MAUSAM, **54**, 2 (April 2003), 495-504

551.509.33 : 551.553.21 : 551.577(540)

Updated operational models for long-range forecasts of Indian summer monsoon rainfall

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(*Received 15 January 2001, Modified 13 June 2002*)

सार – भारत मौसम विज्ञान विभाग वर्ष 1989 से 16 प्रचालनात्मक प्राचल निदर्शों के आधार पर समूचे देश के लिए मानसून (जून–सितंबर) के दीघ्र अवधि पूर्वानुमान जारी कर रहा है। मानसून के वर्गीकरण (न्यून, सामान्य एवं अधिक) के गुणात्मक पूर्वानुमान पिछले ग्यारह वर्षों (1989–99) से सही साबित हुए हैं। यद्धपि मात्रात्मक पूर्वानुमानों की त्रुटियां, विशेषकर 1996 से 1999 के दौरान चार प्रतिशत की घटबढ़ की निदर्श त्रुटि की अपेक्षा अधिक थी इस लिए हाल ही के वर्षों में मानसून वर्षा के साथ जिन 16 प्रचालनात्मक प्राचल निदर्शों (प्राचलिक एवं शक्ति समाश्रयण) के संबंध कमजोर पड़ गए थे, उन्हें चार नए प्रागुक्तों के साथ अद्यतन किया गया है। मॉडलों में प्रयुक्त किए गए नए प्रागुक्त है : – अरब सागर एस.एस.टी., दक्षिणी हिंद महासागर एस.एस.टी. यूरोप दाब ग्रेडिएंट और डार्विन दाब प्रवृत्ति। 1971–95 की अवधि के आंकड़ों के साथ मॉडल कांस्टेंट का पुनः परिकलन किया गया है। इन अद्यतन निदर्शों के कार्य हाल ही के वर्षों में विशेष रूप से कहीं बेहतर पाए गए है। 1991–99 की अवधि के अद्यतन निदर्शों से पूर्वानुमान की संपूर्ण माध्य त्रुटि प्रचालनात्मक पूर्वानुमानों के 7.0 प्रतिशत की तुलना में 3.2 प्रतिशत है। चूंकि इन अद्यतन निदर्शों के सही होने की संभावना अधिक पाई गई है। अतः वर्ष 2000 के भारतीय ग्रीष्मकालीन मानसून वर्षा के प्रचालनात्मक दीर्घ अवधि पूर्वानुमान को जारी करने के लिए उनका प्रयोग किया गया है।

ABSTRACT. Based on operational 16 parameter models, the India Meteorological Department, since 1989, has been issuing the long-range forecasts for monsoon rainfall (June-September) for the country as a whole. Qualitative forecasts of category of monsoon (deficient, normal and excess) proved accurate on all the 11 years (1989-99). However, the errors in the quantitative forecasts, particularly from 1996-99 were more than the model error of ± 4 %. Therefore the operational 16-parameter models (parametric and power regression) were updated by replacing four predictors whose relationship with monsoon rainfall has weakened in recent years. The new predictors introduced into the models are Arabian Sea SST, South Indian Ocean SST, Europe Pressure Gradient and Darwin Pressure Tendency. The model constants were recalculated with the data for the period 1971-95. The performance of the updated model was found to be far better especially during the recent years. The absolute mean error of the forecasts from the updated model for the period 1991-99 was 3.2 % as against 7.0 % of the operational forecasts. As these updated models showed promise, they were introduced in 2000 for issuing the operational long-range forecasts of Indian summer monsoon rainfall.

Key words – Indian summer monsoon rainfall, Long-range forecasting, Sea surface temperature, Power regression.

1. Introduction

Inter-annual variation of Indian summer monsoon rainfall (ISMR) has many social and economic impacts. Therefore, the long-range forecast of Indian summer monsoon rainfall becomes very crucial. India was the first country to start operational long-range forecasts about a century ago. The first operational forecast was issued on 4 June 1886 based on the observed relationship between Indian monsoon and Himalayan snow cover (Blanford, 1884). Walker (1923, 1924) introduced the first objective technique, namely multiple regression. Subsequently several forecast techniques were developed. During the early 1980s, models based on the Dynamic Stochastic technique were introduced (Thapliyal 1982). During the late 1980s a few models based on new techniques like Power Regression and Parametric were introduced (Gowariker *et al*. 1989, 1991). Subsequently, a variety of models like principal component regression (Rajeevan *et al*. 1999), canonical correlation analysis (Rajeevan *et al*. 1999; Prasad and Singh 1996), Neural network (Navone and Cecatto 1995; Goswami and Srividya 1996; Guhathakurta *et al*. 1999) and Power Transfer (Thapliyal 2001) were developed.

TABLE 1

List of 16 parameters used in the operational model of IMD

Parameter No.	List of parameters used in the operational model of IMD till 1999	List of parameters used in the operational model of IMD after 1999
X_1	50 hPa East-West Wind (January + February)	50 hPa East-West Wind (January + February)
X_2	500 hPa Ridge Position (April)	Darwin Pressure Tendency (April-January)
X_3	Darwin 09 hrs Pressure (Spring)	South Indian Ocean SST (February + March)
X_4	East Coast Minimum Temperature (March)	East Coast Minimum Temperature (March)
X_5	Northern India Minimum Temperature (March)	Arabian Sea SST (January + February)
X_6	Central India Temperature (May)	Central India Temperature (May)
X_7	N. H. Temperature (January + February)	N. H. Temperature (January + February)
X_8	N. H. Pressure (January to April)	N. H. Pressure (January to April)
X_9	Southern Oscillation Index (SOI) (March to May)	Southern Oscillation Index (SOI) (March to May)
X_{10}	Indian Ocean Equatorial Pressure (January to May)	Indian Ocean Equatorial Pressure (January to May)
X_{11}	Himalayan Snow (January to March)	Himalayan Snow Cover (January to March)
X_{12}	Eurasian Snow cover (December)	Eurasian Snow Cover (December)
X_{13}	10 hPa Zonal wind over Balboa (January)	Europe Pressure Gradient (January)
X_{14}	El Nino (Same Year)	El Nino (Same Year)
X_{15}	El Nino (Previous Year)	El Nino (Previous Year)
X_{16}	Argentina Spring Pressure	Argentina Spring Pressure

The operational 16 parameter model used up to 1999 consisted of 16 predictors, which include global and regional atmosphere-land-ocean parameters, covering the antecedent period from December to May. These parameters have been utilised for developing the operational Parametric and Power regression models (Gowariker *et al.* 1989,1991) and are given in Table 1. Since 1989, India Meteorological Department has been issuing operational long-range forecasts based on these models. The operational forecast of IMD has two parts; a forecast for the category of monsoon (like normal/excess or deficient) and a forecast for the quantitative value of monsoon (June-September) rainfall over the country as a whole. The parametric model is used to prepare the monsoon categorical forecasts and the Power regression model is used for the quantitative monsoon rainfall forecasts. The power regression model developed with the data of 1958-87 has the model error of ± 4%. This figure was obtained as the RMSE of the model during the training period. The verification of the operational forecasts issued based on these models for the period 1989 to 1999 is given in Table 2. From this table, it can be seen that during the period, 1989-99, monsoon was normal (within ± 10 %) in all 11 years. Thus the forecast for the monsoon category for all the 11 years was correct. However, the errors of the quantitative forecasts were higher than expected, particularly during the recent 4 years (1996-99) though the largest error of 18 % occurred in 1994. The root mean square error of the operational forecasts during this period (1989-99) was 8.0 %, which is double the model forecast error of ± 4%. We have therefore critically examined the reasons for these large errors during the recent years. While examining the predictor – rainfall relationships, we have found that few predictors out of 16 predictors have lost the significant relationship with monsoon rainfall. This corroborates the findings of many earlier results as described below in detail. We have therefore updated the operational model

TABLE 2

Performance of the operational long range forecast model of IMD period : 1989-99

	Observed		Forecast		Hindcasts from the updated 16 parameter model
Year	Category	% of LPA	Category	% of LPA	
1989	Normal	101	Normal	102 (–1)	
1990	Normal	106	Normal	101 (5)	
1991	Normal	91	Normal	94 (–3)	93 (–2)
1992	Normal	93	Normal	92 (1)	96(–2)
1993	Normal	100	Normal	103 (–3)	107 (–7)
1994	Normal	110	Normal	92 (18)	98 (–12)
1995	Normal	100	Normal	97 (3)	100 (0)
1996	Normal	103	Normal	96 (7)	105 (–2)
1997	Normal	102	Normal	92 (10)	101 (–1)
1998	Normal	105	Normal	99 (6)	108 (–3)
1999	Normal	96	Normal	108 (–12)	96 (0)
	Absolute Mean Error (91-99)			7.0%	3.2%

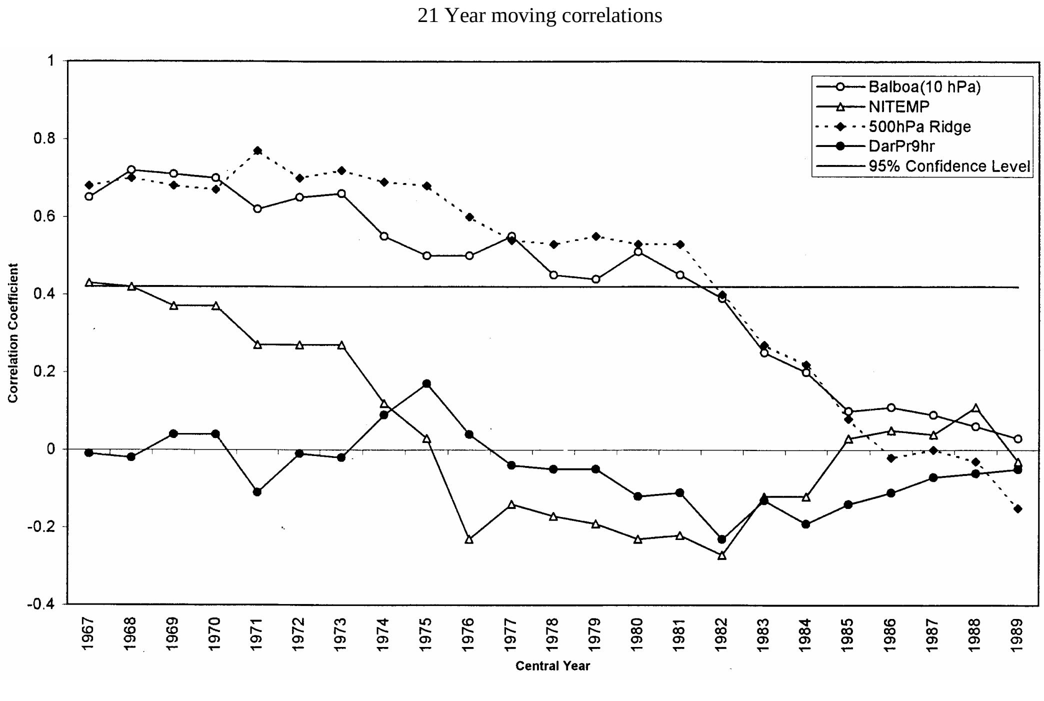

Fig. 1. 21 Year moving correlations of four predictors (10 hPa wind at Balboa (open circle), N.I. Temp. [(triangle), 500 hPa Ridge (filled square) and Darwin 0900 hr pressure (filled circle)]. Data period : 1958-99. The 95% confidence level is shown as horizontal line

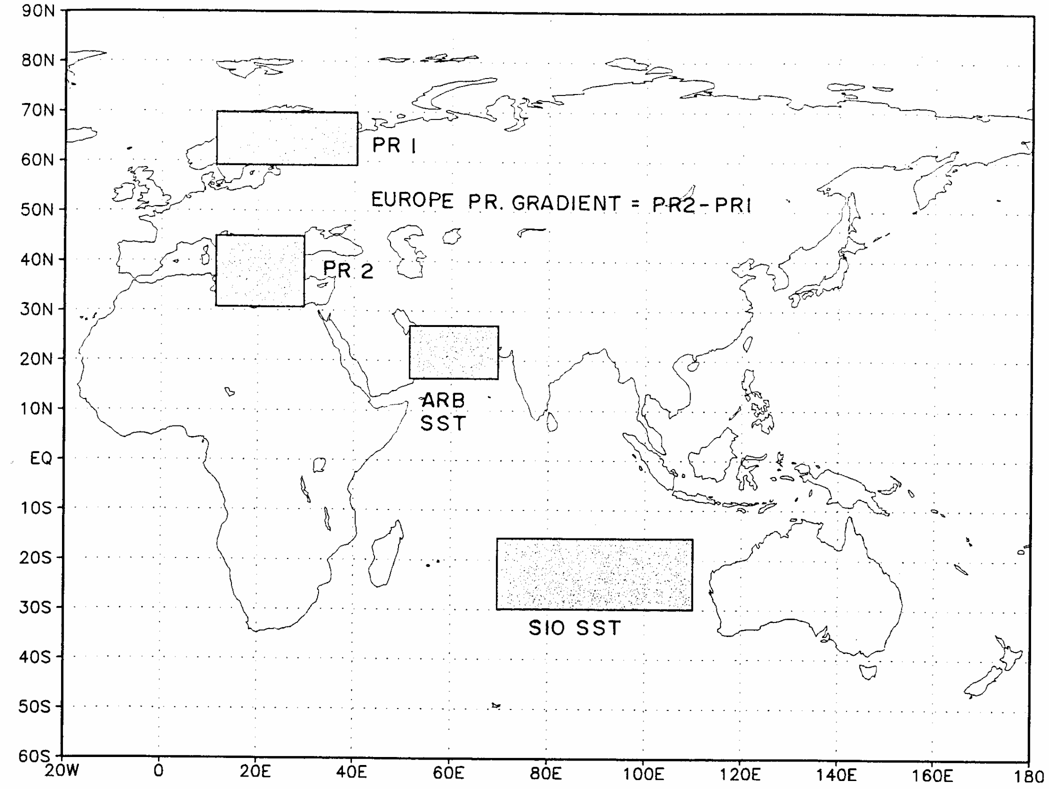

Fig. 2. Schematic diagram showing the geographical regions of new four predictors used in the updated model

by replacing four weakly related predictors with new four strongly predictors. The model constants were then recalculated, using the new predictors.

In this paper, we have discussed the basis of updating the models, which utilises the secular variation of the relationship of the predictors with Indian monsoon rainfall. Details of the newly identified predictors, the development and performance of updated operational model are also discussed.

2. Basis for updating model

For predictions, all 16 parameters are used to extrapolate relationship in future, which is observed between a predictor and monsoon rainfall during the past several years. Recently, Thapliyal (2001) has carried out a detailed analysis of this relationship, though many investigations have examined its temporal variations (Parthasarathy *et al.* 1988 1993; Thapliyal 1990, 1997; Parthasarathy *et al.* 1991, Hastenrath and Griescher 1993 and Rajeevan 2001). All the studies have noted that the predictor-monsoon relationship varies with time, showing strong relationship during some epochs and weak relationships during some other epochs. This secular variation of relationship poses serious problems on the accuracy of the forecasts during the independent period. Recently, Kripalani and Kulkarni (1997) and Krishnakumar *et al.* (1999) have addressed the weakening of the relationship between ENSO and ISMR. Thapliyal (1990, 2001) also reported similar feature wherein he reported that the weakening and strengthening of ENSO and ISMR relationship has been noted during the past hundred years also. We have therefore, examined in detail the secular variation of all the 16 predictors of the model (Table 1). It has been found that four predictors, 500 hPa ridge position in April, North India Minimum temperature (March), 10 hPa Zonal wind (January), and Darwin pressure (Spring)) have consistently lost the significant relationship with ISMR. Fig. 1 shows the 21-year moving correlations of these four predictors with ISMR. The horizontal line in Fig. 1 indicates the 95% confidence level for the 21- year period of data (0.42). It can be seen that the 500-hPa ridge and 10-hPa zonal wind were significantly correlated with ISMR till about 1982. However the correlations deteriorated drastically

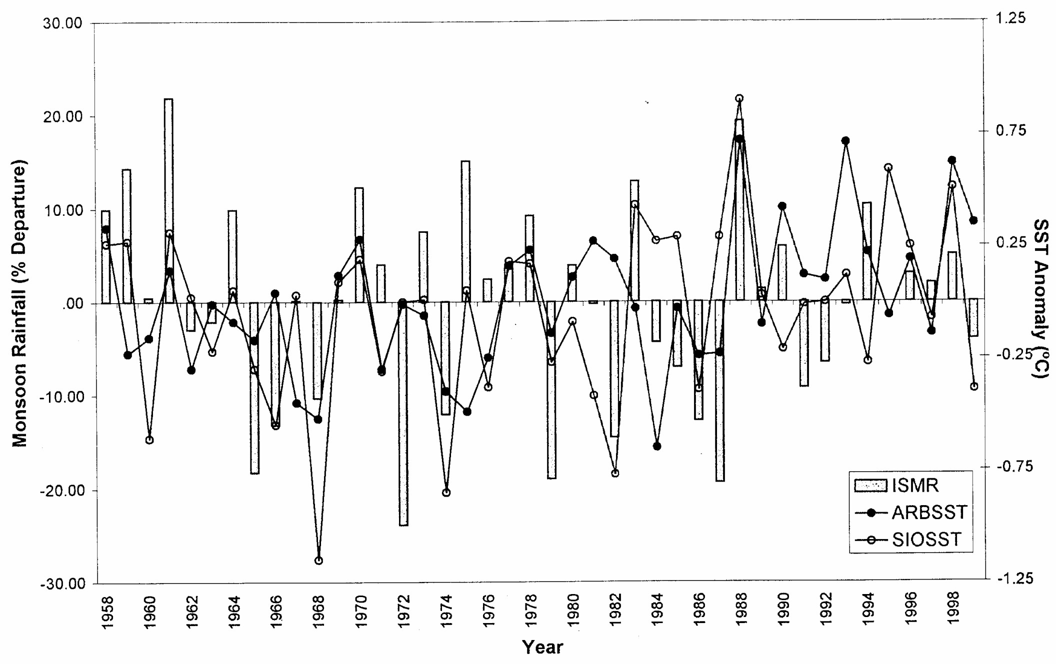

Fig. 3. Time series of Arabian Sea SST (continuous line with filled circle), South Indian Ocean SST (continuous line with open circle) anomalies and Indian summer monsoon rainfall anomalies (vertical bars). Period : 1958-99

afterwards and in case of 500-hPa ridge, even the sign of the correlation has been changed from positive to negative. The correlations of other two predictors are statistically insignificant throughout the period. For the recent years, the correlation of all the four predictors is very close to zero. Therefore these 4 predictors have been replaced with new predictors. In the next section, we discuss the newly identified predictors.

3. Identification of new predictors

Better understanding of inter-annual and decadal variabilities of ISMR is very crucial for improving the skill of long-range forecasts of ISMR anomalies. Therefore, diagnostic studies on teleconnections and identification of new predictors are integral parts of research on long-range forecasting. This also provides new strong predictors to replace those predictors of the forecast model whose relationship with monsoon rainfall has become very weak in the operational period.

Relationship of ISMR anomalies with equatorial Pacific Ocean SST anomalies is known for many years and has been extensively used in statistical models for long range forecasts of ISMR. Recently due to availability of more accurate and longer data sets of sea surface temperatures from the Indian ocean, the relationship of Indian Ocean SST anomalies with Indian Summer monsoon rainfall has been examined in detail (Clark *et al.* 2000 and Rajeevan *et al.* 2002). These studies observed that the SST anomalies over Arabian Sea and South Indian Ocean are very crucial for the inter-annual variability of ISMR. Rajeevan *et al.* (2002) have identified two areas (Fig. 2) where the SST anomalies during the winter and spring are positively correlated with ISMR anomalies. The SST anomalies over NW Arabian Sea (15° N-25° N, 50° E-100° E) averaged January and February are positively and significantly correlated (CC= 0.44, significant at 99 % confidence level period 1958-99) with ISMR. Similarly, the SST anomalies over the south Indian ocean (15° S-30° S, 70° E-110° E) averaged for the months February and March are also positively and significantly correlated (C.C=0.49, significant at 99 % confidence level Period 1958-99) with ISMR anomalies. The year-to-year variations of the Arabian Sea SST, South Indian SST anomalies and ISMR anomalies are shown in Fig. 3. Arabian Sea SST Index was negative during major deficient years like 1951, 1966, 1968, 1972, 1974, 1979, 1986 and 1987. Similarly this index was positive during the period 1970 and 1988. South Indian Ocean SST index was negative during major deficient years like 1951, 1965, 1966, 1968, 1974, 1979, 1982 and 1986. These two new indices are promising as

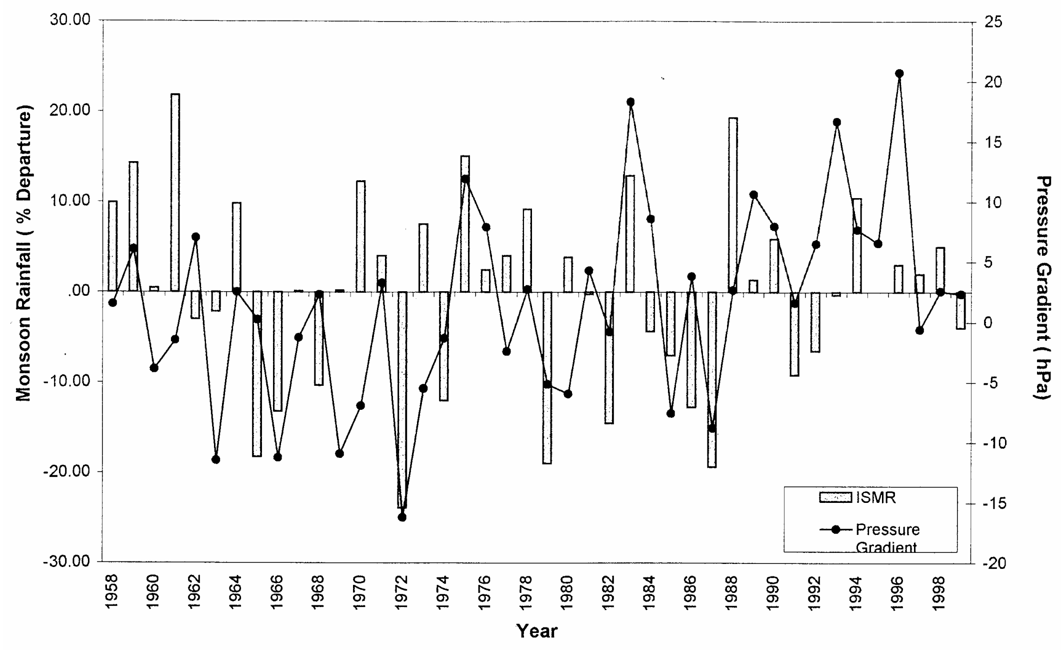

Fig. 4. Time series of Europe pressure gradient (continuous line) and Indian summer monsoon rainfall (vertical bars). Period : 1958-99

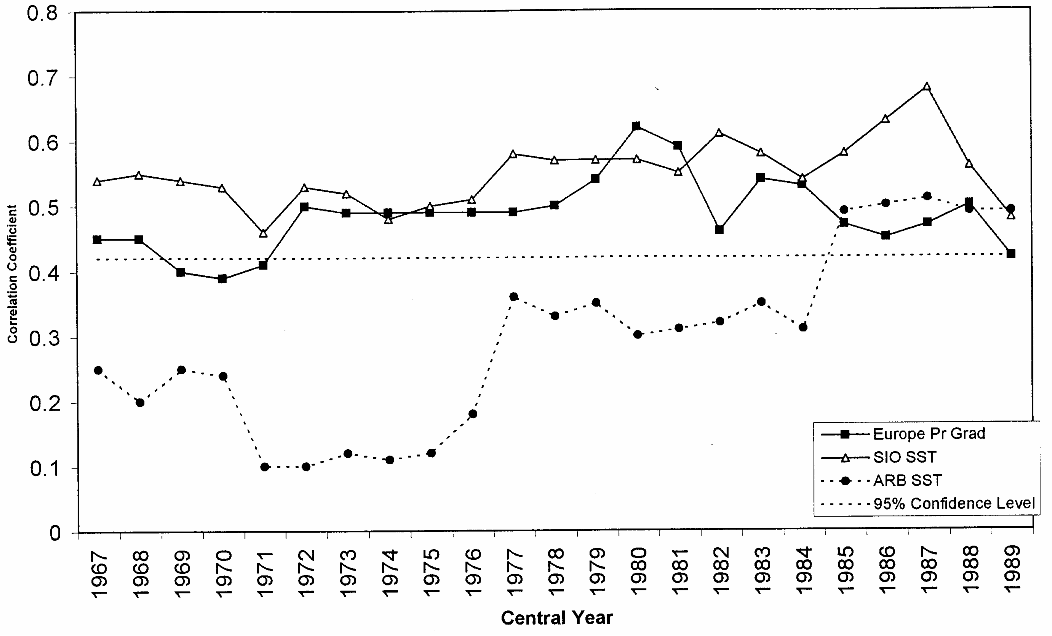

Fig. 5. 21 Year moving correlations of new predictors, Europe pressure gradient (filled squares), South Indian Ocean SST (triangle) and Arabian Sea SST (filled circle). Period : 1958-99

TABLE 3

Inferences based on signals from 16 parameters (updated model) period 1951-99

Favourable parameters	No. of occasion	Monsoon condition		Remarks
		Normal	Deficient	
≥ 80	5	5	0	
≥ 70	9	9	0	
≥ 60	22	21	1*	1966(–3)*
≥ 50	38	37	1	
< 50	11	2	9	
≤ 40	10	1	9	
≤ 30	6	1*	5	1957(–2)*
≤ 20	2	0	2	
≤ 10	1	0	1	
0	1	0	1	

the predictors for long range forecasting of ISMR anomalies.

Rajeevan *et al*. (1998) have suggested that the zonal temperature gradient over western parts of Europe during the month January is significantly and physically related to Indian summer monsoon activity. It has been observed that during good monsoon years, the temperature gradient over NW Europe is directed towards equator. Hydrostatically, it means that the pressure gradient anomaly is directed towards the pole. During the deficient years, it has been observed that the poleward pressure gradient becomes weaker. This pressure gradient is ultimately related to anomalous mid-latitude activity including blocking activity etc during the spring season (Raman and Rao, 1981). Using the mean sea level pressure data (Basnett and Parker, 1997) an index was derived for the Europe Pressure gradient for the month of January (Rajeevan 2002). The pressure gradient is calculated as the difference of pressure anomalies averaged over two latitude bands, one averaged over the box, 60° -70° N, 10° - 40° E and the other averaged over the box 30° - 45° N, 10° - 30° E as shown in Fig. 2. The year-to-year variation of this pressure index with ISMR anomalies is shown in Fig. 4. The pressure index is positively and significantly correlated (0.34, confidence at 99% confidence level during the period 1958-99) with ISMR anomalies. Below normal pressure gradient indicates below normal rainfall activity.

The 21-year moving correlations of the SST anomaly indices and the pressure gradient index with ISMR are shown in Fig. 5. The 95% significance level is shown as a horizontal dashed line. It can be seen that the south Indian Ocean SST and the Pressure gradient is significantly correlated with ISMR throughout the period. But the Arabian Sea SST is significantly correlated with ISMR only after 1980s. During the recent years, this index is very significantly correlated with ISMR.

The fourth predictor used in the model is the Darwin Pressure tendency as defined by Shukla and Paolino (1983). This index is derived as the difference of mean sea level pressure of Darwin for April and January. This parameter has a correlation coefficient of –0.55 (1958-99) which is significant at 99% level. This parameter indicates that when the Darwin pressure increases from January to April more than normal, than the ensuing ISMR is likely to be less than normal.

The revised list of 16 predictors is also given in Table 1. Using these 16 atmosphere-land-ocean parameters, the parametric and power regression models were developed. The details of the model development and the performance of new models are given in following sections.

4. Updated 16 parameter parametric model

The model utilises the 16 parameters listed in Table 1 for assessing the performance of subsequent monsoon over India. By definition normal monsoon indicates that the seasonal rainfall lies within ±10 % of the normal which is 881 mm for the country as a whole. For

TABLE 4

Constants of the updated Operational Model

Parameter	Alpha α	Beta β	C	P
Rainfall	0	100	15.132740	1
50 hPa wind	50	10	−0.0001454057	2.0
Darwin pressure tendency	0	10	−0.06782597	2.1
South Indian Ocean SST	0	10	0.01478873	4.0
East Coast India temperature	0	10	0.01292454	4.0
Arabian Sea SST	0	10	0.002425759	4.0
Central India Temperature	0	10	0.002954027	4.0
N.H. temperature	50	10	411.2762	-4.0
N.H. pressure	0	10	−0.0000411012	4.0
S.O.I (Tahiti-Darwin)	50	10	0.0006681639	4.0
I.O. Equatorial pressure	0	1000	−13.59197	-3.8
Himalayan snow cover	50	10	242.30460	-4.0
Eurasian snow cover	0	10	1.53494	-4.0
Europe pressure gradient	50	10	−2.634577	-2.0
El Nino (same year)	50	10	−126.0996	-4.0
El Nino (previous year)	50	10	−77.30029	-4.0
Argentina pressure	0	100	−0.0004461816	3.9

the two categories classification, both the normal monsoon and the excess monsoon are included as good monsoon. Thus the monsoon performance for different years can be categorised as either deficient or good. By utilising 50 years of data (1951-99), Favourable (F) and Unfavourable signals (U) for good monsoon have been obtained from all the 16 parameters. To obtain signals for monsoon rainfall, a predictor's past relationship with seasonal monsoon rainfall is used. A parameter having a positive (negative) correlation coefficient (CC) with the monsoon rainfall indicates a favourable (unfavourable) signal for good monsoon if its anomaly is positive (negative) in the particular year. On the other hand, a parameter having negative CC indicates favourable (unfavourable) signal for good monsoon if its anomaly is negative (positive). Following this procedure, the percentage number of parameters favourable (out of the 16) is determined for all 50 years (1951-99) and the frequency analysis is presented in Table 3. In the same table, the performances of the subsequent monsoon *vis-à-vis* percentage of favourable predictors are also indicated. It is seen from the Table that whenever 70% or more parameters are favourable for good monsoon, there is 100% probability for ensuing monsoon rainfall to be good. Similarly, when less than 50% parameter are favourable, there is 78% probability for deficient monsoon. When it is less than 40%, the probability for deficient monsoon increases to 90%. This analysis brings out an interesting feature and indicates that the confidence on wet monsoon forecast is higher than the deficient monsoon forecast.

5. Updated power regression model

The power regression model utilises the same set of 16 parameters that are used in parametric model, discussed above. Unlike the parametric model, which gives equal weightage to all 16 parameters, the PR model gives an appropriate weightage to each of the 16 predictors. The model tries to account for some kind of non-linear interactions among the predictors and the

ISMR. We have used 25 years of data (1971-95) for developing the regression coefficients. The general form of the model is given below:

$$\frac{R + \alpha_0}{\beta_0} = C_0 + \sum_{i=1}^{i=16} C_i \left[\frac{X_i + \alpha_i}{\beta_i} \right]^{P_i}$$

Where, *R* is monsoon rainfall, *X* is the predictor mentioned in Table 1 and α, β, *P* and *C* are constants. The mathematical form of the model suggests that the adverse poising of any one climate forcing alone, no matter how significant it appears to be, should not create an impression that the monsoon is going to be deficient or good, since the resultant signal obtained from all the parameters is important. The constants calculated with the data 1971-99 are given in Table 4.

The comparison of the hindcast ISMR anomalies from the updated model with the operational forecasts of IMD for the period 1991-99 is given in Table 2.

From the Table, it can be seen that since 1994 the forecasts from the updated 16-parameter model were closer to the actual ISMR. With the updated 16-parameter model, comparatively much smaller errors were observed in 1994, 1997, 1998 and 1999. The average absolute error of the old 16 parameter model for the period 1991-99 is 7.2 whereas that of the updated model for the same period is 3.2 % only, which indicates large improvements in the performance of the model. This analysis showed that the updated 16-parameter model performs better than the old 16-parameter model, which was used by the IMD for the operational forecasts from 1989 to 1999. In 2000, this updated forecast model was adopted for issuing the operational long-range forecasts of all Indian monsoon rainfall. In 2000 and 2001, the updated model correctly indicated the normal seasonal monsoon over India as a whole.

6. Conclusions

The 16 parameter operational model was updated by replacing four weekly related predictors with the predictors, which showed strong relationship with monsoon rainfall. The new predictors introduced in the model are Arabian Sea SST, South Indian Ocean SST, Europe Pressure Gradient and Darwin Pressure tendency. The performance of the updated Power regression model including these new predictors was found to be much better than the operational models. Especially during the recent years, the forecast errors from the updated model were much smaller than the errors from the operational forecasts. Since, 2000 the updated models are being used for the long-range forecasts of summer monsoon rainfall over India.

The present study once again emphasizes the need of constant review of the performance of the predictors and statistical models. It is also essential to encourage systematic diagnostic studies to understand the monsoon variability and predictability of monsoon rainfall. Concerted efforts need to be made to identify new promising predictors for forecasting rainfall for small periods and regions.

Acknowledgements

We are thankful to Dr. R. R. Kelkar, DGM for his encouragement and support extended to us for completion of this study. We are also thankful to all officers and staff members of LRF Section, for their sincere and dedicated support given during the course of this study.

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