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CHARACTERISTICS OF MEDIUM RANGE RAINFALL FORECASTS OF THE ASIAN SUMMER MONSOON

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ABSTRACT

Mean characteristics of the rainfall forecasts produced by the global data analysis–forecast system of India are examined for the summer monsoons of 1993–1996. Further, daily rainfall forecasts (accumulated for 24 h) extending from day 1 to day 5 are utilised to compute monthly/seasonal mean forecast fields to study their consistency and reliability. Global patterns of rainfall forecasts are also compared with the large scale rainfall climatological fields. In addition, observed rainfall distributions over India are used for regional verification of the medium range rainfall forecasts.

The forecasts appear to reproduce most of the large scale features of rainfall, except the sharp gradients over the Deccan plateau (leeside of the Western Ghats—west coast mountains over the south of Peninsular India) and the Gangetic plains over the north of India. Further, it is found that the forecast model has a characteristic tendency to reduce the quantum of rainfall over northwest India and the north Indian plains to the south of the Himalayas. In addition, in this study, certain aspects of the year-to-year variability of the predicted rainfall fields and their associated characteristics are examined along with the other systematic errors of the model. It is found that in this case, the sources of systematic errors could at least partially be eliminated, the rainfall forecasts up to day 3 or so can become a very useful product of interest. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: monsoon rainfall prediction; medium range forecast; systematic errors; monsoon variability; monsoon rainfall characteristics; Asian summer monsoon; global spectral model (India)

1. INTRODUCTION

The influence of the summer monsoon and its associated intense rainfall activity is spread over many countries of southeast Asia (known as Mai-Yu in China, Mae-Ue in Korea and Baiu in Japan). Seasonal transition of the atmospheric circulation and associated precipitation pattern are the characteristic features associated with the summer monsoon. Over India, in particular, 80% of the annual precipitation is received during the 4 month summer monsoon period (June–September). Hence, the main emphasis of the numerical weather prediction efforts in India are directed towards achieving success in predicting this most important variable. However, considerable variations exist in both spatial and temporal characteristics of the precipitation within the summer monsoon season over India. Variations in the climatologically observed rainfall distribution are generated either by the alignment of mountain barriers or by the behaviour of principal rain-bearing systems (monsoon depressions, intensity variations and location of the monsoon trough over the north Indian plains, midtropospheric circulation systems, off-shore vortices, etc.). Interestingly, the regions which usually receive large amounts of rainfall are characterised by low standard deviations and regions that traditionally receive less rainfall are characterised by large rainfall variability (Das, 1984). This aspect of the observed rainfall variability bears great significance in terms of the prediction as it becomes essential to concentrate and improve the forecast skill over those sectors of

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high rainfall variability in particular. On the other hand, forecasts over the regions where rainfall differs little from one season to another are of less demanding nature for the forecasting community.

Efforts to predict monsoon rainfall began in the 1970s (Murakami *et al*., 1970; Hahn and Manabe, 1975; Washington, 1981) and a major attempt in addressing this problem of simulating monsoon rainfall and its variability was taken-up under the banner of MONEG (Monsoon experiment group of TOGA/WGNE). It emerged through MONEG experimentation that the monsoon rainfall prediction over India is a very demanding test for atmospheric general circulation models (WCRP, 1992, 1993). A recently culminated massive effort of comparing the results of major atmospheric models under the atmospheric model intercomparison project (AMIP) clearly brought out the problems of generating the robust simulation of the monsoon rainfall and its variability (Gates, 1992). Rainfall pattern simulation is known to be sensitive to model physics, as well as to numerics. Major efforts of the world community under the aegis of WGNE/WCRP so far have been concentrated on assessing the role of slowly varying boundary conditions (such as SST, snow cover, etc.) in influencing the monsoon diabatic heat sources and their interannual variability. It is strongly believed that certain fast varying boundary conditions (such as soil moisture, albedo, etc.) play a crucial role in producing regional intraseasonal variability but efforts to study these aspects have been meagre so far. In the coming years, extensive efforts are planned to examine the water and energy cycles in the Asian monsoon region under the ambitious program of the GEWEX Asian monsoon experiment (GAME). Detailed studies on the rainfall forecasts of the European Centre for Medium Range Weather Forecasts (ECMWF), UK, have been attempted to examine the rainfall systematic error characteristics on the monthly and seasonal scale (Arpe, 1983, 1991; Heckley, 1985; Molteni and Tibaldi, 1985; Janowiak, 1992). In a recent study, Lan Yi (1995) analysed the mean monthly fields of ECMWF (1980–1989) to assess the 3D structure of the mean water vapour transport over monsoonal Asia and associated distinct regional aspects over the Indian and East Asian monsoon regions. With this background, the authors in this study attempt to examine the mean characteristics of the medium range rainfall forecasts of the summer monsoon.

2. DETAILS OF THE ANALYSIS–FORECAST SYSTEM

The National Centre for Medium Range Weather Forecasting (NCMRWF) was formed with an objective to provide medium range forecasts over monsoon regions and to provide agro-meteorological advisory services to the farming community in India. The global data assimilation and forecasting system (GDAFS) of the NCMRWF comprises a global spectral model adapted from National Center for Environmental Prediction (NCEP), USA, which is currently implemented at T-80/L-18 resolution and an intermittent data assimilation scheme involving spectral statistical interpolation (SSI) (Parrish and Derber, 1992). In the assimilation cycle, however, 6-h forecasts of the global model are utilized to serve as first guess for the subsequent analysis. The GDAFS was installed on a CRAY XMP/216 computer system in 1993 and, after extensive experimentation and testing, it was made operational on 1 June 1994. Five-day forecasts are produced daily on real time based on 00UTC analysis. Details of the global spectral model are described in Kanamitsu (1989). A brief description of the model is presented in the following table:

Brief description of global spectral model

Model elements	Components	Specifications
Grid	Horizontal	Global spectral, T-80 (256×128)
	Vertical	18 sigma layers [$\sigma = 0.995$, 0.981, 0.960, 0.920, 0.856, 0.777, 0.688, 0.594, 0.497, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.124, 0.074, 0.021]
	Topography	Mean

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	Prognostic variables	Relative vorticity, divergence, virtual temperature, log (surface pressure), water vapour mixing ratio
Dynamics	Horizontal transform	Orszag's technique
	Vertical differencing	Arakawa's energy conserving scheme
	Time differencing	Semi-implicit with a 900s time step
	Time filtering	Robert's method
	Horizontal diffusion	Second-order over quasi-pressure surfaces, scale selective
Physics	Surface fluxes	Monin–Obukhov similarity
	Turbulent diffusion	K-theory
	Radiation	Short wave, Lacis and Hansen; long wave, Fels and Schwarzkopf
	Deep convection	Kuo scheme modified
	Shallow convection	Tiedtke method
	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. Climatological SST, bulk formulae for sensible and latent heat fluxes
	Gravity wave drag	Lindzen and Pierrehumbert scheme

The model uses a simple land–surface scheme that includes: (i) exchange coefficients computations based on Monin–Obukhov similarity theory, (ii) Penman–Monteith method of evapotranspiration over land, which includes vegetation effects, (iii) prognostic surface temperature equation, (iv) three-layer of surface and soil temperature prediction, (v) interactive bucket hydrology, (vi) evaporation by bulk method over ocean and (vii) Charnock's roughness length computation over the ocean.

Detailed examination on the evolution of summer monsoon onset over the southern tip of the Indian peninsula, its advancement and withdrawal over the Indian subcontinent, was carried out using analyses–forecasts of the model for three successive monsoon seasons (1994–1996). It was found that all important characteristics of the monsoon advancement, withdrawal including stagnation and revival, etc., over India were brought out reasonably well by the GDAFS (Mohany *et al.*, 1995; Ramesh *et al.*, 1996; Swati Basu *et al.*, in press).

The data base used in this study was derived from the archives of the NCMRWF for the four summer monsoons (1993–1996). For this purpose, forecast fields (day 1–day 5) of rainfall (accumulated for 24 h) were utilised.

3. INTERPRETATION OF THE RESULTS

In this study, the global climatological characteristics of the medium range rainfall fields are examined to establish the correspondence of the seasonal mean (June–August) predicted fields with the well-known global rainfall climatology of Legates and Willmott (1990). Subsequently, regional characteristics of the predicted fields of rainfall are studied over India. In addition, the regional verification of the predicted fields is carried out with observed rainfall distributions that were obtained from the climate diagnostic

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bulletins of the India Meteorological Department. Further, certain aspects of the year-to-year variability of the predicted rainfall fields over India are examined in association with the observed large scale/synoptic scale activity of the summer monsoon.

3.1. Rainfall characteristics of the Indian summer monsoon

As mentioned earlier, 4 years of rainfall forecast fields (day 1–day 5) are utilised to obtain the forecast rainfall climatology. Despite the prevailing problems associated with the rainfall prediction of a global spectral model and the short period (4 years) considered for this purpose, it is believed that these average fields would provide valuable information about the forecast model's ability to produce climatological features of the seasonal rainfall distribution and associated features.

Figure 1(a) shows the Legates and Willmott (LWC) rainfall climatology for the summer season (JJA). During this season, the zone of maximum precipitation is observed to the north of the equator in the vicinity of the intertropical convergence zone (ITCZ), which penetrates deep into the south Asian continent up to around 24°N and brings considerable amounts of rain. Over the African continent, the ITCZ lies around 15°N, whereas over the equatorial Atlantic ocean and the east Pacific ocean it lies close to the equator. In addition, LWC shows a secondary zone of rainfall maximum observed over the foothill sectors of the Himalayas (Figure 1(a)).

The geographical distribution of mean model rainfall in the day 1 forecasts (Figure 1(b)) are found to be generally weaker than the corresponding day 3 (Figure 1(c)) and day 5 (Figure 1(d)) fields. The authors attribute this to the known initial imbalances (spin-up) that exist during the early stages of the forecast model integration. Subsequently, a general increase in the rainfall amounts over the tropics is noticed in day 3–day 5 fields particularly over the equatorial African continent, west coast of India, Bay of Bengal and the Indonesian regions. On the other hand, the model tends to overestimate the rainfall amounts as compared with that of LWC over north-eastern sectors of Africa, Indonesia and over the foothill sectors of the Himalayas. While the rainfall maximum over the west coast zone of peninsular India in day 3 fields (Figure 1(c)) is found to compare quite well with LWC, another such zone observed along the Myanmar coast becomes prominent only in day 5 forecasts (Figure 1(d)). However, the model also shows a tendency

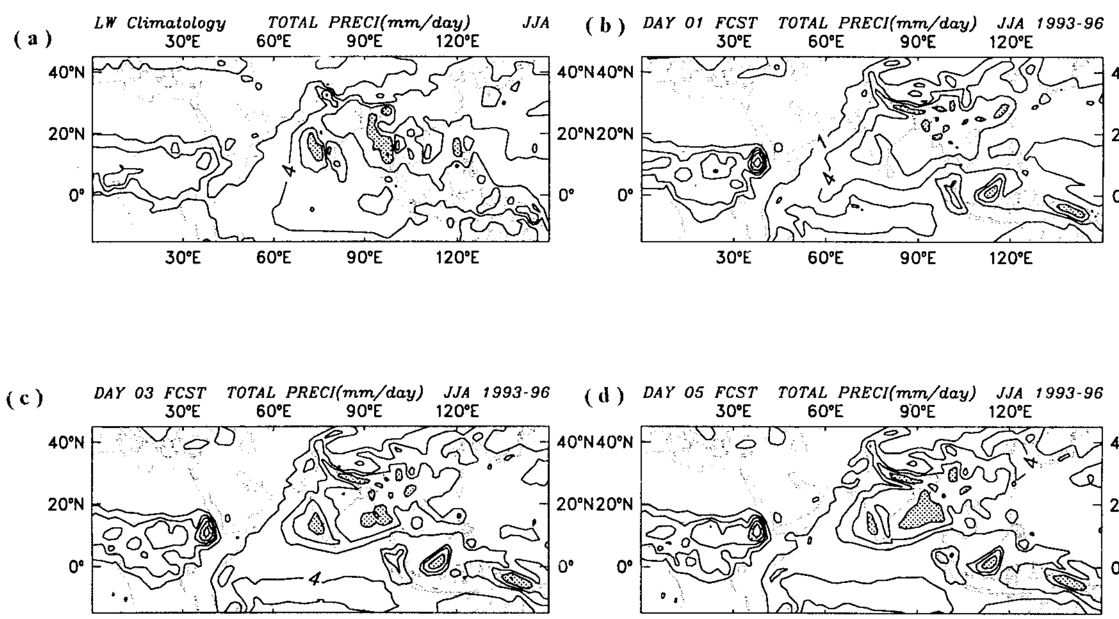

Figure 1. Global distribution of seasonal rainfall (JJA). (a) Legates–Willmott climatology; (b) day 1 FCSTs; (c) day 3 FCSTs; (d) day 5 FCSTs [isopleth interval: 1, 4, 8, 16, 24 mm/day; areas above 16 mm/day are shaded; units: mm/day]

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to reduce the rainfall amounts marginally beyond day 3 over the west coast of India. Similarly, the east–west gradient of rainfall observed in LWC along 10–15°N over southern Peninsular India and the adjoining Bay of Bengal is not captured well by the forecast model, which could be attributed to the problems associated with the treatment of orography in the model. Further, mean patterns of predicted rainfall fields compare closely with those of Category A (comprising 11 out of 30 global models of AMIP) group of models that were able to simulate a mean rainfall pattern over the Indian region reasonably well (Gadgil and Sajani, 1997).

Regional orographic features play a dominant role in the rainfall distribution over India. The mountain ranges along the west coast (Western Ghats) cause a large gradient in the rainfall amounts in the east–west direction. The seasonal rainfall (June–September) (Rao, 1976) amounts towards the west of the Western Ghats are very large and exceed 250 cm. The other region of orographic influence, namely northeast India also has amounts of seasonal rainfall exceeding 250 cm. To the east of the Western Ghats, rainfall decreases considerably with a steep gradient resulting in a rainfall minimum over the extreme south-eastern peninsula, where the seasonal amounts are less than 10 cm.

A semi-permanent feature of the monsoon circulation is the presence of a trough of low pressure (monsoon trough) across the northern parts of India. The monsoon trough is seen from the surface to about 500 hPa level, tilting southwards with height. Considerable rainfall activity is seen in the neighbourhood of this trough, particularly to its south. To the north of this trough, the Himalayan mountain ranges also influence the rainfall activity. However, it may be noted that a belt of minimum rainfall is observed close to the monsoon trough. The amounts of rainfall decrease from east to west across the northern parts of India. The northwest part of India is a region of sparse rainfall.

To further examine the regional characteristics of the rainfall predictions, geographical distributions of the rainfall (1993–1996) as accumulated in successive day 1, day 3 and day 5 forecasts (Figure 2(a)–(c)) of the NCMRWF for the 4-month season of the summer monsoon are analysed. As seen earlier, day 1 rainfall forecasts (Figure 2(a)) show considerable underestimation of rainfall over the west coast.

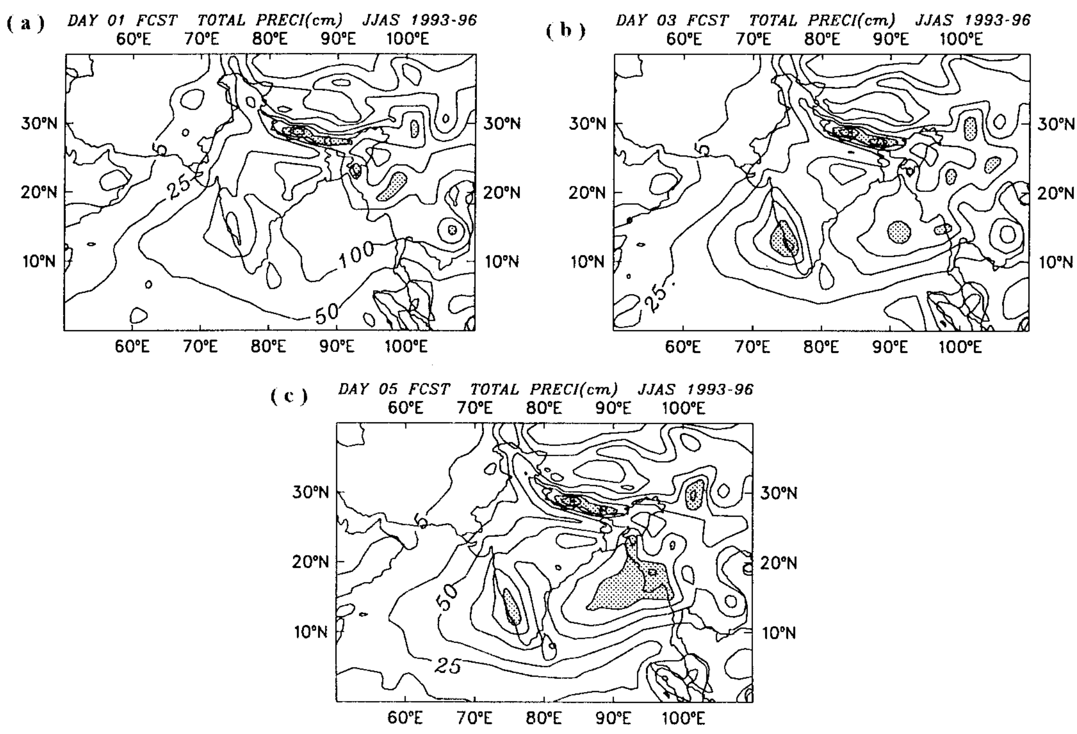

Figure 2. Geographical distribution of total seasonal rainfall forecast climatology (JJAS 1993–1996) over India [isohyet interval: 5, 25, 50 and in steps of 50 cm there after; units: cm]. (a) day 1 FCSTs; (b) day 3 FCSTs; (c) day 5 FCSTs

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Moreover, the sharp gradient in the rainfall amounts towards the east is not reproduced, there by overestimating the rainfall amounts over south-eastern sectors of Peninsular India. Thereafter, an increase in the rainfall amounts in the day 3 forecasts (Figure 2(b)) is noticed over the west coast of Peninsular India due to the increasing tendency seen earlier in the predicted rainfall rate of the forecast model in general. The rainfall amounts over the west coast now compare better with the seasonal rainfall climatology (Rao, 1976). However, the increase in rainfall over the west coast spreads over to the leeward side of the mountains also, thereby not reproducing the observed east–west gradient of rainfall and overestimates the rainfall over the south-eastern sectors of Peninsular India. Also, a marginal increase of rainfall over the Himalayan ranges, sectors of north India, Arabian Sea, Bay of Bengal and Myanmar, etc., is noticed. The characteristics of day 5 rainfall forecasts (Figure 2(c)) appear to be same as found earlier with a decrease in total rainfall over the west coast of India. Similar characteristics of the rainfall spin-up in the regional scale were seen in the ECMWF forecasts of the monsoon (Arpe, 1991).

Efforts to reduce model spin-up of the hydrological cycle on the global scale have not been able to ensure the corresponding modulations with the forecast length over the regional scale due to the systematic errors of the forecast model. In order to study these aspects further, the seasonal (June–September) rainfall as predicted by the successive day 3 forecasts of the model (Figure 3(a)) are compared with the corresponding observed seasonal rainfall pattern over India during the monsoon in 1996 (Figure 3(b)). It is found that both the regional zones of rainfall maxima located to the west of the Western Ghats along the west coast of India and over the southem slopes of the Himalayas (close to north/northeast India), respectively, are captured quite well in respect of their intensity in day 3 forecasts of the model. As explained earlier, the areal extent of the west coast maximum in the forecasts is getting extended on to the conventional rain shadow region observed to the eastern side of the Western Ghats due to which the zone of minimum over south-eastern peninsula is not seen. The absence of such an observed characteristic feature of sharp east–west gradient of rainfall could also be attributed to coarser horizontal resolution of the forecast model (T-80). Similarly, a northwest–southeast oriented zone of rainfall minimum along the monsoon trough region could not well be demarcated in day 3 forecasts. An observed zone of maximum over the central Indian peninsula is found to have displaced over to the east in day 3 forecasts. Nonetheless, a narrow local minima of rainfall observed over the desert regions of extreme north-western parts of the country is captured quite well in the model forecasts of rainfall.

Further, the systematic error characteristics in the rainfall prediction of the model are examined in this study to explore the modulations in the predicted quantum of seasonal rainfall from day 1 to day 5 (Figure 4(a) and (b)). It shows that the forecast model displays a characteristic tendency to decrease the

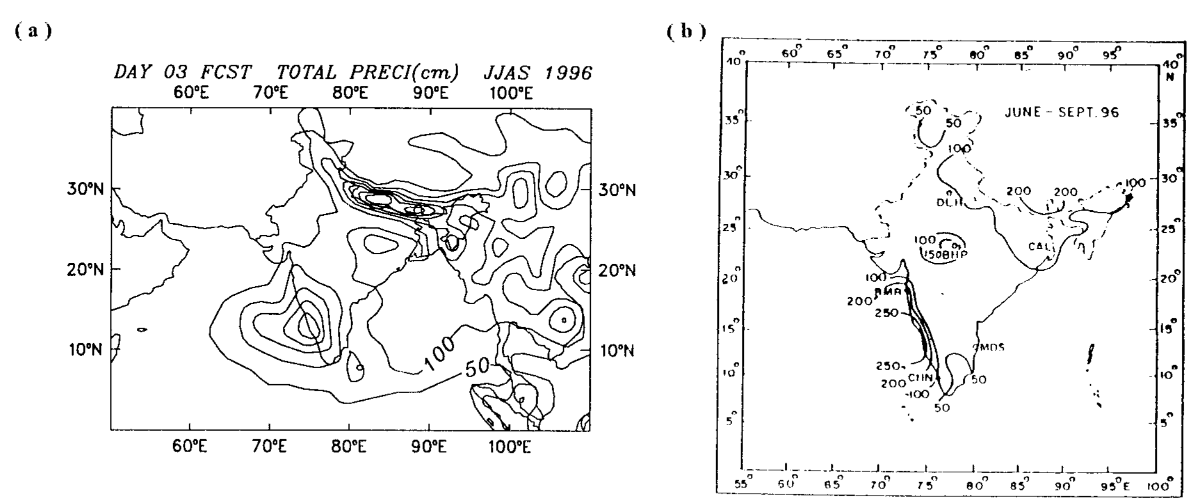

Figure 3. Geographical distribution of total seasonal rainfall of monsoon 1996 over India [isohyet interval: 50 cm; units: cm]. (a) Day 3 FCSTs; (b) observed

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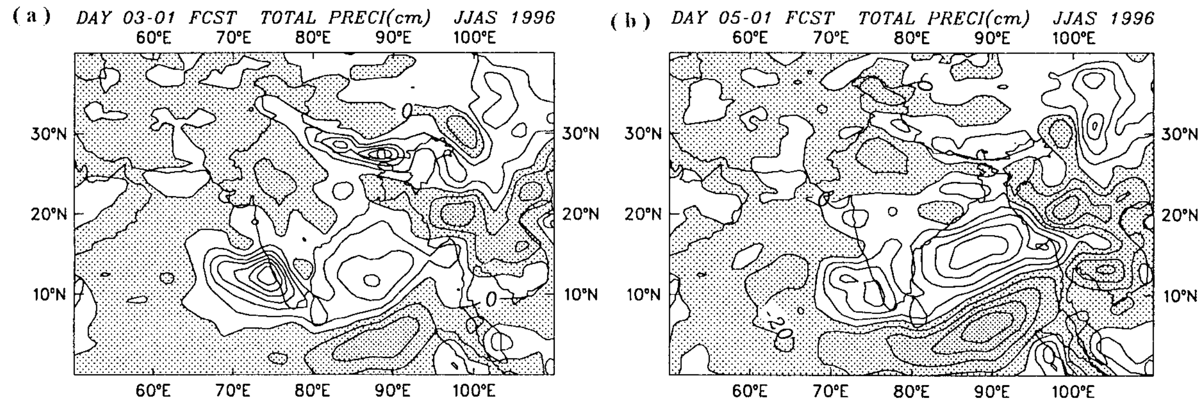

Figure 4. Geographical distribution of systematic rainfall forecast errors over India during monsoon 1996 [isopleth interval: 20 cm; units: cm]. (a) Differences between day 3 FCSTs and day 1 FCSTs; (b) differences between day 5 FCSTs and day 1 FCSTs

magnitude of rainfall prediction over the northwest India and adjoining regions, Jammu and Kashmir, small sectors over the eastern peninsula, west central Arabian Sea and the southern/south-eastern parts of Bay of Bengal. On the other hand, a clear increasing tendency in the rainfall predictions is noticed over the eastern Arabian Sea and the west coast of India up to day 3 and a decreasing tendency thereafter and a persistent increase from day 1 to day 5 predictions over the east coast of India and adjoining regions, north Bay of Bengal and adjoining eastern India. In general, it is found that the forecast model has a characteristic tendency to reduce the intensity of rainfall over the north Indian plains from day 1 to day 5. The main features of systematic rainfall forecasts of the GDAFS of the NCMRWF are:

(i) an increasing trend in rainfall amounts over the west coast up to day 3,
(ii) a decreasing trend in the northwest region up to day 5,
(iii) an initial decreasing trend over central India up to day 3,
(iv) an increasing trend over central Bay of Bengal and Arakan coast up to day 5 and
(v) a decreasing trend over the north Indian ocean up to day 5.

3.2. Year-to-Year variability characteristics of the rainfall forecasts

As mentioned earlier, large spatial and temporal variability in the monsoon rainfall activity takes place from one season to another depending upon the location and intensity of the ITCZ. Apart from this, the magnitude of summer monsoon rainfall depends primarily on the strength of the circulation itself along with other semi-permanent features, such as the low level westerly jet over the Arabian Sea, Tibetan anticyclone, upper level easterly jet, heat low and Mascarene high, etc. Further, the genesis, intensification and movement of monsoon circulation systems are also linked to the ITCZ. The total number of synoptic scale monsoon circulation systems (lows/depressions/storms) in a monsoon season also constitute one of the factors causing the intraseasonal variability of the monsoon. In addition, established linkages of the interannual variability between El Niño–Southern Oscillation (ENSO) with the summer monsoon rainfall have a significant role (Krishna Kumar *et al.*, 1995). The present day general circulation models are successful in simulating the impact of slowly varying boundary forcings. On the other hand, forecast models have significant systematic errors in simulating the modulations of regional scale monsoon meridional circulation primarily due to their sensitivity to the representation of various physical processes (Goswami, 1994). Hence, the variability of the summer monsoon circulation in the forecast fields is to be examined in the light of above mentioned factors. From the All-India seasonal rainfall values of the monsoon seasons (mean value of 880.7 mm for 1901–1996) as obtained from the climate diagnostic bulletin of India published by the India Meteorological Department, it was found that India received above normal rains during the summer monsoon seasons of 1993 (4%), 1994 (10%), 1996 (3%) and below normal during 1995 (− 7%).

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In the light of the above mentioned observed variability in summer monsoon rainfall over India during 1993–1996, an attempt is made to examine whether rainfall forecasts can reproduce year to year variability. Figure 5 presents the areal mean rainfall forecasted by the model over the Indian region (5–40°N, 60–100°E) for the months of June, July and August during 1993–1996. Despite the rainfall forecast error characteristics of the GDAFS (as discussed in earlier sections), it is evident that the areal mean rainfall rates as predicted by the model reflect the observed year-to-year variability with regard to the forecast rainfall rate over the Indian region in respective monsoon seasons (1993–1996) reasonably well (Figure 5(a)–(c)). The other regional simulated rainfall features, such as the spin-up effect up to day 2, forecasts and reduction beyond day 3 forecasts have shown up prominently in the areal mean rainfall rates also. The extreme nature of variability, such as the below-normal rainfall received during 1995 and comparatively above-normal rainfall received during 1994, within the four monsoon seasons (1993–1996) is brought out quite nicely in all ranges of model forecasts.

In order to examine the characteristics of year-to-year variability further, relative contributions of rainfall events of varied intensity over the Indian monsoon region are considered. Most of the rain spells over India during monsoon season would fall with in the quantum of 20 mm/day (which can be considered as normal range of activity). Only during the weak monsoon conditions, rainfall amounts would be below the range of 2 mm/day. Under the active monsoon conditions, intense rainfall events (exceeding the 20 mm/day rain rates) are accounted by the presence of synoptic scale cyclonic circulation systems. In view of the above, it is appropriate to categorise the rainfall events broadly in three categories as they are chosen based on the realistic factors. Moreover, similar categorisations have become acceptable after the studies of Molteni and Tibaldi (1985) to examine the characteristics of daily rainfall rates predicted by the ECMWFs global forecast model. Hence, three broad categories are 0–2, 2–20 and above 20 mm/day. Also, total monthly magnitudes due to each of the above categories are computed. Rainfall forecasts for the month of July are only considered to assess this aspect of the forecast model as July is normally considered as a representative month for the summer monsoon activity (Table I).

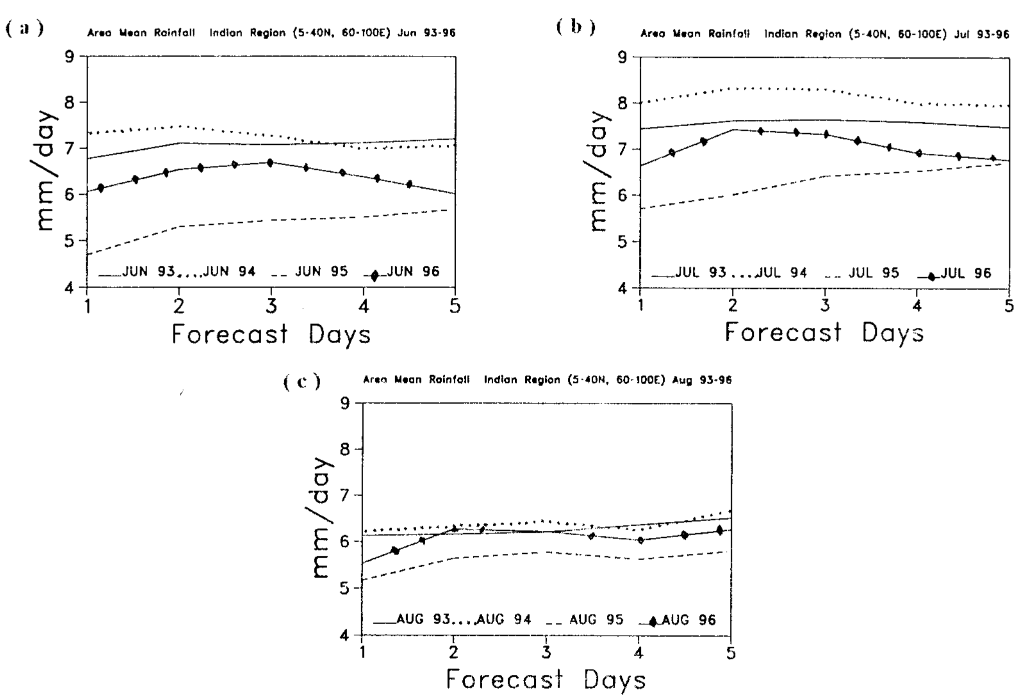

Figure 5. Area mean model rainfall forecasts over the Indian region (5–40°N, 60–100°E) [units: mm/day]

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Table I. Comparison of global mean values of rainfall for July

Averaged field type (1993–1996)	Amount (mm)
LW climatology	88.70
Jaeger climatology	86.10
Day 1 forecasts	84.64
Day 2 forecasts	91.38
Day 3 forecasts	91.70
Day 4 forecasts	91.10
Day 5 forecasts	91.15

Table II shows the contributions of the rainfall events in the above three categories for the four July months from 1993 to 1996. In general, the major contribution to total rainfall is from the category of moderate rainfall events (2–20 mm/day) and the minimum contribution is through the weak category of rain events (0–2 mm/day) in the observations. As most of the monsoon rainfall is accounted usually by the moderate categories of rain events, it is good to find that the forecast model also demonstrates such an important characteristic of monsoon rainfall. On the other hand, intense rainfall events during the monsoon season are accounted by the synoptic scale cyclonic circulation systems only and the quantum of rain from this category increases with the increased level of synoptic scale activity over the Indian region. During the period under consideration, four systems formed in July 1993, seven systems formed in July 1994, two systems in July 1995 and three systems in July 1996. The relative contributions from the moderate rainfall events are found to be more dominant (more than 80%) during July 1995, as the period experienced a reduced level of synoptic scale monsoon activity (with only two cyclonic systems) and hence

Table II. Averaged monthly rainfall contributions over Indian region (units: mm/day)

Field type	Category I	Category II	Category III	Total
July 1993				
Day 1 FCST	0.13(1.75)	6.91(93.0)	0.39(5.25)	7.43
Day 2 FCST	0.15(1.96)	6.02(79.0)	1.45(19.04)	7.62
Day 3 FCST	0.15(1.96)	5.68(74.24)	1.82(23.80)	7.65
Day 4 FCST	0.18(2.36)	5.43(71 44)	1.99(26.20)	7.60
Day 5 FCST	0.18(2.40)	5.37(71.70)	1.94(25.90)	7.49
July 1994				
Day 1 FCST	0.14(1.75)	5.94(74 15)	1.93(24.10)	8.01
Day 2 FCST	0.14(1.68)	5.64(67.70)	2.55(30.62)	8.33
Day 3 FCST	0.19(2.28)	5.54(66.66)	2.58(31.06)	8.31
Day 4 FCST	0.20(2.49)	4.93(61.47)	2.89(36.04)	8.02
Day 5 FCST	0.24(3.01)	4.86(60.98)	2.87(36.01)	7.79
July 1995				
Day 1 FCST	0.12(2.09)	5.39(94 24)	0.21(3.67)	5.72
Day 2 FCST	0.16(2.65)	5.60(93.03)	0.26(4.32)	6.02
Day 3 FCST	0.19(2.95)	5.81(90.35)	0.43(6.70)	6.43
Day 4 FCST	0.22(3 35)	5.58(85.20)	0.75(11.45)	6.55
Day 5 FCST	0.27(4.02)	5.58(83.04)	0.87(12.94)	6.72
July 1996				
Day 1 FCST	0.15(2.25)	6.17(92.93)	0.32(4.82)	6.44
Day 2 FCST	0.15(2.01)	6.33(85.87)	0.90(12.12)	7.43
Day 3 FCST	0.17(2.32)	6.00(81.86)	1.16(15.82)	7.33
Day 4 FCST	0.17(2.45)	5.92(85.55)	0.83(12.00)	6.92
Day 5 FCST	0.22(3.25)	5.58(82.30)	0.98(14.45)	6.78

Figures in parentheses denote percentage of total predicted rainfall rate realised in respective categories.

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the contribution of monthly rainfall from intense rainfall category was found to be comparatively less (amounting to a maximum of about 12% only). Due to the formation of a higher number of synoptic circulation systems during July 1994, the relative contributions from the third category of rainfall events are comparatively higher. Similarly, relative contributions from this category of intense rainfall events are found to be appropriately varying as per the number of intense rain producing circulation systems during 1993–1996. This analysis also reveals the fact that the relative contributions in respect of moderate and intense categories of rainfall events reflect the year-to-year variability as observed during the July months of the four consecutive years (1993–96).

4. SUMMARY AND CONCLUSIONS

Based on the above discussions on the medium range rainfall forecasts of the Asian summer monsoon produced by the GDAFS of the NCMRWF, the results may be summarised in the following manner:

The seasonal summer monsoon rainfall climatology patterns of LWC over the Indian region display most of the regional characteristics quite well. In particular, an observed secondary zone of precipitation found along the foothill sectors of the Himalayas is represented in LWC fields. Further, the relative strengths of other rainfall maxima over the equatorial sectors of West Africa, Pacific and Atlantic are found to be stronger in LWC fields.

Though the global mean rainfall forecasts do not show significant spin-up, the effect of the existence of initial imbalances (spin-up) is, however, clearly visible over the regional scale. While the crucial west coast of India' rainfall maximum becomes quite comparable with the patterns of LWC by day 3, a similar zone found along the Myanmar coast and the adjoining north-eastern Bay of Bengal becomes more prominent only by day 5. Invariably, forecast models tend to overestimate rainfall (as compared with LWC) over the foothill sectors of the Himalayas, Indonesia, north-eastern sectors of Africa.

It is found that the areal mean rainfall forecasts over the Indian region reflect the interannual variability characteristics, as observed within the four monsoon seasons considered here, reasonably well despite difficulties associated with the forecast model spin-up and systematic errors.

The impending improvements in the forecast model with regard to its horizontal resolution and efforts for reducing the systematic errors *viz*. improved representation of initial state thermodynamic variables through increased utilisation of non-conventional remote sensing data over the tropical oceans; realistic representation of certain fast varying boundary conditions, such as soil moisture, vegetation, albedo, etc.; improved representation of various physical processes, are expected to bring about positive improvements in the regional rainfall forecast characteristics over the Indian region.

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