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Long range prediction of summer monsoon rainfall over India : Evolution and development of new models

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सार – भारत में कुल मिलाकर ग्रीष्म मानसून वर्षा (जून से सितम्बर) के दीर्घावधि पूर्वानुमान के मूल्यांकन और संभावना की समीक्षा करने का प्रयास किया गया है। इसके अतिरिक्त नये दीर्घावधि पूर्वानुमान (एल आर एफ) मॉडल विकसित किए गए हैं और इस शोधपत्र में उनकी चर्चा की गई है। हाल ही में विकसित एक मॉडल के और आगे किए गए विश्लेषण से सुझाव मिलता है कि वायुमंडल का गतिक प्रसंभाव्य स्थानांतरण स्मरण एक दशक के क्रम का है। इस प्रकार की अटकलबाजियों की विश्व के अन्य क्षेत्रों और मौसमों के लिए इसी प्रकार के निदर्शों के विकास द्वारा परीक्षण करने की आवश्यकता है।

ABSTRACT. An attempt is made to review the evolution and prospects of long range prediction of summer monsoon (June to September) rainfall over India as a whole. In addition, a variety of new Long Range Forecast (LRF) models has been developed and discussed in this paper. Further analysis of a recently developed model suggests that the dynamic stochastic transfer memory of the atmosphere is of the order of a decade. This speculation needs to be examined by developing similar models for other regions and seasons of the globe.

1. Introduction

Despite significant advances in science and technology over several centuries, the critical dependence of Indian economy on monsoon rainfall still continues. Jagannathan (1960), Rao (1965) and Thapliyal (1986) have reviewed some of the LRF techniques used in India for over past hundred years. For improving the accuracy of LRF, basically two approaches have been followed. In the first approach, a number of parameters have been identified by following the correlation approach. In the second approach, attempts have been made to develop Multiple Regression, Multiple Power Regression, Dynamic Stochastic Transfer techniques etc. In this article, an attempt has been made to review the evolution and prospects of LRF techniques used in India. In addition, several new LRF models have also been developed for forecasting monsoon rainfall over India as a whole.

2. Data used

All India, summer monsoon (June to September) rainfall data for fairly long periods have been reported in the literature (Mooley and Parthasarathy 1984). However, these long period rainfall data are based on the rainfall of plains of India only and do not include rainfall of hilly regions and island regions of the country. The main problem in preparing a truely homogeneous monsoon rainfall series for a big country, like India, arises from the fact that the number of stations reporting rainfall data vary considerably from month to month and year to year. For example, the number of stations recording the rainfall in India has varied from nearly 200 in the first decade of this century to about 5000 during recent decades.

The country is divided into 35 meteorological sub-divisions and for each one of these sub-divisions, the yearly actual rainfall (*i.e.*, the average of all the sub-divisional stations for which data are available in that month) and yearly normal rainfall (*i.e.*, the average of 1950 normals for all those sub-divisional stations which have been considered for computing the actual rainfall in a particular month) are computed by the India Meteorological Department. Yearly actuals and yearly normals for all the 35 meteorological sub-divisions have been collected from the National Data Centre of India Met. Dept. and used for computing the long period monsoon rainfall series for the country as a whole. On utilizing the area weighted rainfall of all the 35 meteorological sub-divisions, the yearly-actuals and the yearly-normals for country, as a whole, have been computed and are given in Table 1. Analysis of 80 years (1901 to 1980) data reveals that the normal monsoon rainfall over India, as a whole, is equal to 876 mm and its standard deviation is equal to 92 mm. For the same period, the coefficient of variation of the rainfall is equal to 10.5 per cent. In this study, yearly monsoon rainfall expressed as percentage of yearly normal has been used.

3. Multiple regression technique

3.1. *Multiple regression models*

For developing the LRF models, Walker (1923) used those weather factors as predictors which had shown significant correlation coefficient (CC) with the predictand (Indian monsoon rainfall). Among several factors he finally chose those which had least inter-correlation among themselves. Walker issued first operational

TABLE 1

All India monsoon (June to September) rainfall values (in mm)

Decade	Year 0	1	2	3	4	5	6	7	8	9
1900		751 (865)	785 (863)	887 (864)	761 (863)	711 (861)	897 (862)	774 (860)	925 (862)	923 (863)
1910	934 (864)	736 (863)	825 (864)	778 (865)	960 (870)	788 (870)	1004 (887)	1090 (887)	663 (883)	939 (887)
1920	739 (887)	920 (887)	917 (886)	864 (886)	923 (887)	859 (888)	952 (891)	910 (892)	813 (890)	830 (888)
1930	838 (886)	915 (889)	854 (887)	1030 (896)	941 (898)	872 (898)	952 (897)	877 (898)	938 (894)	816 (894)
1940	869 (892)	771 (889)	1012 (889)	920 (887)	930 (888)	919 (887)	950 (890)	938 (892)	915 (899)	899 (894)
1950	917 (885)	719 (884)	809 (882)	966 (880)	906 (879)	956 (868)	982 (864)	857 (878)	965 (878)	999 (874)
1960	880 (876)	1055 (866)	841 (867)	865 (884)	970 (883)	711 (870)	754 (869)	870 (869)	773 (862)	863 (861)
1970	977 (870)	882 (848)	659 (866)	913 (849)	746 (848)	991 (861)	880 (859)	879 (845)	938 (859)	679 (838)
1980	885 (852)	848 (850)	729 (853)	965 (855)	812 (849)	794 (854)	740 (848)	695 (862)	1018 (853)	

Note — Values within brackets indicate yearly normals.

forecast in 1909 based on Multiple Regression (MR) model. The predictors used since the time of Walker in different MR models are defined in Table 2.

Separate monsoon rainfall forecasts for two large homogeneous regions of India, namely, Peninsula and northwest India are being operationally issued by India Met. Dept. since 1924. The author (Thapliyal 1986) has reviewed the performance of these MR models and has found that during the years 1924-1982, the MR models have provided correct forecast on 65% occasions. However, due to non-availability of suitable MR models separate LRFs of monsoon rainfall for India, as a whole, were not being issued between 1917 and 1987. In recent two decades, efforts have, therefore, been made by using correlation approach to identify physically linked monsoon predictors (*e.g.*, Banerjee *et al.* 1978, Sikka 1980, Kung and Sharif 1980, Joseph *et al.* 1981, Pant and Parthasarathy 1981, Shukla and Paolino 1983, Shukla and Mooley 1987, Thapliyal 1984, Raman and Maliekal 1985, Verma *et al.* 1985, Bhalme *et al.* 1987, Parthasarathy and Pant 1985, Parthasarathy *et al.* 1988) so that scientifically sound MR models can be developed for India as a whole also. On studying, in detail, the stability of monsoon rainfall relationship with these parameters, the following MR model has been developed by the author :

$$\hat{R} = 3.2\,\hat{F}_6 + 7.6\,\hat{F}_7 - 2.6\,\hat{F}_8 + 1.1\,\hat{F}_9 - 0.3\,\hat{F}_{10} - 1.3 \quad (1)$$

where R is monsoon rainfall over India, F indicates different predictors defiend in Table 2 and symbol $\wedge$ indicates departure of factor from its normal value.

In 1988, the above model was used for preparing the operational forecast and it indicated that the rainfall during monsoon 1988 would be around 111 per cent of the normal. The actual rainfall in 1988 was 119 per cent of the normal.

3.2. *New multiple regression model*

While reviewing a large number of predictors, the author (Thapliyal 1986) has noted that 8 predictors, namely, the Darwin pressure (Walker 1923), the latitudinal position of 500 hPa April sub-tropical ridge

TABLE 2

Predictors used for issuing operational long range forecast of monsoon rainfall over India

Predictors	Details of predictors
F_1	Himalayan snow accumulation at the end of May
F_2	South American (Buenos Aires, Cordoba & Santiago) pressure (.5 March + April + .5 May)
F_3	Mauritius pressure (May)
F_4	Zanzibar district rain (April + May)
F_5	Ceylon rainfall (May)
F_6	500 hPa Indian April ridge position along 75° E longitude
F_7	Indian east coast temperature (March mean minimum temperature over Calcutta, Visakhapatnam, Madras and Masulipatnam)
F_8	Darwin pressure (March + April + May)
F_9	Peru coast *El Nino* category (previous year)
F_{10}	North Indian temperature (March minimum temperature over Jaisalmer, Jaipur and Calcutta)
F_{11}	East-west extention of 50 hPa trough ridge system over northern hemisphere (January + February)
F_{12}	Central India (Akola, Nagpur) temperature (May)
F_{13}	Darwin MSL pressure anomaly (January—April)
F_{14}	10 hPa zonal wind over Balboa (January)
F_{15}	Northern hemispheric pressure anomaly over 5° latitude belt (35° N to 40° N) from 0 to 155° E longitude
F_{16}	Northern hemispheric temperature anomaly (January + February)
F_{17}	Eurasian snow-cover (previous December)
F_{18}	Argentina pressure (Buenos Aires and Cordoba), (April)
F_{19}	Tahiti—Darwin pressure (spring)
F_{20}	Peru coast temperature (previous August)
F_{21}	Peru coast temperature (January—March)
F_{22}	Equatorial pressure (Jakarta, Jan to Apr; Port Darwin Mar to May and Seychelles, Feb to Mar)
F_{23}	Himalayan snow-cover (January to March)

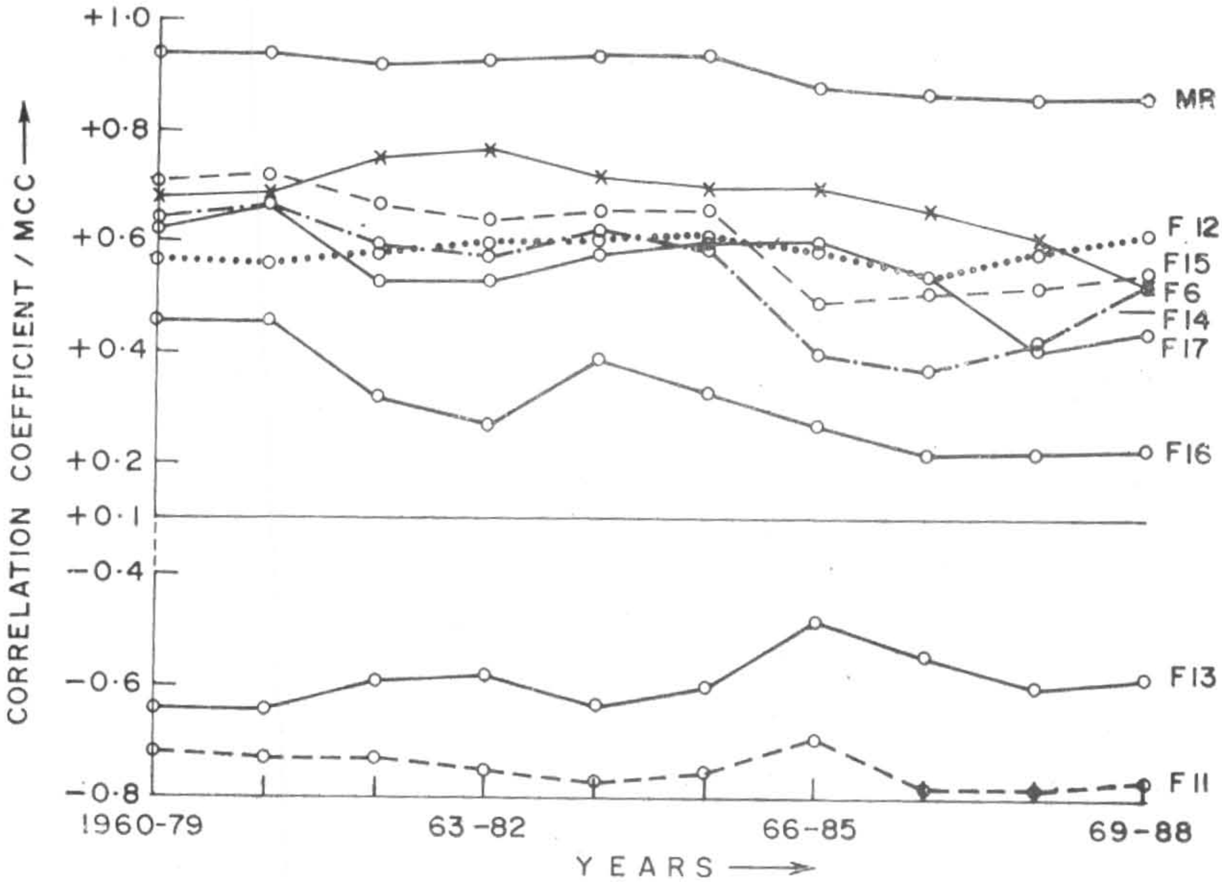

Fig. 1. Changes in 20-year sliding period correlation and multiple correlation coefficients, as a function of time, between Indian monsoon rainfall and various predictors

along 75°E longitude (Banerjee *et al.* 1978), the Darwin pressure tendency from winter to spring (Shukla and Paolino 1983), the east-west extent of ridge-trough system at 50 hPa over northern hemisphere during winter (Thapliyal 1984 a), the northern hemispheric surface temperature during winter (Verma *et al.* 1985), westerly January winds at 10 hPa (Bhalme *et al.* 1987) and northern hemispheric pressure anomaly (January to April) have shown significant relationship with the Indian monsoon rainfall. For testing the stability of different parameters, 20 years sliding period CCs for each predictor have been computed and are shown in Fig. 1. It is seen from the figure that during past 28 years, the CCs of all the factors have changed their magnitude but have not changed their sign. A new multiple regression model, given below, has thus been developed :

$$\hat{R} = 4.31 + 19.65\,\hat{F}_{12} - 10.73\,\hat{F}_{13} + 13.51\,\hat{F}_{6} + 31.01\,\hat{F}_{7} + 0.91\,\hat{F}_{14} - 0.01\,\hat{F}_{15} + 0.06\,\hat{F}_{16} \qquad (2)$$

The MR model, given above, is based on 26 years (1958-1983) data and has multiple CC (MR) equal to 0.92 (significant at 1% level). The model fitting appears to be good as it has accounted for 85 per cent of the variance. For studying the stability of the model, the 20 years sliding period multiple CCs, shown in Fig.1, have been analysed. It is seen from the figure that during recent 20 years period (1968-1987) the multiple CC of the MR model is lowest (0.85) and during an earlier 20-year period (1964-1983) it is highest (0.94). In fact during recent 28 years (1951-1988), the model's multiple CC remained fairly constant. This suggests the stability of the model which accounts for more than 72 per cent of variance. Verifications of the model forecasts for a part of the sample (1980-83) and test period (1984-88) are shown in Fig. 3. It is seen from the figure that the model forecasts are found closer to realised rainfall during both the sample and test periods. In 1989, the model forecast has indicated that the rainfall during June to September 1989 is likely to be 109% of the normal.

3.3. *Limitations of multiple regression techniques*

Correlation coefficients between the predictand and the predictors change their magnitude and sign with time (*e.g.*, Jagannathan 1960, Rao 1965, Thapliyal 1986, 1989). This limits the accuracy of MR models. Based on time dependent variation of the CC between Indian monsoon rainfall and a few known important predictors, the author has proposed a hypothesis (Thapliyal 1986) that the climatic association (ρ) observed for a particular period is made up of two types of associations as given below :

$$\rho = \bar{\rho} + \check{\rho} \qquad (3)$$

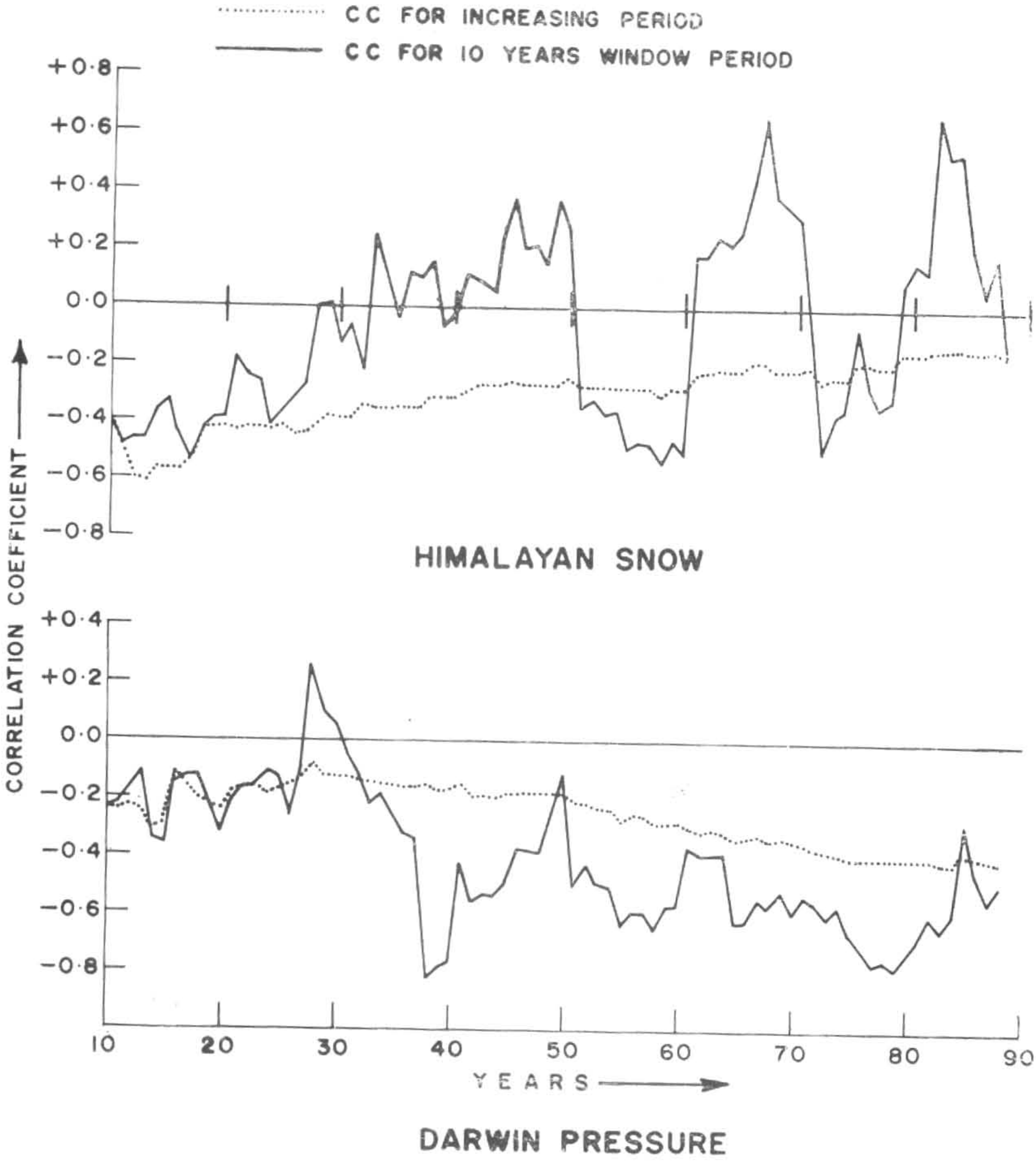

Fig. 2. Changes in 10-year sliding period and increasing period correlation coefficients (CC) between Indian monsoon rainfall and two physically linked predictors. Ten-year sliding period CCs are plotted on the end of the period.

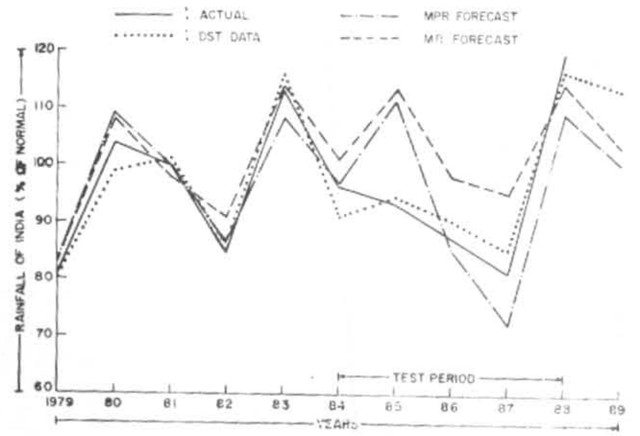

Fig. 3. Verification of forecast obtained from different models for a small part of the sample period (1979-1983) and the test period (1984-1989)

where, $\bar{\rho}$ is the basic climatic association (proportional to long period CC) and $\check{\rho}$ is the superimposed perturbed climatic association (proportional to short period CC).

For examining the above hypothesis, the CCs between Indian monsoon rainfall and two physically linked predictors, namely, Darwin pressure (spring) and Himalayan snow-cover (January to March) have been studied in detail. For this purpose, the correlation coefficients of these predictors with the Indian monsoon rainfall have been computed for the increasing periods, like, 10, 11, 12,......,88 years as well as for the 10-year sliding periods starting from 1901 and are shown in Fig. 2. In the figure the solid line indicates CCs for increasing periods while dotted line indicates the CCs for 10-year sliding periods. It is seen from the figure that the magnitude and sign of the basic (CCs for 50 years or more period) and perturbed climatic association (CCs for 10-year sliding period) vary differently with time. The increasing period CC ($\bar{\rho}$) approaches to its asymptotic value as the period increases beyond 50 years. On the other hand, the 10-year sliding period CC ($\check{\rho}$) shows random fluctuations over past 88-year period. Similar patterns for the basic and the perturbed climatic associations are also found when monsoon association with other important predictors, like Darwin pressure (January-April), mean monthly temperature along Peru coast (January-March), temperature of northern hemisphere etc are studied. Thus the above analysis corroborates the hypothesis that the climatic association is the vector sum of basic climatic association and superimposed perturbed climatic association.

4. Auto-regressive integrated moving average technique

For developing a new class of forecast model, some experiments with Auto-Regressive Integrated Moving Average (ARIMA) technique have, therefore, been conducted in India and abroad. For forecasting monsoon rainfall over two major homogeneous regions of India, namely, Peninsula and northwest India, ARIMA models have been developed which have shown marginal forecast skill (Thapliyal 1986). In this paper, an attempt is made to develop ARIMA model for forecasting monsoon rainfall over India as a whole.

By applying the known techniques (Thapliyal 1986) to the long series of monsoon rainfall data (1901-1980) a model of the type of ARIMA (1, 1, 1) has been found most suitable for forecasting monsoon rainfall of the country as a whole one year ahead. Details of the forecast model are given below :

$$R_t = 0.89\ R_{t-1} + 0.17\ R_{t-2} - 0.78\ a_{t-1} \qquad (4)$$

where a s are random shocks.

The verification of the forecasts during the sample and test periods (1981 to 1988) has shown marginal forecast skill.

5. Parametric technique

It has been shown above that the CCs of different predictors with Indian monsoon rainfall change with time. This limits the accuracy of the monsoon forecast particularly when a few predictors are used in the model. It is felt that if a large number of predictors are collectively used, the resultant signal from the group of predictors may improve the accuracy of the forecast. To test this concept a parametric model utilising signals from 15 global and regional parameters have recently been developed (Gowariker *et al.* 1989). Some of these parameters are global in nature while others are regional and appear to have some physical link with the Indian monsoon rainfall. The parametric model is purely a qualitative decision making tool where equal weightage is given to the signals of all the parameters for forecasting the rainfall.

For the past 38 years (1951-1988), signals from 15 parameters have been analysed (Gowariker *et al.* 1989) in terms of F and U, where F indicates favourable signal for good monsoon (normal + above normal) and U indicates unfavourable signals for good monsoon. The analysis has revealed that whenever 60 per cent or more predictors out of the 15 were favourable, the subsequent monsoon rainfall over India was good on all the occasions. However, whenever 40 per cent or less parameters were favourable, monsoon was deficient (rainfall less than 90 per cent of normal) on 75 per cent occasions only. The model was put to operational use for 1988 and 1989, when 87 and 73 per cent of parameters were favourable for good monsoon. The forecast proved to be correct for both monsoon seasons.

6. Multiple power regression technique

In the parametric model, discussed above, signals from all the predictors have been assigned equal weightage. However, the influence of each predictor on monsoon rainfall varies considerably as is indicated by a fact that in 1957, the 500 hPa Indian ridge was the only predictor out of 12 (available at that time) which was favourable in that year and still subsequent monsoon rainfall was normal. To tackle such anomalous situations, a Multiple Power Regression (MPR) model utilizing all the 15 predictors of the parametric model mentioned above has recently been developed (Gowariker *et al.* 1989). The authors have first determined the magnitude and the sign of the influence of each predictor and subsequently used them for developing the following MPR model :

$$R = C_0 + \sum_{i=1}^{15} C_i X_i^{p_i} \qquad (5)$$

where R is monsoon rainfall of India, Xs are different predictors used in the parametric model (Gowariker *et al.* 1989).

The MPR-model, given above, has shown encouraging performance. In this paper, different MPR models which use various combinations of 18 parameters (F_6 to F_{23}) given in Table 2 have been studied. Performance of these models have shown that the best results are obtained when the parameters are arranged in order of their decreasing CCs. Another important result has also been noted that the MPR models which use more than 14 parameters do not improve upon the forecast. In this paper, an attempt has, therefore, been made to develop a new MPR-model which uses the 14 best parameters in order of their decreasing CCs. The details of the model are given below :

$$
\begin{aligned}
R = {} & 4254.4 - 3220.0\,(10)^{-4} X_{11}^{2} + 1450.7\,(10)^{-1} X_{6}^{-0.8} - \\
& - 2296.2\,(10)\,X_{12}^{-4} - 4166.5\,(10)^{-2} X_{13}^{1.4} - \\
& - 2333.2\,(10)^{-2} X_{14}^{-0.8} + 1500.0\,(10)^{-5} X_{15}^{4} + \\
& + 5704.4\,(10)^{-4} X_{7}^{4} + 1046.2\,X_{17}^{-4} - \\
& - 1887.1\,(10)^{4} X_{18}^{-4} - 4715.1\,(10)^{-4} X_{16}^{4} - \\
& - 1478.1\,(10)^{2} X_{19}^{-4} - 3149.6\,(10)^{-4} X_{20}^{4} - \\
& - 5318.8\,X_{21}^{-4} - 8872.0\,(10)^{-2} X_{10}^{-4}
\end{aligned}
\tag{6}
$$

where $X_1, X_2, \ldots\ldots, X_{23}$ are the predictors which are obtained by using a suitable transformation to F_1, F_2, ..., F_{23} respectively.

The new MPR-model, given above, has been developed by using the data of past 26 years (1958 to 1983). During the sample period, the model forecast have accounted about 96 per cent of the variance. On utilizing the new model the forecasts have been obtained for a small part of sample (1979 to 1983) and for the recent test period (1984-1989) and are shown in Fig. 3. During these periods, the model forecasts are quite close to the realized rainfall (Fig. 3) except for the year 1985 when the model forecast has over estimated the rainfall. Thus, the technique of multiple power regression seems to be a potential one.

7. Dynamic stochastic transfer technique

Monsoon being a complex system, it is not yet possible to develop a deterministic model for LRF of monsoon rainfall over India. Recently, the author (Thapliyal 1982) has developed suitable Dyanamic Stochastic Transfer (DST) models for LRF of monsoon rainfall. These models have shown encouraging results as compared to other operational models like regression and multiple regression (Thapliyal 1986). In this paper, an attempt has been made to develop a suitable DST model for LRF of monsoon rainfall over India as a whole.

7.1. *Formulation of the problem*

Let us assume that the atmosphere is a linear dynamic system and it converts an input series X into an output series Y. For such an atmosphere, the dynamic transfer relationship between continuous input X_t and output Y_t can be represented by a linear differential equation (Thapliyal 1986) of the form given below :

$$
\begin{aligned}
& (1 + K_1 D + \ldots\ldots + K_m D^m)\, Y_t \\
& \quad = (1 + C_1 D + \ldots\ldots + C_n D^n) X_{t-b}
\end{aligned}
\tag{7}
$$

where D is differential operator (d/dt), Ks, Cs, and ms and ns are unknown constants and b is pure delay between the input and the output.

For discrete input output data set, as generally is the case in meteorology, the dynamic transfer relationship, expressed in Eqn. (7) can be represented in the form given below (Thapliyal 1986) :

$$
R_t = \frac{\omega(B)}{\delta(B)}\, X_{t-b} \tag{8}
$$

where,

$$
\begin{aligned}
\omega(B) &= \omega_0 - \omega_1 B - \ldots\ldots\ldots - \omega_g B^g \\
\delta(B) &= 1 - \delta_1 B - \ldots\ldots\ldots - \delta_h B^h
\end{aligned}
\tag{9}
$$

ω, δ, g and h are unknown constants and B is backward shift operator (*i.e.*, $BR_t = R_{t-1}$).

Model represented in Eqn. (8) considers only one input and is referred as dynamic transfer function model. Since there are numerous other inputs, outputs and feedback forces which are operative in the atmosphere, their non-inclusion in the dynamic transfer model (Eqn. 8) is bound to introduce some error in the model forecast. By using the dynamics of ARIMA process, given above, the effects of all these forces can be added to one input dynamic transfer model. Let us assume that the inputs other than X_t, outputs other than Y_t and the numerous feedback forces operative in the atmosphere are responsible for introducing an error in the predicted output, obtained from the one input dynamic transfer model (Eqn. 8) by an amount, E_t according to :

$$
R_t = \frac{\omega(B)}{\delta(B)}\, X_t + E_t \tag{10}
$$

where E_t is the forecast error (or noise) and is supposed to be independent of X_t.

It is seen from Eqn. (10) that if E_t can be predicted, the one input model forecasts can be improved by applying an appropriate correction to it. For this purpose, a suitable forecast model for E_t is developed by using its past values which can be obtained as the error of the one input model forecasts. By using the dynamics of ARIMA process, the general form of forecast model for E_t can be represented as follows :

$$
E_t = \frac{\phi(B)}{\theta(B)}\, a_t \tag{11}
$$

where,

$$
\begin{aligned}
\phi(B) &= 1 - \phi_1 B - \ldots\ldots\ldots - \phi_g B^g \\
\theta(B) &= \theta_0 - \theta_1 B - \ldots\ldots\ldots - \theta_h B^h
\end{aligned}
\tag{12}
$$

and a s are random shocks or white noise.

TABLE 3

Values of constants for dynamic stochastic transfer model

	0	1	2	3	4	5
δi	—	–0.6000	–0.8750	–0.5000	–0.9950	–0.1625
ωi	0.0249	–0.0188	–0.0451	–0.0228	–0.0613	0.0200
θ_{i+1}	0.9500	–0.5000	0.2250	–0.4000	0.0250	–0.0500
θ_{i+7}	–0.6750	0.1623	–0.0751	0.1475	–0.3000	0.0500
a_{1971+i}	0.1323	–0.0411	0.0210	0.0033	–0.0170	0.0772
a_{1977+i}	–0.0142	–0.0748	–0.1095	–0.0248	–0.0115	–0.0060
a_{1983+i}	–0.0305	0.0520	–0.0134	–0.0275	–0.0534	0.0264

The forecast model for E_t given in Eqn. (11) is known as stochastic transfer function model. On using Eqn. (11) into Eqn. (10), the dynamic stochastic transfer (DST) model can be expressed as follows :

$$R_t = \frac{\omega(B)}{\delta(B)} X_{t-b} + \frac{\phi(B)}{\theta(B)} a_t \; ; b \geqslant 0 \qquad (13)$$

For the sake of generality let us assume that the input, output and noise series are non-stationary and by differencing them d times they become stationary, so that :

$$r_t = \nabla^d R_t \; ; \; x_t = \nabla^d X_t \text{ and } e_t = \nabla^d E_t \qquad (14)$$

where, $\nabla = 1 - B$ and is known as backward difference operator.

On using Eqn. (14) into Eqn. (13), the general form of the forecast DST model is given below :

$$r_t = \left[\frac{\omega(B)}{\delta(B)} \cdot x_{t-b}\right] + \left[\frac{\phi(B)}{\theta(B)} \cdot a_{t-1}\right] \qquad (15)$$

where symbols have been defined above.

The first and second functions on the right hand side of Eqn. (15) are respectively known as dynamic and stochastic transfer function models. From the DST model given above, an optimal output forecast of an atmospheric variable r_t, say monsoon rainfall, can be obtained when the current value of input becomes available.

7.2. *DST forecast model for monsoon rainfall over India*

The position of 500 hPa April sub-tropical ridge over India (along 75° E longitude) has been considered as the input (X_t) and the monsoon rainfall during June to September over India as a whole as the output (R_t) of the atmosphere. The location of the 500 hPa ridge over India shows a direct relationship with the Indian summer monsoon rainfall (Banerjee *et al.* 1978) and has been utilized by the author for developing suitable DST model for forecasting the monsoon rainfall over two major sub-divisions of India, namely, Peninsula (Thapliyal 1981) and northwest India (Thapliyal 1984). Since the models have shown encouraging results a new DST model for forecasting monsoon rainfall over India, as whole, has been developed. For this purpose, the 33 years period (1951-1983) data for the input (500 hPa ridge) and output (Indian monsoon rainfall) have been studied in detail the author. On utilizing the standard procedures described by Thapliyal (1981) elsewhere, following DST model has been developed :

$$R_t = \left[\frac{R_{t-1} \prod_{i=1}^{5} (R_{t-i} / R_{t-i-1})^{\delta i}}{\exp\{-\omega_0 (X_t - X_{t-1}) + \sum_{i=1}^{5} \omega_i (X_{t-i} - X_{t-i-1})\}}\right] \cdot \left[\frac{1}{\exp \sum_{i=1}^{12} \theta_i a_{t-i}}\right] \qquad (16)$$

R_t is monsoon rainfall (in centimetre) over India, X_t is the latitudinal location of April 500 hPa sub-tropical ridge along 75° E longitude and ω s, δ s and θ s are model constants which are given in Table 3. For recent 18 years (1971-1988), the values of a s which have been obtained from Eqn. (11) are also given in Table 3.

At the end of April when X_t becomes available, the forecast for monsoon rainfall, R_t can be obtained from the model given in Eqn. (16). Model forecasts for a small part of sample period (1979-1983) and the test period (1984-1989) have been obtained and are shown in Fig. 3. It is seen from the figure that the predicted rainfall amounts are very close to the realized ones. The model has provided reasonably good forecasts not only during the normal years, but also during the drought (1982, 1986 and 1987) and excess rainfall (1983 and 1988) years. It may be noted from the figure that the DST model forecast indicates good rainfall (113% of the normal) during June to September 1989.

7.3. *Relative performance of DST model*

For comparing the performances of different models, forecasts have been obtained from MR, MPR and DST models and are shown in Fig. 3. It is noted from the figure that the DST model forecasts are much closer to the realized rainfall as compared to the forecasts which have been obtained from other two models. For recent test period (1984-88) the root mean square error of DST, MPR and MR models have been found 3.5, 9.9 and 12.4 per cent of normal, respectively. This indicates that the performance of the DST model is superior to other forecast models.

7.4. *Interpretation of DST forecast model*

Mathematical form of the DST model given in Eqn. (16) reveals that the forecasts, R_t is the function of the product of 7 inputs, (X_t to X_{t-6}), 6 outputs (R_{t-1} to R_{t-6}) and 12 random shocks (a_{t-1} to a_{t-12}). Thus the model utilizes 25 parameters for forecasting monsoon rainfall over India. This indicates that some kind of non-linearity, produced by the interaction of atmospheric climatic processes among themselves, has been incorporated in the model.

DST model can be devided into two parts, namely, the dynamic transfer model and the stochastic transfer model. The first part of the model shows that the input and the output of the past 6 and 7 years respectively, contribute to the forecast. This suggests that the dynamic transfer memory of climatic processes, linked with the Indian monsoon, is of the order of half a decade. The second part of the model (stochastic transfer) shows that the random shocks of past 12 years make significant contributions to the forecast. Detailed analysis of these shocks reveals that some of the shocks are associated with the annual quasi-biennial and southern oscillations.

8. Concluding remarks

Two approaches have generally been followed for improving the accuracy of the long range monsoon rainfall forecast. In the first approach, a number of parameters, precursor to the anomalous monsoon rainfall have been identified and used for prediction. Recent studies suggest that the Indian and the extra-Indian pre-monsoon conditions appear to have almost equal influence on the monsoon. However, by using first approach the accuracy of the forecast cannot be increased beyond a certain limit as the correlation coefficients between monsoon rainfall and different known predictors vary with time.

In the second approach, different forecast techniques have been developed by introducing a few new concepts in the field of LRF. These efforts have succeeded in develoing parametric, MR, MPR, ARIMA and DST models which have shown encouraging results. On studying the relative performance of all these models, highest accuracy has been found for the DST model. The mathematical form of the DST model reveals that for forecasting the model utilizes not only the transfer dynamics of the atmosphere but also its non-linearity. The model forecast is a function of the product of 25 parameters which include current year value of the input, past 6 years values of both the input and the output, and past 12 years values of the random shocks. It may be mentioned that some of the random shocks used by the model are related to the annual, quasi-biennial, and southern oscillations. Further analysis of the DST model corroborates the hypothesis (Thapliyal 1986) that the dynamic stochastic transfer memory of the atmosphere is of the order of a decade.

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