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Recent models for long range forecasting of southwest monsoon rainfall in India

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सार – इस देश के प्राचीन भागों में ब्लेन फॉर्ड और वॉकर के समय से ही दक्षिण-पश्चिम मानसून के दीर्घावधि पूर्वानुमान पर भारत के वैज्ञानिक कार्य के संबंध में लम्बी परम्परा रही है। हाल ही के दशक भारत मौसम विभाग में नए दीर्घावधि पूर्वानुमान निदर्शों के विकास के संबंध में वर्धित अनुसंधान का प्रमाण देते हैं जिन्होंने लगातार चार वर्षों, 1988 से 1991 के दौरान कुल मिलाकर, देश में, दक्षिण-पश्चिम मानसून वर्षा के सही दीर्घावधि पूर्वानुमान दिए हैं। इस समय, चार निदर्शों नामतः प्राचलिक, विद्युत समाश्रयण, गतिक प्रसंभाव्य स्थानांतरण और उन्नत बहुविध समाश्रयण निदर्शों का प्रयोग कुल मिलाकर देश में मानसून वर्षा के मौसमी पूर्वानुमान के निरूपणके लिए किया गया है। पूर्वानुमान दो अवस्थाओं में जारी किया गया। पहली अवस्था में, मुख्यतः प्राचलिक निदर्श पर आधारित गुणात्मक प्रकृति वाले अस्थायी अनुमान मध्य अप्रैल से पहले जारी किए जाते हैं जो कि 16 क्षेत्रीय और विश्व प्राचलों से सिगनलों का उपयोग करते हैं और वे भूमी, समुद्र और वायुमंडलीय प्रणोदनों से संबंधित रहते हैं और मानसून के साथ भौतिक बंधनों को प्रकट करते हैं। दूसरी अवस्था में, उपर्युक्त शेष तीन निदर्शों पर आधारित दृढ परिमाणात्मक पूर्वानुमान मई के अंत तक जारी किए जाते हैं हालांकि गत चार वर्षों के दौरान प्रोत्साहक कार्य प्रदर्शित करने वाले विद्युत समाश्रयण निदर्शों को अधिक महता दी गई है। इस शोध पत्र में हाल ही में विकसित इन निदर्शों और इनमें अन्तर्निहित वैज्ञानिक आधारों पर विचार-विमर्श किया गया। पिछले चार वर्षों (1988-91) के दौरान दीर्घावधि पूर्वानुमान के लिए प्रयुक्त इन परिचालित निदर्शों के मान्यकरण पर आधारित आंकड़ों को भी प्रस्तुत किया गया।

ABSTRACT. India has a long tradition of scientific work on long range forecasting of the southwest monsoon ever since the times of Blanford and Walker in the early parts of this century. The recent decades have witnessed increased research in regard to the development of new long range forecast models in the India Meteorological Department which have given correct long range (seasonal) forecasts of southwest monsoon rainfall, over the country as a whole, during the successive four years, 1988 to 1991. Presently, four models namely, Parametric, Power Regression, Dynamic Stochastic Transfer and Improved Multiple Regression models are being used for formulating the seasonal forecast of monsoon rainfall over the country as a whole. The forecast is issued in two stages. In the first stage, a tentative inference which is qualitative in nature, is issued before the middle of April based mainly on the Parametric model which utilizes signals from 16 regional and global parameters that are related to land, ocean and atmospheric forcings and show physical linkages with monsoon. In the second stage, a firm quantitative forecast is issued towards the end of the May and is based on the remaining three models, mentioned above, although higher weightage is given to the Power Regression Model which has shown encouraging performance during the last four years. In this paper, these recently developed models and the scientific basis underlying these are discussed. Data on validation of these operational models, used for the long range forecast during the past four years (1988-91) are also presented.

Key words — Parametric model, Power regression, Dynamic stochastic transfer, Improved multiple regression, Southwest monsoon

1. Introduction

India was the first country to start a systematic development of Long Range Forecast (LRF) technique for estimating, in advance, the seasonal monsoon (June to September) rainfall over the country as a whole as early as 1875. The India Meteorological Department (IMD) has laid a great emphasis on LRF of monsoon rainfall, since its inception. The first operational forecast was issued by it on 4 June 1886 based on observed inverse relationship between the seasonal monsoon rainfall in India and the preceding snow cover over the Himalayas (Blanford 1884). Since then, efforts have been continued for developing better LRF techniques. Forecasting of seasonal monsoon rainfall over India was the motivation for Sir Gilbert Walker's (1923, 1924) pioneering work on the Southern Oscillation. In 1910, he introduced the concept of correlation in the field of LRF and developed a Multiple Regression (Walker 1910) model for forecasting the monsoon rainfall over India. Since then, the correlation technique is widely being used, in some form or the other. During the decade of 1981-1990, concerted efforts to develop new LRF techniques resulted in the development of new types of LRF models, namely, Dynamic Stochastic Transfer (Thapliyal 1982 & 1990), Parametric (Gowariker *et al.* 1989) and Power Regression (Gowariker 1989, 1991).

Presently, the IMD is using these LRF models along with the improved Multiple Regression model for issuing the operational forecasts. Monsoon rainfall forecasts, issued for successive 4 years (1988-1991) have proved to be correct.

In this paper, an attempt is made to describe different kinds of LRF models presently used for issuing the operational forecast of monsoon rainfall over India as a whole. The basis for the development of the new models namely, the Parametric (P), Power Regression (PR), and Dynamic Stochastic Transfer (DST) is also presented. Procedure for issuing forecast in two stages, namely, tentative and final is briefly discussed.

2. Early attempts to develop forecast techniques

Since time immemorial, mankind has been fascinated with the art of forecasting the future weather. In *Brihat Samhita* (an encyclopedia of astronomy and meteorology prevalent in ancient India) compiled by Varahmihira around the sixth century A.D., some meteorological information useful for LRF has been mentioned (Thapliyal 1986). The clouds that are formed in the first half of *Chaitra* (April) will yield water in the later half of *Asvin* (September) and those that are formed in later half of *Chaitra* (April) will rain in the first half of *Kartika* (October) (Couplets 9-12, Chapter XXI). This was, perhaps, an attempt at LRF of winter monsoon rainfall from cloud conditions observed four to five months earlier. Although the verification of the forecasts obtained by using these concepts shows limited success but such forecasts appear to be indicative of some physical phenomenon of the atmosphere like 30 to 60 day oscillations. In the present case, a suitable multiple of such oscillations may provide a basis for the forecast. Subsequent to these historical references, no major efforts seem to have been made till the late nineteenth century, when recurrent climate related disasters led some newly formed weather services, like the India Meteorological Department (IMD) to develop methods for LRF of seasonal monsoon rainfall over the country. Blanford (1884) the then Meteorological Rapporteur to the Government of India issued the first LRF of summer monsoon rainfall over the whole of India and Burma based on pre-monsoon Himalayan snow cover. After a few years, forecast based on this single parameter did not exhibit reasonable accuracy. Besides at that time, objective methods of LRF were not available and this created further problems for the operational forecasts.

A major break-through came in 1907 when Sir Gilbert Walker (1910) the then Director General of the IMD introduced an objective method of correlation into LRF. The method is based on the assumption that the association of various antecedent meteorological factors with the forecast element, found in the past by the correlation technique, will persist in the future also. The first MR-model based on this principle; contained four parameters (predictors) namely, the Himalayan snow accumulation at the end of May, South American pressure for Spring, Mauritius pressure for May and Zanzibar District rain for April and May. The MR model was used to prepare tentative forecast in 1907. Since then a number of predictors as well as MR models have been used for issuing operational forecasts. Utilising the correlation technique, Walker (1923) embarked on a worldwide search for an association between the Indian monsoon rainfall and antecedent weather features in different parts of the world. This monumental work not only brought out many scientific ideas of lasting value such as the Southern Oscillation; the North Atlantic and the North Pacific Oscillations; but also resulted in the development of a few MR-Models for forecasting monsoon rainfall over three homogeneous regions of India, namely, the Peninsula, Northwest India and Northeast India. In recent years, tremendous interest has been generated in the Southern Oscillation as many scientists feel today that the phenomenon, if understood well, is capable of identifying physical linkages among various regions of the atmosphere.

After issuing the forecast for 6 years (1924-30), the forecast for Northeast India was discontinued due to unsatisfactory accuracy. However, the forecasts for the remaining two divisions were issued from 1924 to 1987. The monsoon rainfall forecast for India as a whole was issued from 1886 to 1923 and again since 1988. A brief review is available in the literature (*e.g.*, Jagannathan 1960, Thapliyal 1987 and Shukla 1987). Thapliyal (1987) has verified the forecasts issued during 1924 to 1982 and has found positive skill score. He however, found that the forecasts were correct on about 65 % occasions only. On analysing the reasons for forecast failure, he found that the accuracy of the MR forecast cannot be increased beyond a certain limit (Thapliyal 1991), since the model projects the relationship (measured by correlation coefficient) observed in the past, into the future and this changes with time. To account for this temporal variation in the correlation coefficient, IMD started, since thirties, the periodic updating of its operational MR-models (Thapliyal 1991a). In recent years, however, the upgrading of the MR-model is being done every year which accounts for temporal variations of the relationship, at least partially.

Following the procedure mentioned above, the MR-model based on 37 years (1951-1987) data has been upgraded and the details of the model used for preparing the operational forecast in 1988 (Thapliyal 1990) are given below :

$$R = K_0 + \sum_{i=1}^{4} K_i Y_i + K_7 Y_7 \qquad (1)$$

where, R is seasonal monsoon rainfall (cm) over India, Y's are parameters or predictors (Table 1), and K's are model constants (Table 2).

For improving the performance of the MR model, given in Eqn. (1), two more physically linked parameters have been added (Thapliyal 1991a). The details of the model are given below :

$$R = K_0 + \sum_{i=1}^{7} K_i Y_i \qquad (2)$$

TABLE 1

Parameters used in Multiple Regression Model

Y_1	500 hPa April Ridge	Y_5	Pressure Anomaly (J+F+M+A) 36-40° N
Y_2	E.C. India Temp., March	Y_6	Temp. Anomaly, (Mar-Jan)
Y_3	N. India Temp, March	Y_7	Darwin Pressure Spring
Y_4	Temp. Anomaly Peru Coast, August (El-Nino category of P.Y.)		

TABLE 2

Constants for Multiple Regression Model

	Year and period of data used			
	1988 (1951-1987)	1989 (1951-1988)	1990 (1951-1989)	1991 (1951-1990)
Multiple CC	0.76	0.79	0.79	0.79
K_0	—22.5097	—1.3562	—1.0060	0.3936
K_1	30.1852	28.3105	28.3681	28.3242
K_2	59.6442	67.7058	67.0586	66.6206
K_3	0.1725	—3.2592	—3.2656	—3.0204
K_4	10.2264	2.1996	2.1244	2.2445
K_5	—	1.1506	1.1757	1.1535
K_6	—	—21.0043	—20.7322	—20.7931
K_7	—11.5642	—12.4341	—13.3426	—13.4470
Forecast based on data up to 20 May	108%	98%	101%	100%
Forecast based on data up to 31 May	108%	100%	107%	100%
Actual Rainfall	119%	101%	106%	91%

The regression coefficients of MR-model, given in Eqn. (2) were updated every year adding yearly data. The updated model was used for preparing the forecast for 1989, 1990 and 1991. Actual model forecasts for 1988-1991 are shown in Table 2. It is seen from the table that the forecast rainfall amounts obtained, both by using data up to 20 May and also 31 May, are similar. It may also be noted that these forecasts are quite close to the realised ones. As mentioned above, the MR forecasts were used for framing the final forecasts, issued by the IMD during the 4 years (1988-1991). The forecasts proved to be correct.

It may, however, be mentioned that the problem of LRF is so complex that the correlation technique is still being used in some form or other, by weather services including the advanced ones for issuing their operational LRFs, inspite of the fact that the MR-models have their own limitations. Therefore, better forecast models need to be developed which are able to overcome the limitations of the MR-models.

3. Basis for developing new forecast models

Even the periodic updating of the MR-model has not been able to remove fully the inherent limitation of MR technique. Before attempting to explain the basis for new models, it would be helpful to understand why the forecast obtained from earlier models which were based on regression came correct in some years while failed in others. During 1940's and 1950's, the monsoon was wet on all years, except in 1941 and 1951. However, a large number of forecasts came incorrect during this period. One of the reasons for incorrect forecast, appear to be the non-revision of the MR-models. As mentioned above, the MR-models are based on the assumption that the association measured by the Correlation Coefficient (CC) between predictor and predictant, computed based on past data would persist in future also. However, this does appear to happen in actual practice and, therefore, to examine the validity of this assumption, several investigators (Jagannathan 1960, Thapliyal 1986 & 1987, Parthasarathy *et al.* 1988 and 1990, etc) have studied the time variation of the CCs between different predictors and Indian monsoon rainfall. The studies have revealed that the CC varies with the time and even changes its sign. This temporal variation of the CC, questions the very basic assumption of the regression models and in turn, is responsible (Thapliyal 1987) for limiting the accuracy of the forecast. On detail study, Thapliyal (1987 & 1990) noted epochal pattern of variation of the association (or CC) between the predictor and the monsoon rainfall. He proposed a hypothesis (Thapliyal 1986 & 1990) that the resultant association (ρ_R), operative during a particular period is made up of two types of associations, namely, climatic (ρ_C) and perturbed (ρ_P) as given below :

$$\rho_R = \rho_C + \rho_P \tag{3}$$

To serve as an example, the CCs in respect of Darwin Spring pressure (an index of Southern Oscillation, an important climate forcing) have been computed for increasing periods, like, 10, 11, 12..........88 years as well as for running 10-year periods starting from 1910 and are shown in Fig. 1. In the figure, the dotted line indicates the CC for increasing periods while the solid line indicates the CC for running (sliding) 10-year periods. The latter indicates the association between the perturbed (short term) climatic forcings (ρ_P) and the monsoon rainfall while the former indicates the association between the rainfall and the basic (or long term) climate forcing (ρ_C). It is speculated that the perturbed climate association represents the resultant association between the monsoon rainfall and the climate forcings, having oscillation period up to 10 years. In this short time scale, the Quasi-Biennial Oscillation, Southern Oscillation etc. seem to be important climate forcings. It is seen from the figure that the perturbed climate association shows random fluctuations—during the 88 years. The CC's have changed their magnitude and sign from one epoch to the other. Thus, the assumption of the MR-model that the association observed in the past, can be extended to the future is not valid.

On the other hand, the basic climatic association represented by the increasing period CC, does not exhibit random fluctuations and approaches to its asymptotic value as the period becomes more than 50

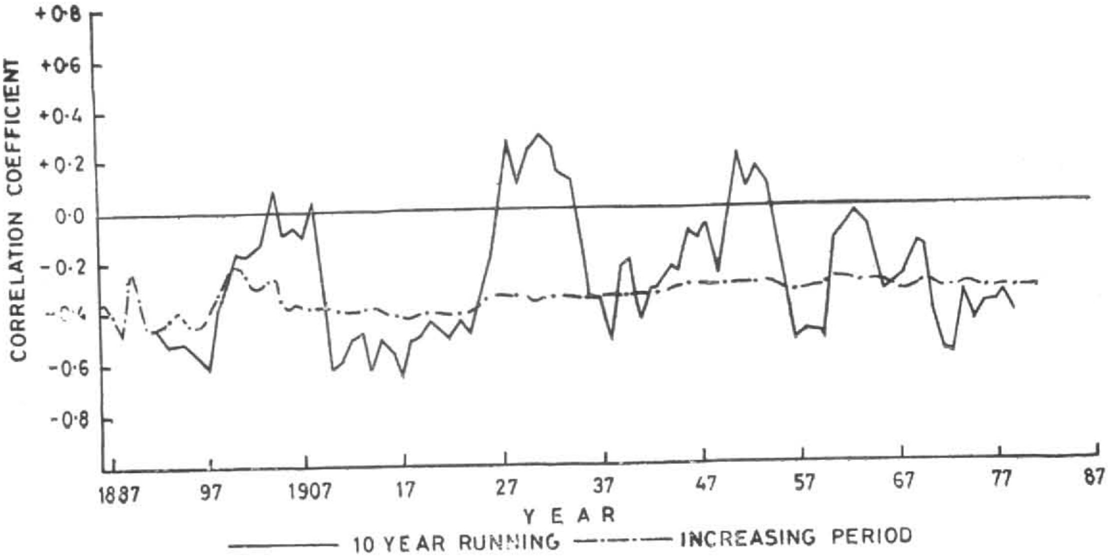

Fig. 1. Correlation coefficient between Indian monsoon rainfall and Darwin pressure (Spring) (Limitation of correlation—An example)

years. It is seen from Fig. 1 that the basic climatic association has not changed during the 80 years and can, therefore, be extended in future also. Thus, the assumption of the MR-model is valid as far as the basic climatic association is concerned. Thapliyal (1987, 1991 b) has speculated that the basic climate association, represents the resultant association between the monsoon rainfall and the mean of the climate forcing over a long period of time, say about 50 years. In this time scale, the ocean atmosphere interaction seems to be the most important forcing.

The effective (or actual) association between a predictor and the rainfall, as mentioned above, is the vector sum of the basic-and perturbed-climate associations and both have to be used for accurate prediction. It may be noted here that for forecasting, the regression model uses the basic climatic association only and leaves out the contribution of the perturbance part. This limits the accuracy of the regression forecast. It can, therefore, be concluded that for improving the forecast accuracy, a new kind of LRF model need to be developed which is able to utilise both the perturbed and the basic climatic associations. Efforts made in this direction have resulted in the development of new LRF models. A brief description of these models is given below.

4. New long range forecast models

Realising the limitations of Multiple Regression technique, concerted efforts were made in India to improve the accuracy of LRF models. Generally, two approaches are followed for improving the accuracy of LRF models (Thapliyal 1987). In the first approach, a number of predictors are identified by following different methods particularly, the correlation. Initially, the spot values of the meteorological elements used as predictors were essentially surface observations from different locations of the world but during the past three decades (1960-1989), predictors related to the troposphere, stratosphere, ocean surface and ocean-atmosphere coupling have been identified. During the past two decades (1970-1989), the regional parameters (500 hPa April sub-tropical ridge over India, Banerjee *et al.* 1978, etc) and the global parameters (50 hPa east-west extension of ridge-trough system, Thapliyal 1984; surface temperature over Northern Hemisphere during winter, Verma *et al.* 1985 etc) have been used as predictors. Though by using this approach the accuracy of the forecast has increased slightly but it need to be improved further. Thus, whatever may be the nature of the predictant-predictor pair, its random temporal variations are going to produce higher forecast errors in some epochs as compared to the other (Fig. 1). Similar pattern is found for almost all known predictors. It suggests that the accuracy (Thapliyal 1987, 1990) of the LRF model can be improved further provided that both the climatic (long term) and perturbed (short term) forcings are used for LRF.

In the second approach, different forecast techniques using both, the climatic and perturbed associations, have been developed by introducing new concepts in the field of LRF. This has resulted in the development of LRF models like Power Regression, Parametric, Auto-Regressive Integrated Moving Average and Dynamic Stochastic Transfer etc. Important aspects of some of these models have been briefly discussed below.

4.1. *Parametric model*

To overcome the limitations of earlier LRF models like, MR it is felt that if a large number of predictors (parameters), well distributed in time and space are collectively used, the resultant signal from a group of predictors may improve the accuracy of the forecast (Thapliyal 1991b). In one scenario, the changing pattern of the association may first emerge at one level and travel subsequently to the other levels. In another possible scenario, the change in the association may appear in one parameter first and then in others. To test this hypothesis, a group of 16 predictors which includes global and regional-atmosphere-land-ocean parameters, covering antecedent period from December to May were selected (Gowariker *et al.* 1989 & 1991). A parametric model was developed by utilising the signals from all the 16 parameters, defined in Table 5 as X_1 to X_{16}. A parameter having positive CC with the monsoon

TABLE 3

Inferences based on signals from 16 parameters (Period : 1951 - 1987)

Favourable parameters (%)	No. of occasions	Monsoon condition		Remarks
		Wet	Deficient	
>80	3	3	0	Rainfall on +ve side of normal
>70	4	4	0	
>60	18	18	0	1963 (—2), 1969 (—2), 1985 (—7)
>50	23	22	1*	*1966 (—14)
<50	14	5	9	
<40	12	3	9	
<30	6	1	5	
<20	3	1*	2	*1957 (—2)
<10	1	0	1	
0	1	0	1	

TABLE 4

Constants of Power Regression Model

I	Model's constants			
	a_i	β_i	p_i	C_i
0	0	1	—	$+0.1303086\times10^{+2}$
1	50	10	1.4	-0.5824688×10^{-1}
2	0	10	—2.0	$+0.3026653\times10^{+2}$
3	0	10	—4.0	$-0.1733019\times10^{+1}$
4	0	10	4.0	$+0.6958737\times10^{0}$
5	50	10	—0.4	$-0.1956036\times10^{+2}$
6	0	10	4.0	$+0.4374519\times10^{0}$
7	0	10	4.0	$+0.4687574\times10^{-2}$
8	0	100	—3.9	$-0.1662928\times10^{+6}$
9	50	10	—4.0	$-0.4617612\times10^{+5}$
10	50	10	4.0	$+0.5844691\times10^{-1}$
11	50	10	4.0	-0.4456572×10^{-2}
12	0	10	4.0	-0.1497441×10^{0}
13	0	1000	3.3	$-0.1183124\times10^{+4}$
14	50	10	4.0	-0.1344925×10^{-1}
15	50	10	—4.0	$+0.1940398\times10^{+5}$
16	0	1000	3.3	$+0.1257985\times10^{+4}$

rainfall, shows favourable (unfavourable) signal for wet monsoon (rainfall greater than or equal to 90% of long period average) if its anomaly is + ve (—ve). Similarly, a parameter having —ve CC shows favourable (unfavourable) signal for wet-monsoon if its anomaly is —ve (+ve). When the monsoon rainfall is normal (*i.e.*, within ±10% of long period, average) or excess (*i.e.*, >110% of long period average), the monsoon is termed as wet. On the other hand, when the rainfall is less than 90% of the long period average, the monsoon is termed as deficient. The long period (1901–1970) average of monsoon rainfall over the country as a whole is 88.1 cm. In parametric model, equal weightage given to each of the 16 parameters which have been selected due to their apparent physical linkage with the Indian monsoon. Following the procedures mentioned above, a parametric model has been developed by using the data for past 37 years (1951–1987). Percentage number of favourable parameters out of the 16, have been determined for each year of the sample period (1951–1987) and are compared with the performance of the subsequent monsoon rainfall over India. The analysis is presented in Table 3. It is seen from the table that whenever 70 per cent or more parameters out of 16 are favourable for wet monsoon (normal or excess), the subsequent monsoons were not only normal but the rainfall was on positive side of the normal on all occasions. However, whenever 20 per cent or less parameters were favourable, the monsoons were deficient (rainfall less than 90% of the long period average) on 66 per cent occasions only. Similarly, wet monsoons were followed on all occasions when 60% or more parameters were favourable, while deficient monsoons were followed only on 75 per cent occasions when 40 per cent or less parameters were favourable. This suggests that higher confidence is obtained for wet, rather than for deficient monsoon forecast.

The parametric model is purely qualitative and it indicates whether monsoon would be wet or deficient.

TABLE 5

Values of parameters used for obtaining PR model forecast as percentage of long period average *versus* actual rainfall

Parameters	1988	1989	1990	1991
(X_1) = 50 hPa wind, (Deg. Long.)	60.0	110.0	0.0	135.0
(X_2) = Eurasian snow (million sq km)	25.7	25.6	26.7	27.1
(X_3) = 500 hPa ridge (Deg. North)	14.5	16.5	15.5	15.0
(X_4) = C. India Temp. (°C)	29.1	28.3	26.1	28.7
(X_5) = 10 hPa zonal wind (m/s)	9.0	—35.0	—11.8	—34.8
(X_6) = E.C. India Temp. (°C)	24.2	22.1	25.3	25.3
(X_7) = N.H. Press. Anom. (hPa)	50.0	53.6	52.9	49.5
(X_8) = Argentina Press. (hPa)	991.1	988.9	987.0	988.1
(X_9) = N.H. Temp. (°C)	0.58	0.40	0.90	0.77
(X_{10}) = SOI (Tahiti—Darwin) (hPa)	2.8	4.6	2.7	0.4
(X_{11}) = El-Nino, P.Y., (Category)	4.0	1.0	1.0	1.0
(X_{12}) = N. India Temp. (°C)	18.5	18.1	17.4	19.4
(X_{13}) = I.O.E. Press. (hPa)	1010.8	1010.2	1011.5	1011.9
(X_{14}) = El-Nino. S.Y., Category	1.0	1.0	1.0	2.0
(X_{15}) = Himalayan snow, Index	1.19	1.2	1.2	3.1
(X_{16}) = Darwin Press. (hPa)	1009.8	1008.8	1011.0	1012.4
Forecast based on data up to 20 May	113%	102%	101%	94%
Forecast based on data up to 31 May	(113%)	(101%)	(102%)	(95%)
Actual rainfall	119%	101%	106%	91%

TABLE 6

Values of constants for Dynamic Stochastic Transfer Model

	Constants	0	1	2	3	4	5	6	Monsoon rainfall in percentage	
									Forecast	Actual
1989	ω_i	0.0249	−0.0188	−0.0351	−0.0228	−0.0513	−0.0100	0.0049	102	101
	δ_i		−0.6000	−0.7750	−0.5000	−0.9250	−0.1625	−0.0875		
	θ_i		0.6000	−0.4500	0.3750	−0.4500	0.0250	0.2500		
	θ_{i+6}		−0.4050	0.3450	−0.1550	0.4700	−0.1550	0.0950		
1990	ω_i	0.0249	−0.0188	−0.0351	−0.0228	−0.0513	−0.0100	0.0049	96	106
	δ_i		−0.6000	−0.7750	−0.5000	−0.9250	−0.1625	−0.1000		
	θ_i		0.6000	−0.4000	0.2750	−0.3500	0.0750	0.2500		
	θ_{i+6}		−0.2800	0.4700	−0.0300	0.2200	−0.2800	0.2200		
1991	ω_i	0.0492	−0.0516	−0.0348	−0.0384	−0.0560	−0.0067	0.0033	93	91
	δ_i		−0.8413	−0.5163	−0.2851	−0.7786	−0.0589	−0.0148		
	θ_i		−0.0657	0.1833	0.3197	0.0040	−0.6160	0.7231		
	θ_{i+6}		−0.5300	0.4700	0.2200	0.2200	−0.0300	0.2200		

However, it enables us for decision making, in advance, for foreshadowing the subsequent monsoon. The performance of the model is encouraging during sample (1951–1987) as well as operational (1988–1991) period. Model was used for preparing the monsoon forecasts, issued by the IMD (Table 7) during recent 4 years (1988–1991). On all the successive four years, the qualitative forecast obtained from the parametric model proved to be correct. In addition, it may be mentioned that the tentative monsoon forecasts are being issued before the middle of April every year, since 1989 (Table7). These forecasts are generally based on the signals obtained from the clinched parameters, after the end of March as well as the estimated signals from the remaining unclinched parameters out of the 16. So far, the performance of the tentative forecasts seem to be encouraging. In addition, the inferences from such forecasts, though tentative, are available two months earlier of the final quantitative forecast which is issued in the second half of May.

4.2. *Power Regression Model*

Maintaining its leading position in the field of operational LRF, India has recently developed a unique long range forecast technique which resulted in the development of Power Regression Model (Gowariker *et al.* 1991). The model utilises 16 important global and regional climate forcings for monsoon, known as parameters. The combination of the 16 parameters represents the land-ocean-atmospheric forcings which appear to have physical links with the evolution of the subsequent monsoon. The model is capable of taking a balanced view by utilising the mathematically derived resultant effect, produced on monsoon by different important climate forces which represent oceanic and other developments as far as twenty thousands kilometres away from India and also at different levels of the atmosphere up to the height of 30 kilometres. The model acknowledges the non-linear interactions of different important climatic forcings with the Indian monsoon and accordingly, the sign and the magnitude of the influence of each parameter or predictor on monsoon rainfall over India have been determined and used for developing the Power Regression Model (Gowariker *et al.* 1991) given below :

$$\frac{R + \alpha_0}{\beta_0} = C_0 + \sum_{i=1}^{16} C_i \left(\frac{X_i + \alpha_i}{\beta_i}\right)^{p_i} \quad (4)$$

where, R is monsoon rainfall over India as percentage of the long period average rainfall; X's are different parameters (defined in Table 5) and α's, β's, p's and C's are model constants (defined in Table 4).

TABLE 7

Long range forecast of total seasonal "monsoon" rainfall over India as a whole as percentage of Long Period Average (LPA)

Year	Forecast type / Date of issue	Forecast	Actual
1988	Final / 27 May	Favourable signals from 86% parameters indicate the normal (±10% of LPA) monsoon but on positive side	Rainfall was on +ve side of normal (119%) —indeed a good monsoon rainfall year
1989	Tentative / 11 April	Present and emerging signals indicate normal monsoon	Monsoon rainfall was normal
1989	Final / 25 May	(a) Favourable signals from 75% parameters indicate normal monsoon but on positive side	Rainfall was on +ve side of normal
		(b) Monsoon rainfall would be 102% of LPA with an estimated error of ±4%	Seasonal monsoon rainfall was 101% of LPA
		(c) 80% of the 35 met. sub-divisions would receive normal/excess (>110% of LPA rainfall)	83% met. sub-divisions received normal/excess rainfall
1990	Tentative / 6 Feb	Present and emerging signals indicate normal monsoon	Rainfall was normal
1990	Final / 25 May	(a) Favourable signals from 55% parameters indicate normal monsoon with 85% probability to be on positive side	Seasonal monsoon rainfall was not only normal but it was on +ve side of the normal
		(b) Seasonal monsoon rainfall would be 101% of LPA with an estimated error of ± 4%	Monsoon rainfall was 106% of the LPA
		(c) 80% met. subdivisions would receive normal/excess rainfall	91% met. sub-divisions received normal/excess rainfall
1991	Tentative / 2 April	Present and emerging signals indicate normal monsoon but on negative side	Rainfall was on —ve side of normal
1991	Final / 27 May	(a) Favourable signals from 50% parameters indicate 96% probability for normal monsoon	Rainfall was on —ve side of normal
		(b) Seasonal monsoon rainfall would be 94% of LPA with an estimated error of ±4%	Rainfall was 91% of LPA
		(c) 75% met. subdivisions would receive normal/excess rainfall	75% met. sub-divisions received normal/excess rainfall

The model has enabled the India Meteorological Department to predict, successfully, the monsoon rainfall over India during the last 4 years, 1988 to 1991. Verification of model forecasts since 1958 is presented in Fig. 2. It is seen from the figure that in most of the years, the observed rainfall is quite close to the model forecast even in the extreme deficient or excess rainfall years. For recent 4 years (1988 to 1991), the actual values of different parameters, as used for computing the operational forecasts are given in Table 5. In the same table, the forecast *versus* the actual rainfall are presented for period (1988-1991) during which the actual forecasts were issued every year. For monsoon 1991, for example, the model forecast has indicated that monsoon rainfall over India as a whole would be 94% (with estimated error ±4%) of the long period average. Besides, about 25% of the meteorological sub-divisions of the country (for meteorological purpose, India is divided into 35 meteorological sub-divisions) are likely to receive deficient rainfall during the season. Performance of monsoon in 1991 validated the forecast.

The model has given rise to a theory that it is a tapestry of several relevant climatic forcings that govern the quality and quantity of the Indian monsoon. At any rate, the adverse poising of any one climatic forcing (or predictor), no matter how significant it is, need not create a unidimensional impression that the monsoon is going to be deficient (Gowariker *et al.* 1991). This mathematical result of the model has been found to be of great utility particularly, while interacting with the users.

4.3. *Dynamic stochastic transfer model*

The atmosphere is a complex dynamic system and it transforms various inputs into numerous outputs, like, monsoon rainfall over India. For such a system, the transfer dynamic relationship between the continuous input and output series can be expressed by a differential equation. However, when the series are discrete, the relationship is expressed by a difference equation of the form, given below :

$$R_t = \frac{\omega(B)}{\delta(B)} z_{t-b} \tag{5}$$

where, R_t is output and z_t is input and other constants are defined below :

$$\left.\begin{aligned} \omega(B) &= \omega_0 - \omega_1 B - \omega_2 B^2 \ldots - \omega_s B^s, \\ \delta(B) &= 1 - \delta_1 B - \delta_2 B^2 \ldots - \delta_r B^r, \end{aligned}\right\} \tag{6}$$

B is backward shift operator and ω's and δ's are unknown constants.

Following this approach, the Dynamic Stochastic Transfer Model (DST) has been developed by considering the April wind patterns at the height of 6 km over India as the leading forcing (or input series) to atmosphere and the rainfall over India during subsequent monsoon

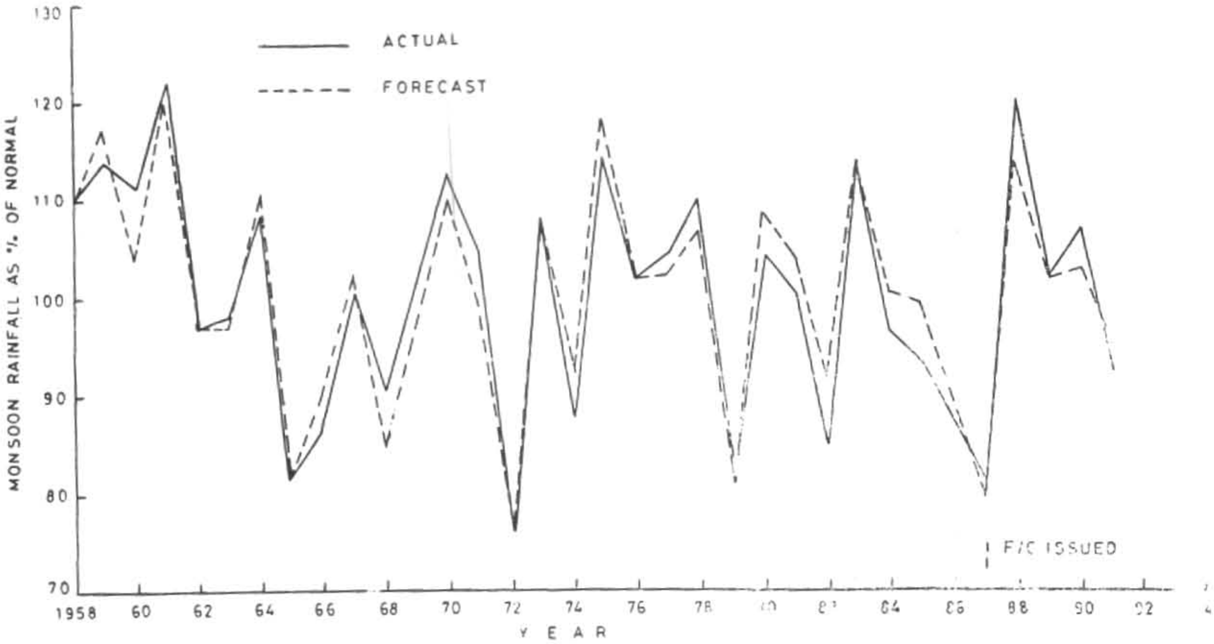

Fig. 2. Verification of forecasts obtained from Power Regression Model

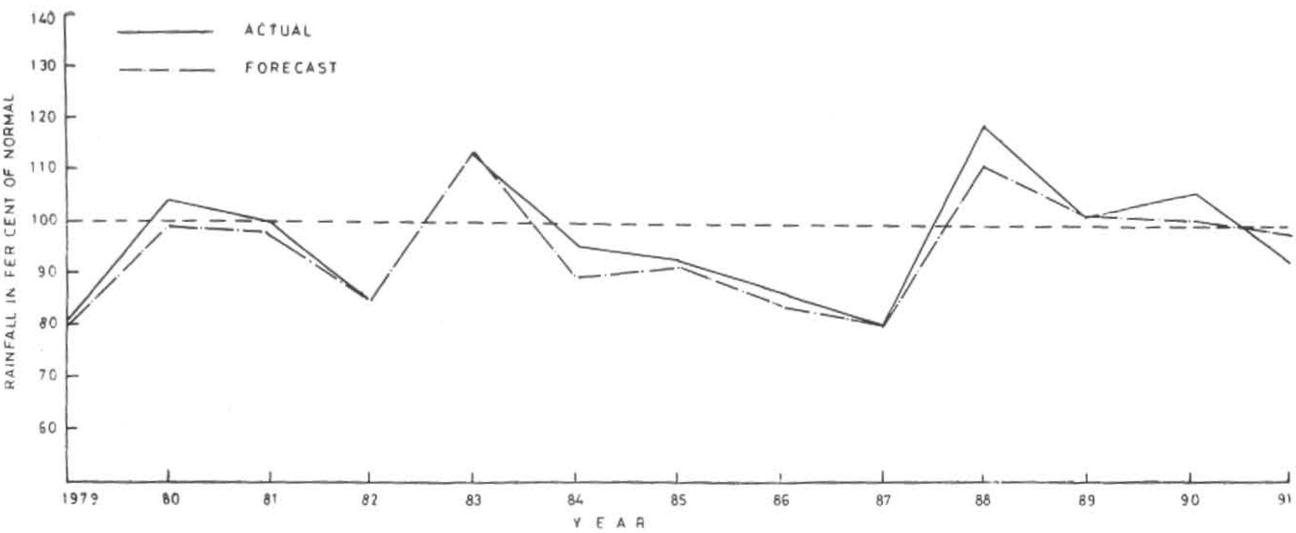

Fig. 3. Verification of forecast obtained from Dynamic Stochastic Transfer Model

season as the output from the atmosphere. The general form of the DST Model (Thapliyal 1990) is given below :

$$\frac{R_t}{R_{t-1}} = \left[\prod_{i=1}^{6} (R_{t-i}/R_{t-i-1})^{\delta i} \exp \{\omega_0 (z_t - z_{t-1}) - \sum_{i=1}^{6} \omega_i (z_{t-i} - z_{t-i-1})\}\right] \left[\exp (-1) \sum_{i=1}^{12} \theta_{i-} a_{t-i}\right] \quad (7)$$

where, R is seasonal monsoon rainfall for India, as percentage of long period average, z is location of 500 hPa April ridge line along 75°E longitude over India and ω's, δ's, θ's are model constants, and a's are climate forcings. For 1989 to 1991, the values are given in Table 6.

At the end of April, when input wind parameter of the current year becomes available, the subsequent monsoon rainfall can be forecast using the DST model given in equation (7). Model forecasts obtained for a few years are shown in Fig. 3. It is seen from the figure that the forecast rainfall amounts are quite close to realised rainfall. For 1991, the model indicated that the monsoon rainfall over India would be 93% of the long period average value. The realized rainfall in 1991 has been found 91% of the average. The accuracy of the DST model forecast is better than other models but is comparable with the PR Model. Thus, the application of a new concept of transfer dynamics of the atmosphere in the field of LRF has not only improved the accuracy of the forecast, but has also helped to develop such LRF models which are capable of using both the climate associations (basic and perturbed) through the non-linear interactions among the inputs and the outputs of the atmosphere of immediately past 6 to 12 years.

5. Forecasts issued during recent four years based on new model

On experimental basis, the parametric model was introduced in 1988. Since then, the seasonal monsoon rainfall over India as a whole is being issued every year. The summary of the forecast issued every year *versus* its verification is given in Table 7. The monsoon forecasts currently being issued are in two stages. Before the mid April, a tentative monsoon forecast is issued based on available signals from the clinched parameters and also the estimated signals from the remaining unclinched parameters. The tentative forecast is followed by the final forecast which is issued in the last week of May. The final forecast is based on the Parametric Power Regression, Dynamic Stochastic Transfer and updated Multiple Regression Models. Due weightage is given to the forecasts obtained from different models particularly, the PR and DST in view of their encouraging performance. The details of the forecast, issued for 1988-1991 by the IMD are given in Table 7. It is seen from the table that both the tentative and final forescasts issued by IMD based on new models, have proved correct in successive four years, 1988 to 1991.

6. Concluding remarks

Different forecast models have been developed which have shown remarkable accuracy since their inception in 1980's. The monsoon forecast issued by IMD based on these models, have proved correct during 1988 to 1991. During all these years, the IMD has received appreciation from different user agencies (*e.g.*, IMD, 1991). The forecast is now issued in two stages, first a tentative inference, in qualitative terms, by middle April, followed by the final quantitative forecast after two months towards the end of May.

The detailed analysis of the inherent limitations of MR technique has resulted in a hypothesis that for improving the accuracy of the LRF, both climatic and perturbed associations should be used by LRF model for forecasting. Application of this hypothesis (Thapliyal 1991b) in space and time has given rise to Parametric/Power Regression and Dynamic Stochastic Transfer Models which have shown reasonable accuracy. In view of these developments, the decade 1980-90 has witnessed increased research activity in regards to the development of new LRF models in IMD. This has helped the department to issue accurate forecast of southwest monsoon rainfall over the country as a whole during past successive four years, 1988 to 1991.

For further improvements of these models, it is necessary to obtain better physical insight into the atmospheric processes. This in turn is likely to provide know how for developing suitable forecast models for smaller regions. Presently, the long range forecast is issued for the country as a whole and for the entire four month season. Further research is necessary to develop similar forecast models for smaller regions and valid for shorter time periods.

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