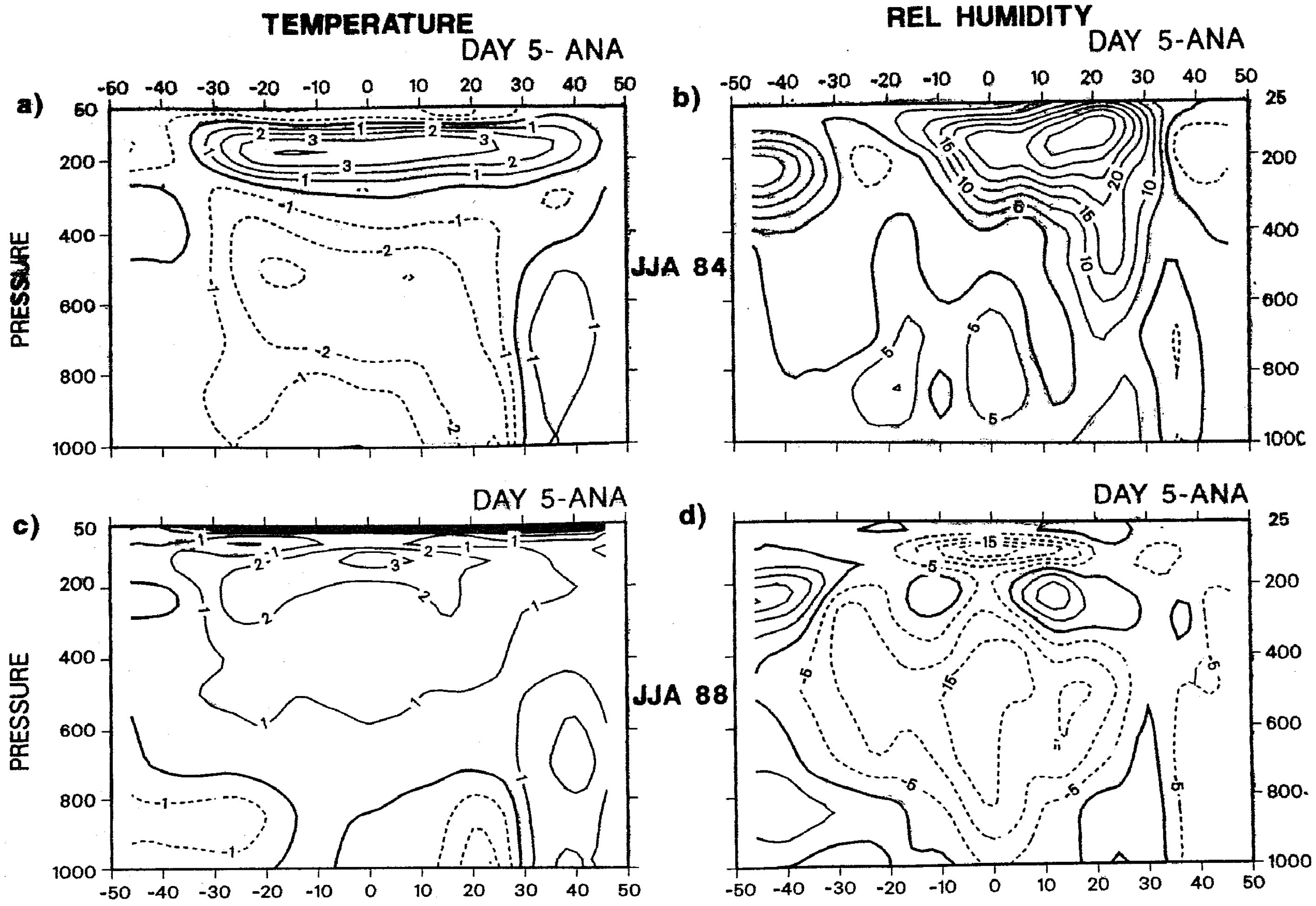


Figure 14a–d. Sectorial mean (45°E–100°E) cross sections of forecast errors at day 5. **a)** temperature for JJA 1984; **b)** relative humidity for JJA 1984; **c)** temperature for JJA 1988; **d)** relative humidity for JJA 1988. [Units: temperature in °C and relative humidity in %].

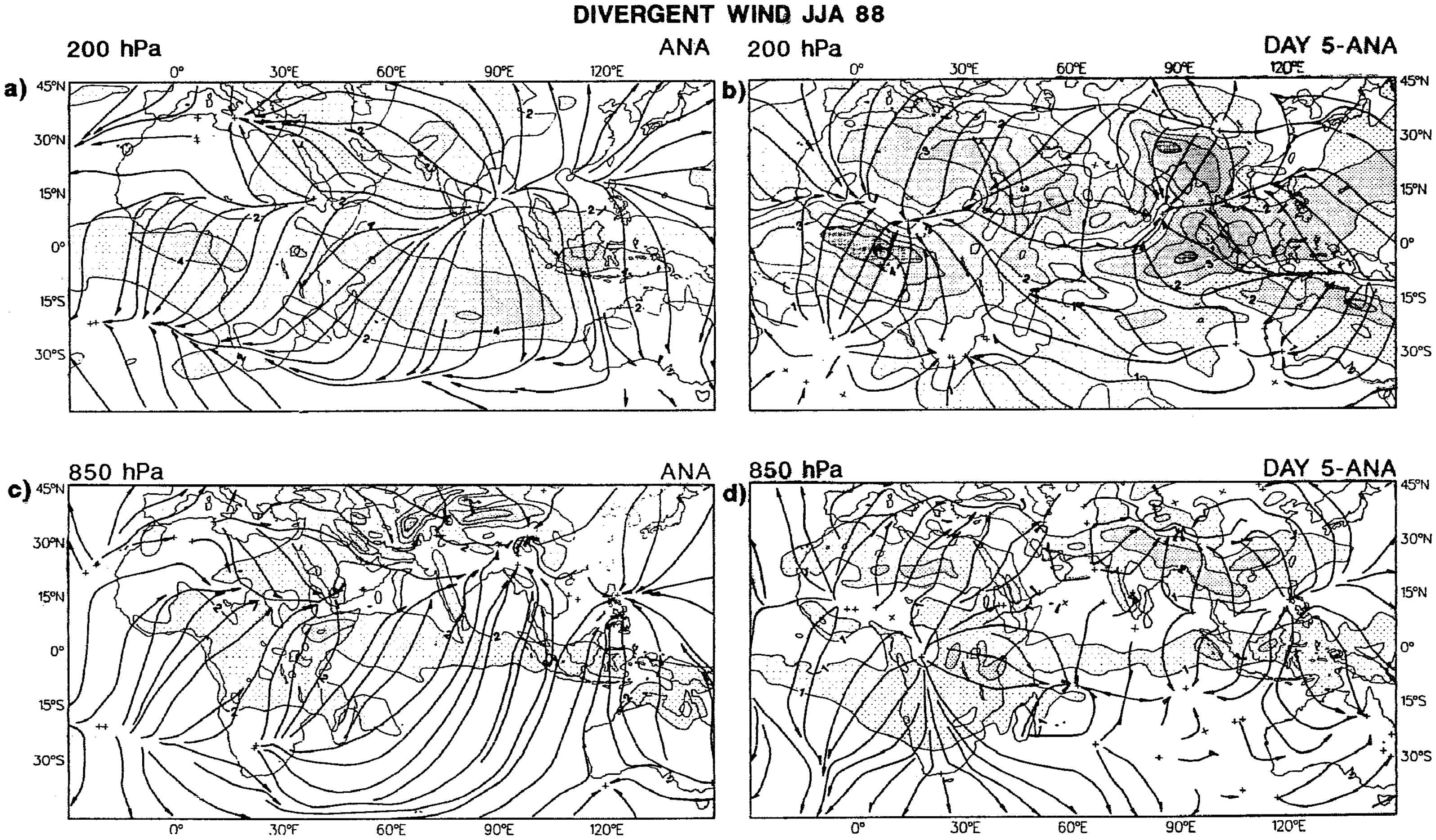


Figure 15a–d. Mean divergent wind during JJA 1988 at 200 hpa. [Units: ms^{-1}]. **a)** analysis, contour interval 2 ms^{-1}, values over 2 ms^{-1} are shaded; **b)** day 5 forecast errors at 200 hpa, contour interval 1 ms^{-1}, errors larger than 1 ms^{-1} are shaded; **c)** same as a) but for 850 hpa; **d)** same as (b) but for 850 hpa.

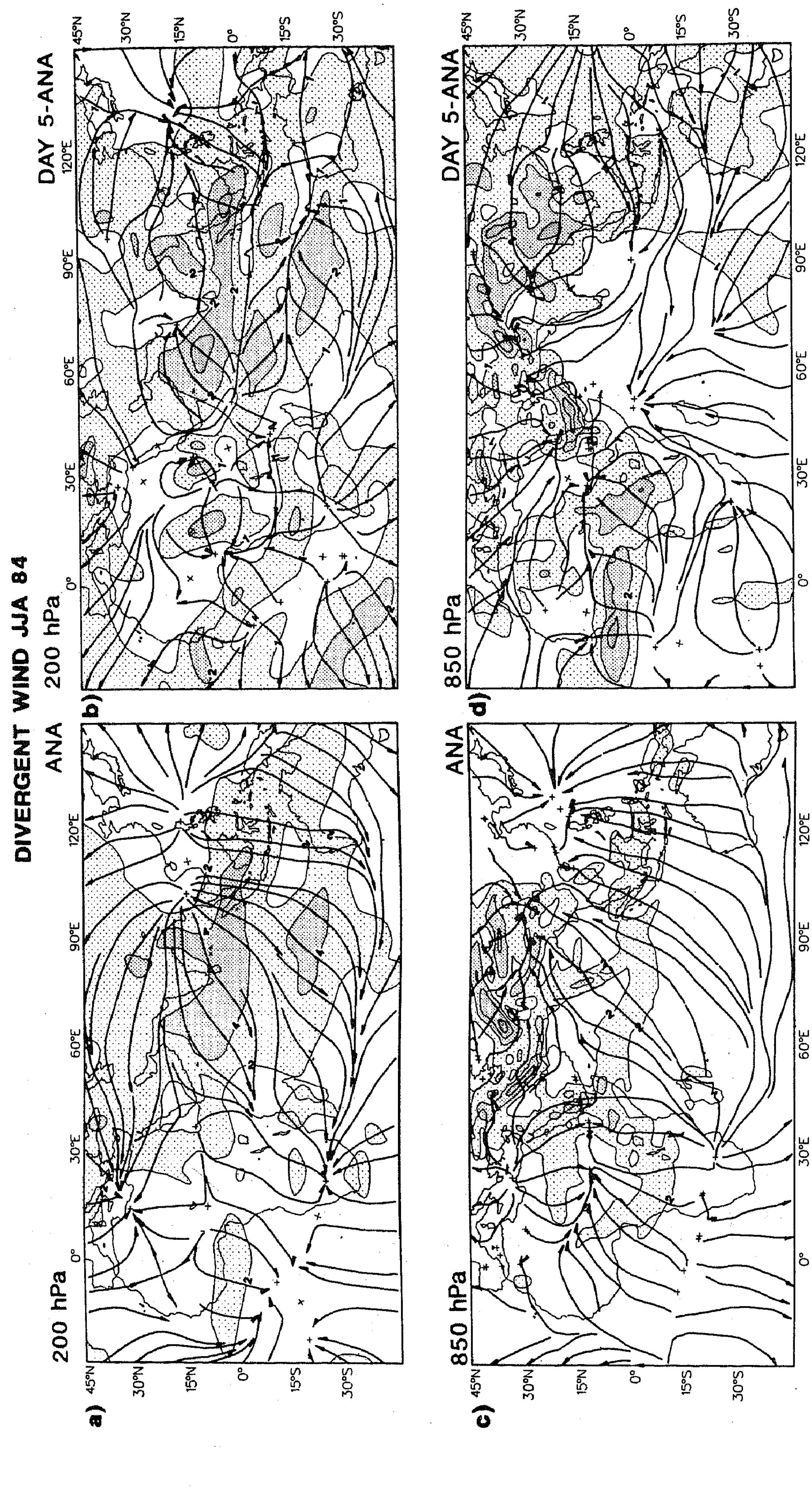


Figure 16a–d. Same as figure 15, but for JJA 1984.

indicating a more vigorous vertical circulation consistent with the more active hydrological cycle as discussed earlier. Moreover, the forecasts are found to be similarly more intense during JJA-1988. In particular, the descending motion seen during JJA-1984 (figure 17a-d) over the Bay of Bengal and South China Sea is more intense and

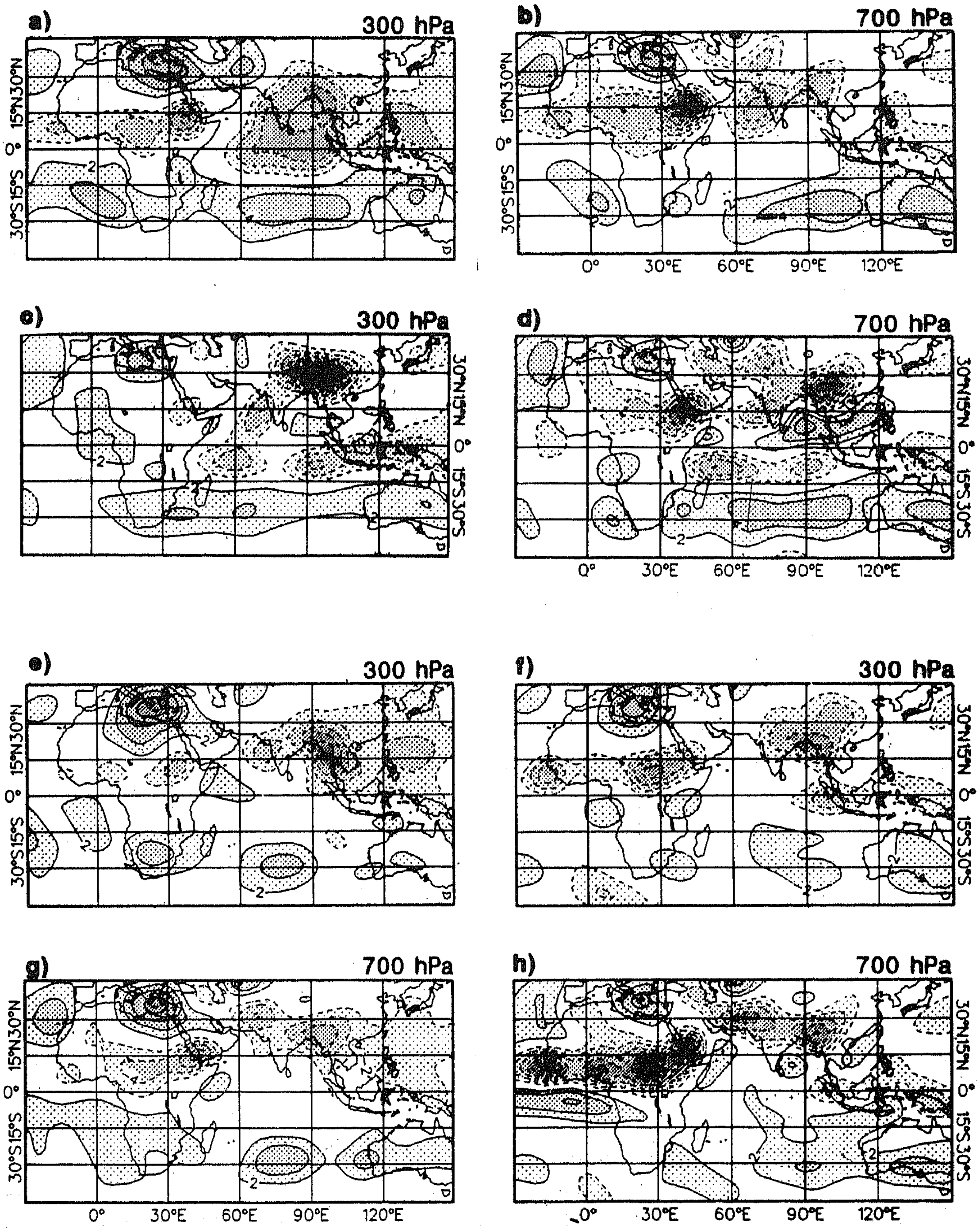


Figure 17a–h. Omega field [Units: 10^{-2} Pa s^{-1}]. **a)** analysis at 300 hpa; **b)** analysis at 700 hpa; **c)** day-5 forecast at 300 hpa; **d)** day-5 forecast at 700 hpa for JJA-1988; **e-h)** same as **(a-d)** but for JJA-1984. Contour interval: 2×10^{-2} Pa s^{-1}; areas with more than $| \pm 2 \times 10^{-2}$ Pa s$^{-1}|$ are shaded and dashed contours indicate negative values (ascent).

widespread in JJA-1988 (figure 17e-h). Also, the ascending motion which is largely confined to Indonesia spreads westwards in JJA-1988 along 0°–10°N. Subsequently, on both sides, it splits into two separate zones of upward vertical velocity, one over the Indo-Burma region and the other over the south of the equator.

Sectoral mean vertical cross-sections of the ω-field (figure 18) essentially demonstrate the above features. During JJA-1984, the ascending motion is observed to the north of the equator and descent to the north/south of it, where the forecast field is relatively intense compared to the analysis. In contrast, JJA-1984 analysis is more vigorous than JJA-1984 with a well defined Hadley circulation. But in the forecasts of JJA-1988, the ascent around the equator is replaced by a weak descent and ascent occurring on either sides of it. Accordingly, the descent in the Southern Hemisphere is shifted southwards and that of the Northern Hemisphere northwards.

8. Conclusions

Based on the results discussed above the following conclusions may be drawn:

- Monsoon forecasts of the ECMWF demonstrate an increasing trend of forecasting skill in general and its predictive skill has improved further after major revisions in the physical parameterizations of radiation, convection and land-surface processes.
- The upper level flow is more predictable than that of the lower level and wind forecasts show better skill than temperature. However, the impact of the above changes in the parameterization of physical processes is significant in the lower troposphere after day-3. A notable increase in the magnitudes of persistence error statistics indicates that the monsoon circulation in the analyzed fields become more and more intense with the introduction of changes in the operational forecasting system of the ECMWF from time to time. Due to an increase in the spin-up during 1988, no significant improvement is found in the day-1 forecasts.
- An analysis of the flow characteristics demonstrates that improvements in physical parameterization schemes have contributed to the improved quality of prediction up to day-5. For longer periods, the model starts drifting towards its preferred climatology. Thus, the nature of systematic forecast errors remains almost similar at day-10, although considerable reduction in their magnitudes is observed.
- Although, the hydrological cycle in the operational forecasts of the ECMWF appears to have been enhanced during JJA-1988 with the major modifications and improvements in the physical parameterizations, certain regional peculiarities have developed in the simulated rainfall distribution over the monsoon region.
- A marked reduction in forecast errors of temperature and moisture is found in JJA-1988 forecasts. This is largely accounted for by changes in the treatment of long-wave radiation. This reduces errors in the middle troposphere of the monsoon atmosphere. Moreover, the introduction of shallow convection also helped because it enhanced vertical transports of heat and moisture from the lower troposphere. The above changes have contributed to drying up of the model atmosphere as more of the available moisture was being utilized for heating and less for moistening the environment.

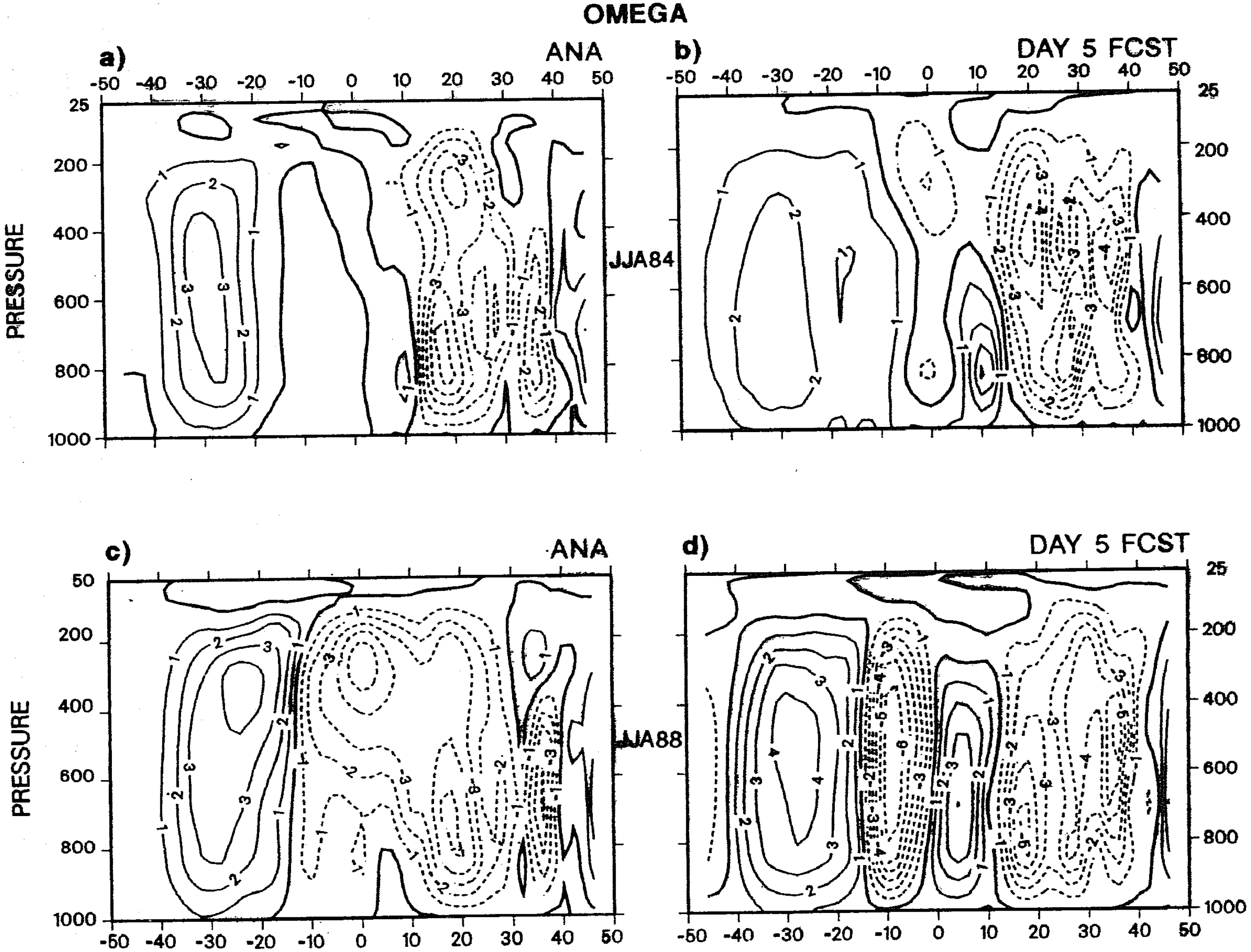


Figure 18a–d. Sectorial mean (45°E–100°E) cross sections of omega. [Units: 10^{-2} Pa s^{-1}]. **a)** analysis during JJA 1984; **b)** day 5 forecast for JJA 1984; **c)** analysis during JJA 1988; **d)** day 5 forecast for JJA 1988. Dashed contours indicate negative values (ascent).

- Despite considerable reduction of systematic errors in the prediction of the summer monsoon, it is believed that more improvements in the formulations of physical processes is needed for further reduction of systematic forecast errors.

9. Acknowledgements

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