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Present operational long range forecasting system for southwest monsoon rainfall over India and its performance during 2010

D. S. PAI, O. P. SREEJITH, S. G. NARGUND, MADHURI MUSALE and AJIT TYAGI*

India Meteorological Department, Pune, India

**India Meteorological Department, New Delhi, India*

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e mail : sivapai@hotmail.com

सार – इस समय भारत मौसम विज्ञान विभाग नवीनतम सांख्यिकीय तकनीकों के आधार पर तैयार मॉडल्स का कुशलतापूर्वक उपयोग करते हुए दक्षिणी–पश्चिमी मानसून ऋतु के विभिन्न प्रकार के मासिक और ऋतुनिष्ठ प्रचालनात्मक पूर्वानुमान जारी कर रहा है। प्रचालनात्मक मॉडल्स पर नियमित रूप से पुनर्विचार किया जाता है और शोध कार्यों के द्वारा इसमें और सुधार लाया गया है। समूचे देश में दक्षिणी – पश्चिमी मानसून ऋतु (जून–सितम्बर) की वर्षा का पूर्वानुमान देने के लिए अभी हाल ही में लागू किया गया संख्यात्मक इन्सैमबल पूर्वानुमान प्रणाली का उपयोग किया गया है। इसके अलावा देश के चारों भौगोलिक क्षेत्रों (पश्चिमोत्तर भारत, पूर्वोत्तर भारत, मध्य भारत और दक्षिण प्रायद्वीप) में मॉनसून ऋतु की वर्षा का पूर्वानुमान देने के लिए और समूचे देश में मानसून ऋतु के उत्तरार्द्ध में वर्षा के लिए पूर्वानुमान देने के लिए मॉडल्स विकसित किए गए हैं। समूचे देश में जुलाई, अगस्त और सितम्बर के महीनों में होने वाली मासिक वर्षा का प्रचालनात्मक पूर्वानुमान जारी करने के लिए भी मॉडल्स विकसित किए गए है। भारत मौसम विज्ञान विभाग द्वारा वर्ष 2010 के दक्षिणी–पश्चिमी मानसून वर्षा के लिए जारी किए गए प्रचालनात्मक पूर्वानुमानों का विवेचन किया गया तथा इसे प्रमाणित किया गया। इसके अतिरिक्त समूचे देश में ऋतु की वर्षा का भारत मौसम विज्ञान विभाग के अलावा देश के अनेक जलवायु शोध संस्थानों द्वारा संख्यात्मक और गत्यात्मक मॉडल्स पर आधारित किए गए प्रयोगात्मक पूर्वानुमानों पर भी विचार विमर्श किया गया है।

समूचे देश के लिए वर्ष 2010 में दक्षिणी–पश्चिमी मानसून ऋतु में दिया गया मासिक और ऋतुनिष्ठ दीर्घकालीन प्रचालनात्मक पूर्वानुमान सटीक रहा है। हालाँकि चारों भौगोलिक क्षेत्रों (पश्चिमोत्तर भारत, मध्य भारत, पूर्वोत्तर भारत और दक्षिण प्रायद्वीपीय भारत) के लिए ऋतु वर्षा का पूर्वानुमान उतना सही नही रहा। दक्षिणी प्रायद्वीप भारत में वर्षा का पूर्वानुमान वास्तविक वर्षा से अधिक आकलित किया गया था जबकि पूर्वोत्तर भारत में वास्तविक वर्षा का आकलन कम किया गया था। देश के विभिन्न जलवायु शोध संस्थानों द्वारा समूचे देश में ऋतु के दौरान हुई वर्षा के प्रयोगात्मक पूर्वानुमानों में भी काफी भिन्नता पाई गई है (एल.पी.ए. का 91 प्रतिशत – 112 प्रतिशत)।

ABSTRACT. At present, India Meteorological Department (IMD) issues various monthly and seasonal operational forecasts for the south-west monsoon season using models based on latest statistical techniques with useful skill. Operational models are reviewed regularly and improved through in house research activities. For the forecasting of the south-west monsoon season (June – September) rainfall over the country as a whole, a newly introduced statistical ensemble forecasting system is used. In addition, models have been developed for the forecast of the monsoon season rainfall over four geographical regions (NW India, NE India, Central India and South Peninsula) of the country and forecast for the rainfall over the second half of the monsoon season over the country as a whole. Models have also been developed for issuing operational forecast for the monthly rainfall for the months of July, August & September over the country as a whole. Operational forecasts issued by IMD for 2010 south-west monsoon rainfall have been discussed and verified. In addition, the experimental forecasts for the season rainfall over the country as a whole based on both statistical and dynamical models received from various climate research institutes within the country other than IMD are also discussed.

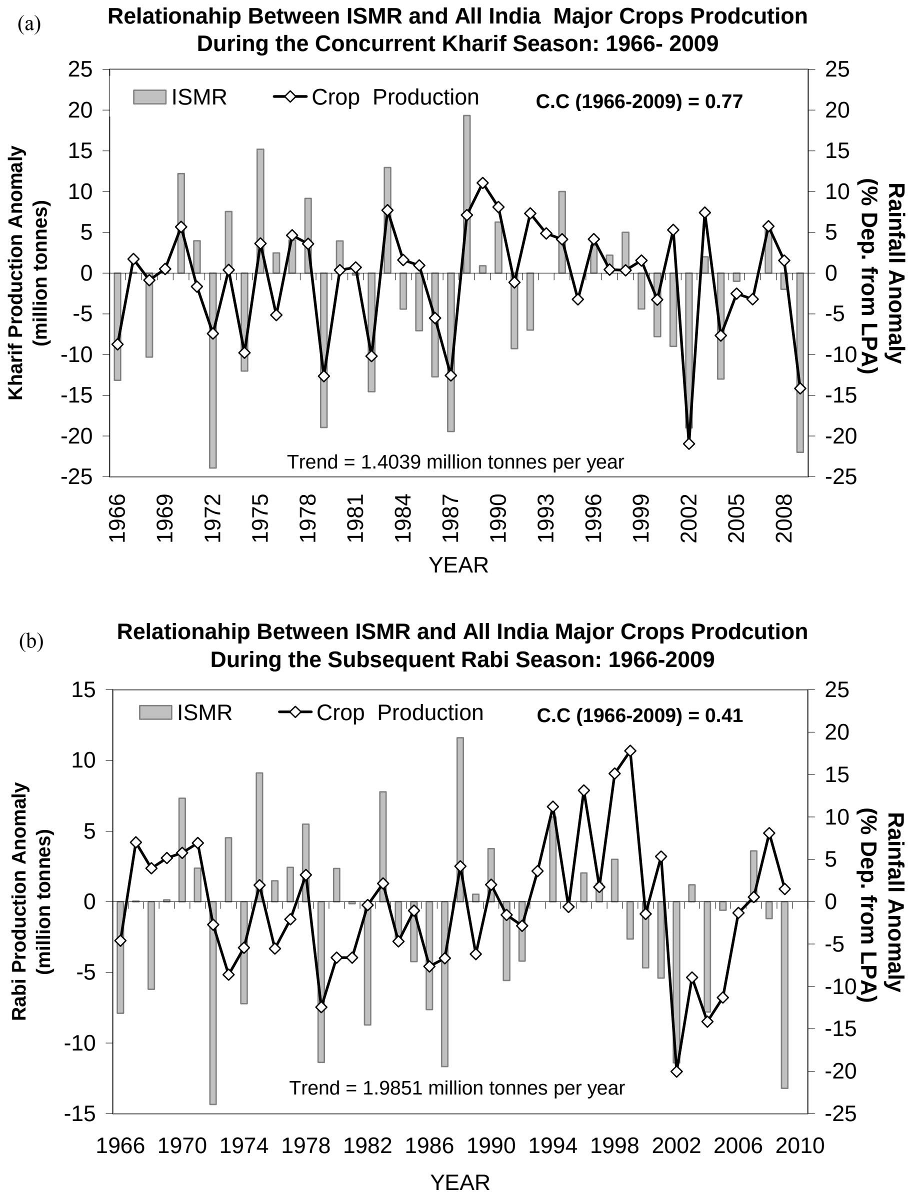
The operational monthly and seasonal long range forecasts issued for the 2010 southwest monsoon season for the country as a whole were accurate. However, forecasts for the season rainfall over the 4 geographical regions (Northwest India, Central India, Northeast India and south Peninsular India) were not accurate as the forecast for South Peninsular India overestimated the actual rainfall and that for northeast India underestimated the actual rainfall. The experimental forecasts for the season rainfall over the country as whole from various climate research institutes within the country showed large variance (91 % - 112% of LPA).

Key words – Operational long range forecasting, Indian southwest monsoon rainfall, India Meteorological Department, rainfall-crop production relationship, Statistical ensemble forecasting system etc.

1. Introduction

The agricultural practices in India have traditionally been tied strictly to the annual cycle of rainfall. The annual rainfall of the country averages around 1,200 mm. The summer monsoon accounts for almost all the annual rain in 75% of the geographical area and 78% of the gross cropped area. About a third of the cropped area is still rain fed. The most significant feature of the annual cycle of the Indian summer monsoon is its regularity. However, the very regularity of the monsoon makes agriculture susceptible to the changes in the annual cycle of the rainfall. Although the Indian southwest monsoon rainfall (ISMR) averaged over the whole of India is found to be stable over the past about 140 years with no noticeable long-term trend, the ISMR has shown considerable inter-annual variation and major droughts/floods have occurred in some years. The long-range forecast of ISMR is very crucial as the inter-annual variation of ISMR has many social and economic impacts. The total monsoon rainfall during the season has a statistically significant relationship with the crop yield, generation of power, irrigation schedule etc. over the country. In general, a weak monsoon year with significantly low rainfall can cause a low crop yield. On the other hand, a strong monsoon is favorable for abundant crop yield, although sometimes too much rainfall may cause devastating floods. Parthasarathy *et al.* (1988) and later Gadgil (1996) and Webster *et al.* (1998) have shown an in phase variation of the rice production in India with the all India summer monsoon rainfall. Figs. 1(a&b) respectively shows the relationship of ISMR with all India major crops production during the concurrent Kharif season and that during the subsequent Rabi season for the period 1966-2009. The crop production time series were first detrended to remove the technology trend from the series and anomalies were computed using normal computed for the base period of 1971-2000. It is seen that there is in phase relationship between the rainfall and the detrended crop production anomalies of the both Kharif and Rabi seasons. This indicates that above normal monsoon rainfall in addition to providing favourable condition for Kharif crops, helps in maintaining improved soil moisture during the subsequent winter season which is vital for the crops during the Rabi season. However, the relationship between ISMR and Kharif crop production is stronger (C.C. = 0.77) than that between ISMR and Rabi crop production (0.41). The amount of rainfall obtained during the monsoon season is also important for various sectors such as water resources, forestry, hydro-electricity etc. Therefore, the long range forecasting (LRF) of ISMR has been one of the first targets of endeavors at tropical climate predictions.

Although the duration of monsoon over various parts of India varies from about 2 months to 6 months, long range forecasts are generally issued mainly for monthly and season (four months of June to September) scale. The year to year variation of ISMR is primarily attributed to its association with the slowly varying boundary forcing such as sea surface temperature, snow cover, soil moisture etc. This is the predictable part of the interannual variability. The unpredictable part of the variability is due to the natural variability (internal dynamics) of the monsoon system. Two main approaches are used for the prediction of ISMR in the long range scale. The first approach is based on the empirical statistical method. The statistical approach uses either the historical relationship between the ISMR and predictors derived from global atmosphere-ocean parameters that are mainly derived from slowly varying boundary forcing (Walker 1914 & 1923, Thapliyal 1982, Gowariker *et al.* 1989 & 1991, Navone and Cecatto 1995, Singh and Pai 1996, Rajeevan *et al.* 2000, 2004 & 2007, Delsole and Shukla 2002, Sahai *et al.* 2003, Pai and Rajeevan 2006 etc.) or time series analysis of past rainfall data series (Goswami and Srividya 1996, Iyengar and Raghukanth 2004, and Kishtawal *et al*. 2003). The second approach towards LRF is based on the dynamical method, which uses General Circulation Models (GCM) of the atmosphere and oceans to simulate the summer monsoon circulation and associated rainfall. The GCM simulation is primarily driven by the sea surface temperature (boundary) conditions provided in the models. In spite of its inherent problems, at present, statistical models perform better than the dynamical models in seasonal forecasts of ISMR. Even after more than 3-4 decades of intensive research world over and lot of improvement in the computing power and numerical modeling, the dynamical models have not yet shown the required skill to accurately simulate the salient features of the mean monsoon and its interannual variability (Latif *et al.* 1994, Gadgil and Sajini 1998, Krishnamurti *et al*. 2000, Kang *et al*. 2002, Gadgil *et al*. 2005, Krishna Kumar *et al*. 2005, Wang *et al*. 2005). Therefore, the India Meteorological Department (IMD) which started issuing operational long range forecasts of the south-west monsoon rainfall since 1886 has been mainly depending on statistical approaches to issue operational long range



Figs. 1(a&b). (a) Time series of all India summer monsoon season rainfall (ISMR) expressed in percentage departure and all India detrended production anomaly (in millions of tones) of major crops during the concurrent Kharif Season. The time series was detrended before anomalies were computed using base period of 1971-2000. The correlations coefficient (C.C.) between the two time series computed for the entire data period (1966-2009) is 0.77 and (b) Same as that for Fig. 1(a) but for subsequent Rabi season. The C.C. between the time series of ISMR and Rabi crop production anomalies for the period 1966-2009 is 0.41

forecasts. However, IMD has an experimental dynamical prediction system in place which was established in 2003, in collaboration with the Indian Institute of Science (IISc), Bangalore which is based on the Seasonal Forecasting Model (SFM) developed by Experimental Climate Prediction Center (ECPC), USA.

At present, IMD issues operational long range forecasts using models based on statistical approach. Currently IMD uses a newly introduced statistical ensemble forecasting system for the forecasting of the south-west monsoon season (June – September) rainfall over the country as whole. The ensemble forecasting system uses the advanced statistical techniques and state of-the-art technology and prediction of the rainfall is done almost two months in advance. In addition, IMD scientists have also developed statistical models for issuing separate monsoon season rainfall forecast for four geographical regions (NW India, NE India, Central India and South Peninsula) and forecast for the rainfall over the second half of the monsoon season over the country as a whole. Models have also been developed for issuing operational forecast for the rainfall during the crucial months of July, August & September over the country as a whole. IMD reviews the operational models regularly and continuously works on improving them through in house research activities. The main objective of the paper is to present details about the development techniques and performance of the various statistical models used in the present operational LRF system for the southwest monsoon rainfall over India. The section 2 describes the brief history of the development of operational LRF in India since the first operational forecast was issued in 1886. The section 3 provides brief details of the operational models used for preparing the forecast for the season rainfall over the country till 2007 when the new empirical ensemble forecasting system was developed for the purpose. Section 4 discusses details of the models used in the present statistical forecasting system for preparing various operational monthly and seasonal forecasts. Section 5 presents the performance of the present forecasting system during the 2010 southwest monsoon season and finally section 6 presents the conclusions.

2. Development of operational LRF system in India

The first operational LRF of Indian summer monsoon rainfall for the region covering whole India and Burma was issued on June 4th, 1886 by Blandford (1884) who established IMD in 1875 and was the first Chief Reporter of IMD. Blandford used the relationship between winter and spring snow falls over Himalayas and subsequent ISMR to prepare successful tentative forecasts from 1882 to 1885 and then to issue the first operational forecast for 1886. Since that attempt, the LRF of the monsoon rainfall became one of the important operational duties of IMD. Over the years, the operational LRF system in India underwent many changes in its approach and scope. Detailed reviews on the LRF of Indian southwest monsoon rainfall are available in the literature (Normand 1953, Jagannathan, 1960, Thapliyal and Kulshrestha 1992, Hastenrath 1995, Krishna Kumar *et al.* 1995, Rajeevan 2001, Gadgil *et al*. 2005). From 1895 onwards the monsoon forecasts for the country were based on three parameters, *viz*., (*i*) Himalayan snow cover (Oct-May), (*ii*) local peculiarities of pre-monsoon weather in India and (*iii*) local peculiarities over the Indian Ocean and Australia. The first operational forecast issued in 1909

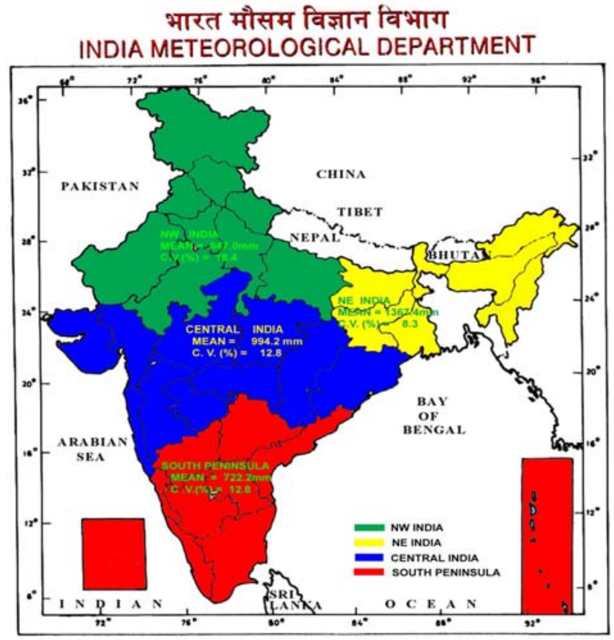


Fig. 2. The four geographical regions of India

for the seasonal monsoon rainfall over the whole India based on regression technique, however, was resulted from the extensive and pioneering work of Sir Gilbert Walker (Walker 1923 & 1924). Later, on realizing that the entire country cannot be taken as homogenous rainfall region, Walker (1924) attempted to develop forecasting equations for smaller regions. He divided the country into three geographical regions, *viz*., (*i*) Peninsula, (*ii*) Northeast India and (*iii*) Northwest India. Between 1924 and 1987, operational forecasts were issued for Northwest India and Peninsular India using regression models initially developed by Walker and updated time to time. Forecast for the geographical regions was discontinued during 1988-1998. During 1988-2002, operational forecast for the season rainfall over the country as a whole was based on the 16 parameter power regression and parametric models (Gowariker *et al.* 1989 & 1991). In view of increasing user demands, the operational forecasts for three geographical regions of the country namely, Northwest India, Peninsular India and Northeast India were reintroduced in 1999. The areas of these geographical regions were however different from that of Walker's geographical regions with the same names. In 2003, a new strategy for issuing LRF for the monsoon rainfall was adopted (Rajeevan *et al.* 2004). Accordingly the long range forecasts are issued in two stages. The first stage forecast issued in April consisted of forecast for seasonal rainfall over the country as a whole and the second stage forecasts issued in the end of June consisted of update for April forecast along with seasonal rainfall forecast for the geographical sub regions of the country and July rainfall forecast for the country as a whole. During 2003 to 2006, the operational first and update long range forecasts for the seasonal rainfall over the country as a whole was issued using the 8 and 10 parameter models based on power regression and probabilistic discriminant analysis techniques. The operational forecast for July rainfall over the country as a whole was also started to issue along with the update forecast from 2003 onwards. In 2004, the country was reclassified into 4 sub geographical regions (Fig. 2). In 2007, a new statistical forecasting system based on the ensemble technique was introduced for the seasonal rainfall forecasting over the country as a whole (Rajeevan *et al.* 2007). In 2009, forecast for August rainfall over country as a whole was started issuing along with other second stage forecasts issued in June. From 2010, operational forecast for the rainfall during the second half of the monsoon season (August-September) and that during the September over the country as a whole were also started.

Though IMD is the only government agency mandated for providing long range forecasts, many institutes in India are involved in the research work related to LRF. Some of these institutes are Indian Institute of Tropical Meteorology (IITM), Pune, Indian Institute of Science (IISc), Bangalore, Space Applications Centre (SAC), Ahmedabad, National Aerospace Laboratories (NAL), Bangalore, Centre for Mathematical Modeling and Computer Simulation (CMMACS), Bangalore, National Centre for Medium Range Weather Forecasting (NCMRWF), Noida and Centre for Development of Advanced Computing (C-DAC), Pune. Many international climate centers like National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasts (ECMWF), International Research Institute for Climate and Society (IRI) etc. are also involved in the research related to seasonal prediction of monsoon rainfall as a part of their efforts to improve global forecasts. IMD makes use of experimental forecasts prepared by these climate research centres both inside and outside India as supportive materials for preparing the operational long range forecasts for India.

3. Earlier operational models for the LRF of seasonal rainfall over the country as a whole

3.1. *The 16-parameter parametric & power regression models: 1988-2002*

The parametric & power regression models were first developed by Gowariker *et al*. (1989) used a group of 16 atmosphere-land-ocean parameters. These models were used by IMD for preparing the operational LRF between 1988 and 1999. In 2000, models were revised (Thapliyal and Rajeevan, 2003) by replacing four of the 16 predictors. From 2000 to 2002, the operational forecasts were prepared based on the revised models.

The parametric model provides categorical forecasts for the summer monsoon rainfall. The model predicts the performance of the monsoon into either of two categories, *i.e.*, wet (normal/excess) or dry (deficient) monsoon. A parameter having positive Correlation Coefficient (C.C.) with the seasonal monsoon rainfall indicates favorable (unfavorable) signal for wet monsoon if its anomaly is positive (negative). Opposite is true for a parameter having negative CC. The frequency analysis of the signals indicated that whenever more than 70 % of the parameters were favorable, the subsequent monsoon was not only wet on all occasions (100%), but the rainfall was also more than the LPA of the rainfall. On the other hand, when less than 30% of parameters were favorable, there was 83% probability that ensuing monsoon rainfall would be deficient.

Unlike the parametric model in which all the predictors get equal weights, in the power regression (PR) model, each predictor gets an appropriate weight that depends on the non-linear relationship between the predictors and the ISMR. The general form of the Mathematical expression of the PR-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 estimated monsoon rainfall over India expressed as the percentage of the LPA of rainfall, *X*'s are the predictors, α's & β's are the scaling parameters and P's & C's are model constants.

3.2. *The 8-parameter and 10-parameter power regression & probabilistic models: 2003-2006*

A critical re-evaluation of the 16-parameter models by Rajeevan *et al.* (2004) revealed that correlations of 10 parameters with the ISMR had rapidly declined in the later years. The remaining 6 parameters along with 4 new parameters that having stable and significant physical and statistical relationship with ISMR resulted in building a set of 10 stable parameters consisting of 6 out of the earlier 16 parameters and 4 new parameters.

Using this 10 parameters set, two power regression (PR) models, one using 8 parameters needing data up to March and another using the full set of 10 parameters were developed. Similarly 8 and 10-parameter probabilistic models were also developed. The 8-

parameter models were used to issue forecast for the summer monsoon seasonal rainfall for the country as a whole in April and the 10-parameter models were used to issue update for the April forecast in June.

The 8 and 10 parameter PR models were used for issuing quantitative forecast of ISMR during the period 2003 to 2006. The mathematical form of the model is given below.

$$R = C_0 + \sum_{i=1}^{i=n} C_i X_i^{P_i}$$

The above equation is nearly same as that given in the section 3.1 except that the predictors and rainfall were not scaled. Here, R is the rainfall, *X*'s are standardized predictors, and C's and P's are constants. '*n*' is the number of predictors (either 8 or 10). The P's, in the above equation varies within ± 2.

The models were developed using data of 38 years (1958-1995) and independently tested using data of 7 years (1996-2002). It was observed that the performance of quantitative forecasts based on the 8 and 10-parameter models were better than that of the 16-parameter model. The root mean square error (RMSE) of the operational forecasts by 16-parameter model during the period 1996-2002 was 11% of LPA, while that of the new 8 and 10-parameter models for the same period was 7% and 6 % of LPA respectively. The model errors of the 8 and 10-parameter models were 5% and 4% of LPA respectively which were of the same order as that of the 16-parameter model at its inception. However, it may be mentioned that though these models showed better performance in general during the drought years in the hindcast mode, they failed to correctly indicate the large rainfall deficiency during 2002 in the hindcast mode and that during 2004 in real time forecast mode.

The probabilistic models were based on the statistical linear discriminant analysis (LDA) technique (Fischer 1936, Wilks 1995, Rajeevan *et al*. 2000). The LDA finds out which predictor variables discriminate between two or more naturally occurring (or a priori defined) predictand groups and estimates the posterior probabilities of the predictand groups. The primary assumption for this model is that prior probabilities of all the predictand groups (or quints) are equal. The model was developed using data for 40 years (1958-1997) and tested for 5 years (1998-2002). The pre defined rainfall categories used were deficient (<90% of LPA), below normal (90-97% of LPA), near normal (98-102% of LPA), above normal (103-110% of LPA) and excess (>100% of LPA).

TABLE 1

Details of the 8 predictors used for the ensemble forecast system for the forecasting of 2010 southwest monsoon rainfall over the country as a whole

No	Predictor	Used for forecasts in	Correlation Coefficient (1971-2000)
1.	North West Europe Land Surface Air Temperature Anomaly (Jan)	April	0.58
2.	Equatorial Pacific Warm Water Volume Anomaly (Feb + Mar)	April	-0.30
3.	North Atlantic Sea Surface Temperature Anomaly (Dec + Jan)	April and June	-0.49
4.	Equatorial South East Indian Ocean Sea Surface Temperature Anomaly (Feb + Mar)	April and June	0.45
5.	East Asia Mean Sea Level Pressure Anomaly (Feb + Mar)	April and June	0.36
6.	Central Pacific (Nino 3.4) Sea Surface Temperature Anomaly Tendency (MAM - DJF)	June	-0.49
7.	North Atlantic Mean Sea Level Pressure Anomaly (May)	June	-0.52
8.	North Central Pacific Zonal Wind Anomaly at 1.5 km above sea level (May)	June	-0.45

In hindcast mode, the 8 & 10-parameter LDA models showed 68% & 78% correct classifications, respectively. In hindcast, both the LDA models correctly gave the highest probability of drought in 8 out of 9 actual drought years except in 2002 and no false alarms of drought were generated in any other years.

4. The present operational forecasting system

4.1. *Statistical ensemble forecasting system for the seasonal rainfall over the country as a whole*

There are three major changes in the statistical forecast system used for operational forecast at present from that used during 2003 to 2006 which was based on the 8/10 Parameter power regression models. These are: (a) use of a new smaller predictor data set (b) use of a new non-linear statistical technique along with conventional multiple regression technique (c) application of the concept of ensemble averaging. The new ensemble forecasting system introduced in 2007 used a set of 8 predictors (given in the Table 1) that having stable and strong physical linkage with the Indian south-west monsoon rainfall. For the April forecast, first 5 predictors listed in the Table-1 were used. For the update forecast issued in June, the last 6 predictors are used that include 3

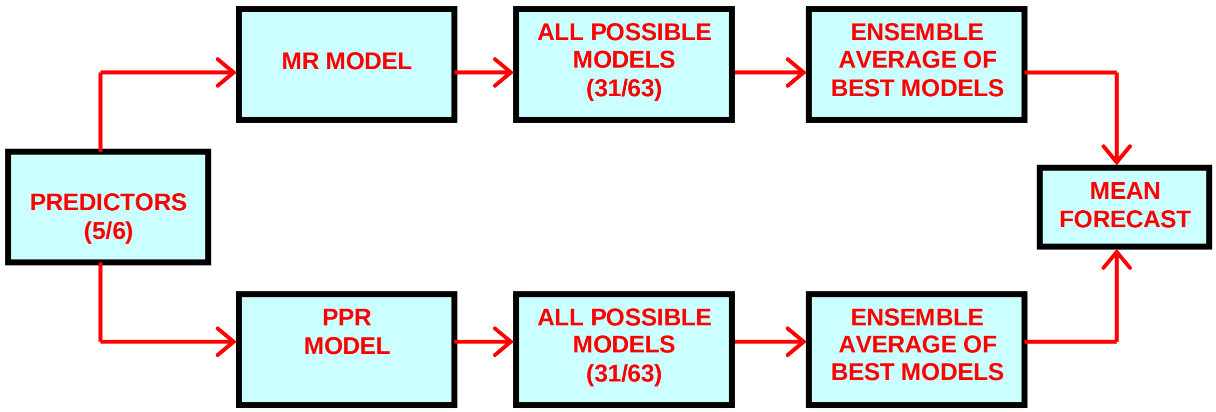


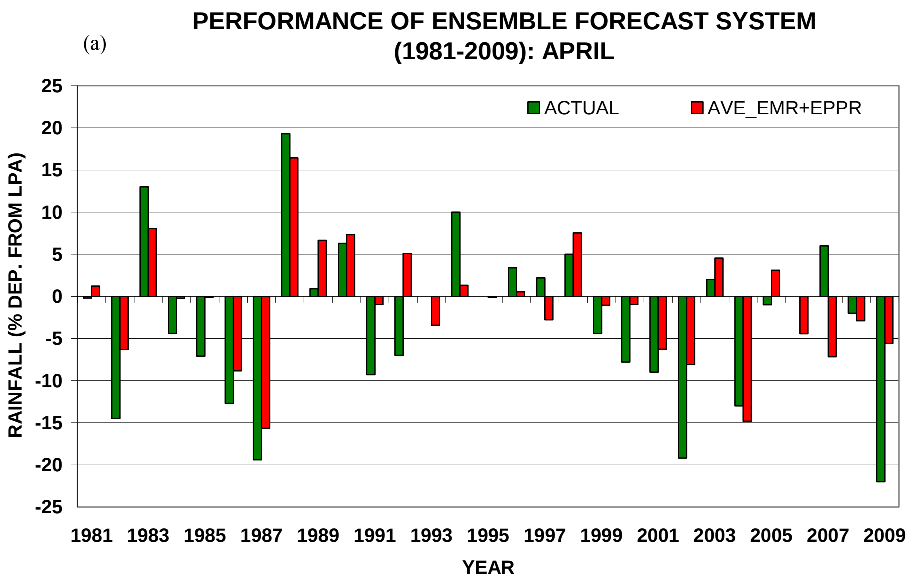
Fig. 3. A Schematic diagram of the new ensemble forecasting system for the monsoon season rainfall over the country as a whole. The average of the ensemble forecasts from best out all possible MR (multiple regression) models and that from PPR (projection pursuit regression) models gives the final forecast

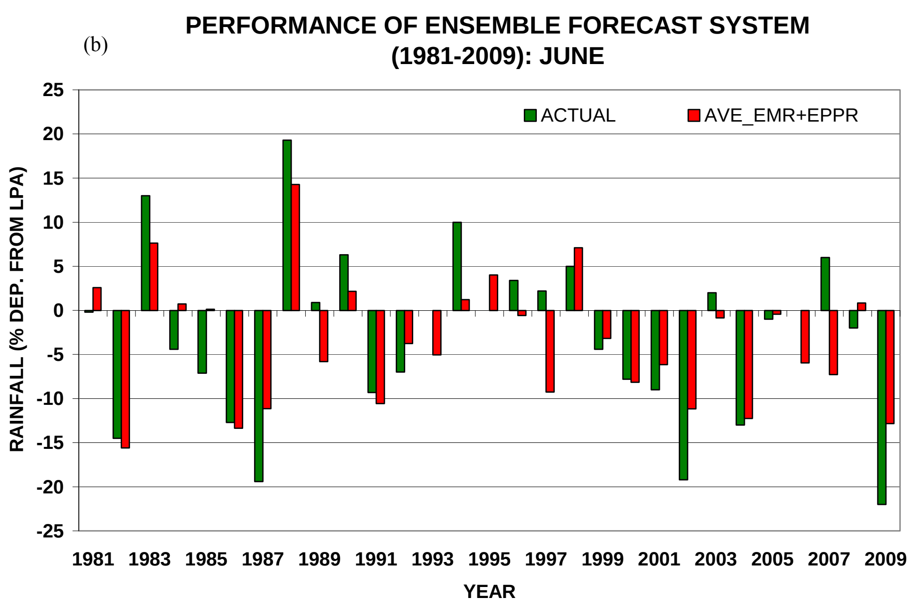
predictors used for April forecast. A schematic diagram of the statistical ensemble forecasting system is shown in the Fig. 3.

In the ensemble forecasting system, the forecast for the seasonal rainfall over the country as a whole was computed as the mean of the two ensemble forecasts prepared from two separate set of models. Multiple linear regression (MR) and projection pursuit regression (PPR) techniques were used to construct two separate sets of models. PPR is a nonlinear regression technique. In each case, models were construed using all possible combination of predictors. Using '*n*' predictors, it is possible to create (2^n-1) combination of the predictors and therefore that many number of models. Thus with 5 (6) predictors it is possible to construct 31 (63) models. Using sliding fixed training window (of optimum period of 23 years) period, independent forecasts were prepared by all possible models for the period 1981-2008. For preparing ensemble average, a set of few best models from all possible MR models and another set of few best models from all possible PPR models were selected. The best models were selected in two steps. In the first step, all possible models (MR and PPR models separately) were ranked based on the objective criteria of likelihood function or generalized cross-validation (GCV) function computed for the period 1981-2008. Accordingly the model with lowest GCV was ranked first; model with second lowest GCV was ranked second; and so on. In the second step, ensemble average of forecasts from the models ranked based on ascending GCV score were computed by using first ranked model [1 member ensemble model (EM1)], first and second ranked models [2 members ensemble model (EM2)], first, second and third ranked models [3 members ensemble model (EM3)] and so on up to all the possible models. The ensemble average forecast from each of the ensemble models (EM1, EM2, etc.) for each year of the independent period 1981-2008 were computed as the weighted average of the forecasts from the individual ensemble members. For this purpose, the weight given for each ensemble member model was the C.C between the actual and model (respective ensemble member model) estimated ISMR values during the training period (of 23 years just prior to the year to be forecasted) adjusted for the number of predictors used in the member model. The RMSE of the ensemble average of each of the ensemble models (EM1, EM2, etc.) was computed. Now the member models used for constructing the ensemble model with lowest RMSE were selected as the best models. In case of the April forecast, 3 best MR models and 12 best PPR models were used to compute the respective ensemble model averages. Similarly, In case of June forecast, 4 best MR models and 11 best PPR models were used to compute the respective ensemble model averages. More details of the methodology used in the ensemble forecasting system can be obtained from Rajeevan *et al.* (2007).

Performance of the April and June forecast for the independent test period of 1981-2008 computed using the new ensemble method is shown in Figs. (4a & 4b) respectively. The operational forecast generated for 2009 is also included in Figs. 4 (a&b). The RMSEs of the independent April & June forecasts for the period 1981-2008 were 5.9% of LPA and 5.6% of LPA respectively.

In addition to the quantitative forecast, the ensemble forecasting system has also been used to generate a five





Figs. 4(a&b). Performance of the ensemble forecast system for the (a) April forecast and (b) June forecast of the seasonal rainfall over the country as a whole

category probabilistic rainfall forecast. For this, the forecasts of the selected best MR models and PPR models of the ensemble forecasting system were categorized into 5 pre-defined rainfall categories. The five rainfall categories defined based on the observed data for the period 1901-2005 are deficient (< 90% of LPA), below normal (90-96% of LPA), normal (96-104% of LPA), above normal (104-110% of LPA) and excess (> 110% of LPA). The climatological probabilities of these five categories are 16%, 17%, 33%, 16% & 17% respectively. At present, for both first and second stage forecasts from 15 models (3 MR models and 12 PPR models for April forecast and MR models and 11 PPR models for June forecast) were categorized into 5 rainfall categories to prepare the probabilistic forecast.

The probabilistic forecast for the independent test period of 1981 - 2009 obtained based on the April

TABLE 2

The details of the predictors used for forecasting 2010 second half of the monsoon season (August-September) rainfall over the country as a whole

S. No.	Predictor	C.C. (1971-2000)
1.	North Pacific (Region-1) Mean Sea Level Pressure (July)	0.53
2.	Central Pacific (Nino 3.4) Sea Surface Temperature Ano. Tendency (AMJ-JFM)	-0.63
3.	Bay of Bengal Sea Surface Temperature (June)	0.34
4.	North Atlantic Mean Sea Level Pressure (May)	-0.47
5.	North Pacific (Region-2) Mean Sea Level Pressure (July)	-0.51

ensemble forecasting system showed that the model forecasted correct category during 14 years (48%), 1 category out during 13 years (45%) and 2 categories out during two years (1992 & 2007) (7%). The corresponding probabilistic forecast obtained based on the June ensemble forecasting system showed that the model forecasted correct category during 17 years (59%), 1 category out during 10 years (34%) and 2 categories out during two years (1997 & 2007) (7%). Examination of probabilistic forecast during the recent 3 deficient monsoon years (2002, 2004 & 2009) showed that April probabilistic forecast indicated correct category (deficient) during 2004 & 2009 and one category out (normal) during 2002. On the other hand, June probabilistic forecast indicated correct category during all the 3 years.

4.2. Model for the forecast of rainfall during the second half of the monsoon season (August-September) over the country as a whole

The operational forecast for the rainfall during the second half of the monsoon season (August – September) was introduced first time in 2010 to meet the demand of user along with forecast for September rainfall over the country as a whole. The forecast for the rainfall during the second half of the monsoon season was issued in the last week of July. For this purpose, a multiple linear regression (MR) Model based on 5 predictors was developed. The details of the predictors used in the model are given in the Table 2. The model was trained using data for the period 1971-2000. The model error (RMSE) of model rainfall estimates during the training period) was 7% of LPA. The model performance during the independent test period (2001-2009) is shown in the Fig. 5. The RMSE of the rainfall forecasts during the independent test period was 10% of LPA.

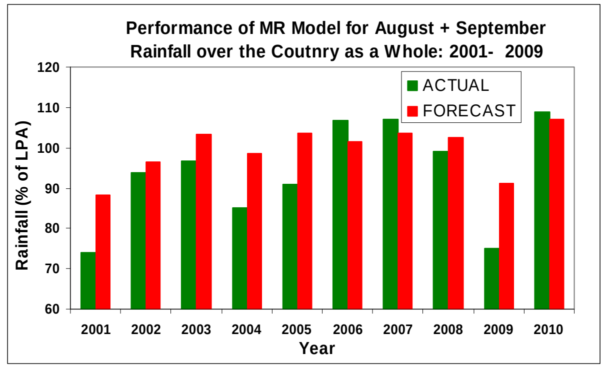


Fig. 5. Performance of the MR model for the forecast of the rainfall during the second half of the monsoons season (August + September) over the country as a whole

4.3. Models for the forecast of monthly rainfall over the country as a whole

Operational monthly rainfall forecast are issued for the months of July, August and September. The forecasts for July and August rainfall are issued in June along with update forecast and that for September rainfall is issued in the last of week of August. The months of July and August are the rainiest months of the south-west monsoon season. September has the maximum rainfall variability and is important as the monsoon withdraws from the country during this month. It has also been seen that among monsoon months, rainfall during the September has the highest association with the ENSO events. It also has the highest CC with seasonal rainfall. The normal rainfall during July, August & September months over the country as a whole accounts about 33 % (293 mm), 29% (263 mm) 19% (175 mm) of the monsoon season's total rainfall respectively with a corresponding coefficient of variation of 13%, 14% and 23%. The severe drought in 2002 was due to the unprecedented deficient rainfall (46% of LPA) in July 2002, which brought down the country's kharif crop production by 15 million tones below that of the previous year. During another severe drought year (2009), though the July rainfall was normal, the monsoon failed during the second half of the season which again hit the Kharif crop production in the country badly [Fig. 1(a)].

For the monthly rainfall forecasts over the country as a whole, principal component regression (PCR) technique was used. In the PCR method, the first few principal components of the predictors are used in regression analysis to develop the prediction algorithm. The PCR technique is recommended when there is significant inter-correlation among the independent variables. The PCR model avoids the inter-correlation and helps to reduce the degrees of freedom by restricting the number of

TABLE 3

The details of the predictors used for forecasting 2010 July rainfall over the country as a whole

No.	Predictor	C.C. (1971-2000)
1.	North Atlantic Sea Surface Temperature (Dec)	-0.54
2.	North Central Pacific Zonal Wind U850 (May)	-0.43
3.	North America Mean Sea Level Pressure (Jan)	0.46
4.	East Asia Mean Sea Level Pressure (Feb)	0.28
5.	North Atlantic Pressure Gradient (Mar)	-0.39

TABLE 4

The details of the predictors used for forecasting 2010 August rainfall over the country as a whole

No.	Parameters	C.C. (1979-2000)
1.	South Atlantic Mean Sea Level Pressure (Apr)	-0.39
2.	South East Pacific Sea Surface Temperature (May)	-0.48
3.	Central Pacific (Nino 3.4) Sea Surface Temperature Ano. Tendency (MAM-DJF)	-0.30
4.	South Pacific Zonal Wind at 850hPa (April)	0.30
5.	Tropical North Atlantic Outgoing Long wave Radiation (Mar)	-0.48

TABLE 5

The details of the predictors used for the forecasting 2010 September rainfall over the country as a whole

No.	Predictor	C.C. (1971-2000)
1.	North Pacific Mean Sea Level Pressure (July)	0.62
2.	Central Pacific (Nino 3.4) Sea Surface Temperature Ano. Tendency (JFM -JJA)	0.67
3.	Bay of Bengal Sea Surface Temperature (June)	0.38
4.	South Pacific Zonal Wind at 850 hPa (April)	0.41

independent variables (Rao, 1964). PCR model has been used for the prediction of ISMR based on predictors from the Indian Ocean only (Singh and Pai, 1996). PCR model has also been used for the prediction of seasonal summer monsoon rainfall over two homogeneous regions of India based on predictors from various observed climatic fields (Rajeevan *et al*. 2000).

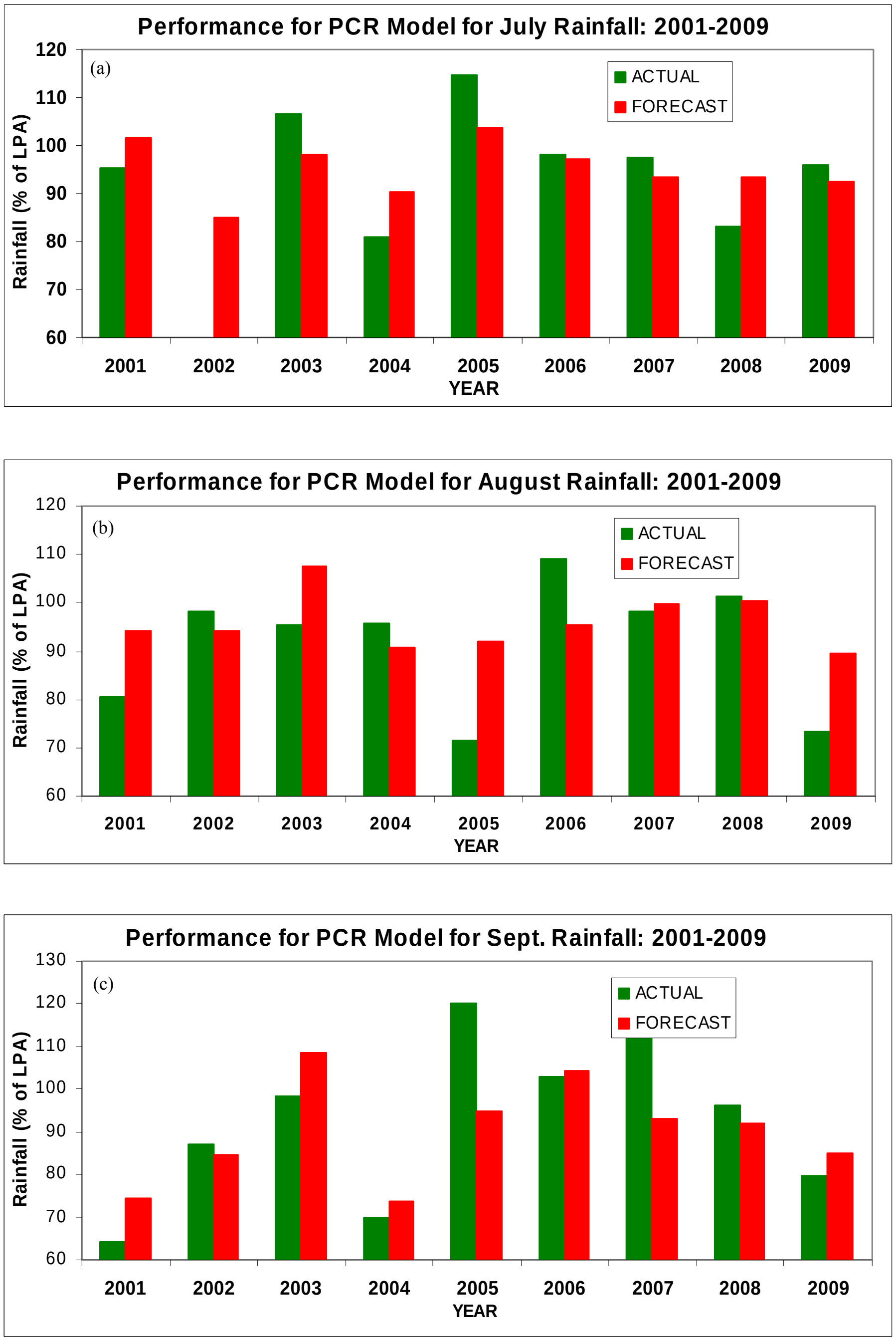
For the forecast of July rainfall over the country as a whole, a set of 5 predictors (listed in the Table 3) were used. The model was trained using data for the period 1958-2000 and the model was tested for the period 2001 to 2009. PCA analysis was carried over the predictor set using data for the training period and first three PCs explaining about 89% of the total variability of the predictor data set was retained for MR analysis. Using the PC loadings of the retained PCs, PC scores were calculated for the independent test period and the same were then used for the prediction of July rainfall for the independent test period. The performance of the PCR model for the July rainfall during the independent test period is shown in Fig. 6(a). It is seen that, though the model could forecast the sign of the rainfall deficiency during 2002 correctly, it failed to capture the magnitude of deficiency correctly. The RMSE during the training period (model error) was 9% of LPA and that during the independent test period was 14% of LPA. Relatively large RMSE during the test period was caused by the large forecast error during 2002, when the actual July rainfall was extremely low.

A set of five predictors (listed in the Table 4) were used for the forecast of August rainfall over the country as a whole. The model was trained using data for the period 1979-2000 and the model was tested for the period 2001 to 2009. PCA analysis was carried over the predictor set using data for the training period and first three PCs explaining about 80% of the total variability of the predictor data set was retained for MR analysis. The performance of the PCR model for the August rainfall during the independent test period is shown in Fig. 6(b). The RMSEs during the training and independent test periods were 9% of LPA and 12% of LPA respectively.

A set of four predictors (listed in the Table 5) were used for the forecast of September rainfall over the country as a whole. The model was trained using data for the period 1971-2000 and the model was tested for the period 2001 to 2009. PCA analysis was carried over the predictor set using data for the training period and first 3 PCs explaining about 88% of the total variability of the predictor data set was retained for MR analysis. The performance of the PCR model for the September rainfall during the independent test period is shown in Fig. 6(c). The RMSEs during the training and independent test periods were 15% of LPA and 13% of LPA respectively.

4.4. *Models for the forecast of the seasonal rainfall over the four geographical regions*

Between 1999 & 2003, IMD was issuing long range forecasts for seasonal rainfall over the 3 broad geographical regions of India, *viz*., North-west India,



Figs. 6(a-c). Performance of the PCR model for the forecast of the (a) July rainfall, (b) August rainfall and (c) September rainfall over the country as a whole

North-east India and Peninsula using 3 individual power regression models based on different sets of predictors. In 2004, the country was reclassified into 4 geographical sub regions, *viz*., Northwest India, Central India, Northeast India and South Peninsular India (Fig. 2). The seasonal forecasts for the 4 geographical regions are issued in June along with the update forecast for the seasonal rainfall over the country as a whole. At present, the forecasts for the season rainfall over the 4 geographical regions are prepared using separate MR models each of which is

TABLE 6

The details of the parameters used for the forecasting of seasonal rainfall over the 4 homogeneous regions India

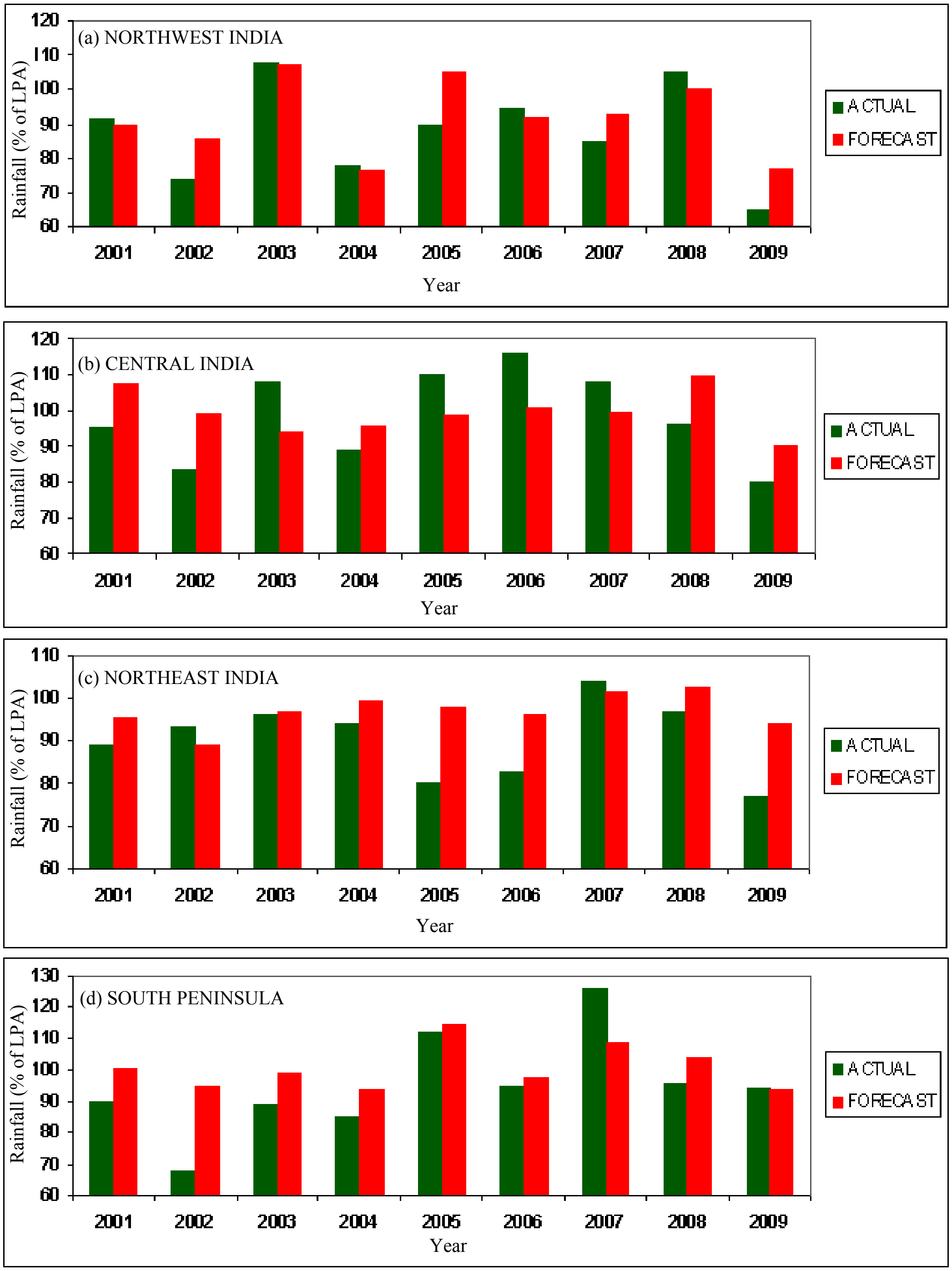
Geographical region	Predictor	C.C. (1971-2000)
Northwest India	North Atlantic Mean Sea Level Pressure Gradient (May)	0.49
	South Atlantic Mean Sea Level Pressure (Jan)	-0.57
	East Asia Mean Sea Level Pressure (Feb + Mar)	0.53
	North Central Pacific Zonal wind at 850 hPa (May)	-0.32
Central India	Northwest Europe Mean Sea Level Pressure (Jan)	-0.47
	North Atlantic Sea Surface Temperature (Dec + Jan)	-0.66
	North Atlantic Mean Sea Level Pressure Gradient (May)	0.60
	North Atlantic Mean Sea Level Pressure (Mar)	0.54
	Equatorial Indian Ocean Sea Level Pressure [Nov (-1)]	-0.58
South Peninsula	South East Equatorial Indian Ocean Sea Surface Temperature [Oct (-1)]	-0.49
	North West Europe Land Surface Air Temperature (Jan)	0.50
	North West Pacific Zonal wind at 850 hPa (Feb)	-0.34
	South East Pacific Mean Sea Level Pressure (May)	0.50
	SE Indian Ocean Mean Sea Level Pressure (May)	-0.37
Northeast India	South Atlantic Mean Sea Level Pressure (Jan)	-0.55
	South West Pacific Sea Surface Temperature (Mar)	0.60
	Central Pacific Sea Surface Temperature (May)	-0.38
	North Atlantic Mean Sea Level Pressure (April)	-0.49

based on different set of predictors. The MR models for Northwest India, Central India, Northeast India and South Peninsular India used 4, 5, 4 & 5 parameters respectively. The list of the parameters used in the MR models for the 4 geographical regions is given in the Table 6. Each of the models was trained using data for the region 1971-2000 and was tested using data for 2001-2009. The RMSEs during the independent test period for the MR models for Northwest India, Central India, Northeast India and South Peninsular India were 8% of LPA, 12% of LPA, 10% of LPA, 10% of LPA respectively. The performance of the models for the 4 geographical regions during the independent test period is given in the Fig. 7.

5. Verification of the performance of the present statistical forecasting system for the 2010 southwest monsoon season

As per the first stage long range forecast issued in April, the season (June-September) rainfall for the country as a whole was expected to be 98% ± 5% of LPA. In the updated forecast issued in June, the forecast for the country as a whole was revised to a higher value of 102% ± 4% of LPA. The updated forecast turned out to be very accurate as the actual area-weighted season rainfall for the country as a whole was 102% of LPA, same as the forecast value. The April and June probabilistic forecasts for the season rainfall over the country as a whole were also correct as both the forecasts were indicating normal rainfall category (96-104% of LPA).

The forecast for the second half of the monsoon season (August – September) for the country as a whole issued in July was 107% with a model error of 7% of LPA. This forecast was also accurate as the actual rainfall over the country as a whole during the second half of the season was 108% of LPA. The forecasts for monthly rainfall over the country as a whole for the months of July, August issued in June were 98% & 101% respectively with a model error of ± 9% and that for September issued in August was 115% of LPA with a model error of ± 15%. All the monthly forecasts turned out to be correct as the actual rainfall were 103%, 105% and 113% of LPA respectively.



Figs. 7(a-d). Performance of the MR models for the forecast of the Season rainfall over the 4 geographical regions of the country for the independent period 2001-2009

Considering 4 broad geographical regions of India, the season rainfall was expected to be 102% of its LPA over northwest India, 99% of LPA over Central India, 103% of LPA over northeast India and 102% of LPA over South Peninsula all with a model error of ±8%. The actual rainfalls over northwest India, central India, northeast India and south Peninsula were 112%, 104%, 82% and 117% of the LPA respectively. Thus, the actual

TABLE 7

Verification of the operational long range forecast for SW monsoon rainfall

Region	Period	Date of Issue	Forecast (% of LPA)	Actual Rainfall (% of LPA)
All India	June to September	23rd April	98 ± 5	102
All India	June to September	25th June	102 ± 4	
Northwest India	June to September	25th June	102 ± 8	112
Central India	June to September	25th June	99 ± 8	104
Northeast India	June to September	25th June	103 ± 8	82
South Peninsula	June to September	25th June	102 ± 8	117
All India	July	25th June	98 ± 9	103
All India	August	25th June	101 ± 9	105
All India	August to September	30th July	107 ±7	108
All India	September	27th August	115 ± 15	113

TABLE 8

Rainfall forecasts for the monsoon season of 2010 received from various research centers within the country other than IMD

S. No.	Institute		Model	First stage (April) Forecast	Update (June) forecast
1.	Indian Institute of Tropical Meteorology (IITM) Pune	Statistical models	Global SST (Sahai *et al*. 2008)	90.5 ± 7% of LPA	No Update
			2-parameter Model (Dugam and Kakade 2004)	94 ± 4% of LPA	
			K.E of mid latitude waves (Bawiskar *et al*. 2005)	112 ± 5% of LPA	
			4-Parameter Model (Munot and Kumar, 2007)	102 ± 4% of LPA	
			Coupled Forecasting System (CFS)	97% of LPA	110% of LPA
2.	Space Applications Centre (SAC), Ahmedabad		Statistical model based on Genetic Algorithm (Kishtawal *et al*. 2003)	102% of LPA	No Update
3.	NCMRWF, Noida		Seasonal Prediction Model (InGLM1)	100%	96% of LPA
4.	Centre for Development of Advanced Computing (C-DAC), Pune		Coupled Forecasting System (CFS)	105% of LPA	112% of LPA

season rainfall over central India was within the forecast limit and that over northwest India was 2% of LPA above the upper forecast limit. However, the forecast for season rainfall over northeast India and south Peninsula were not accurate as the actual rainfall over northeast India is very much less than its lower forecast limit and that over south Peninsula is higher than its upper forecast limit.

The Table 7 gives the summary of the verification of the long range forecasts issued for the 2010 south-west monsoon. As a whole, most of the operational long range forecasts issued for 2010 south-west monsoon season turned out to be correct.

6. Forecasts for the 2010 south-west monsoon season rainfall over the country as a whole from other institutes in India

As mentioned in the Section 2, apart from IMD, many other research institutions in India are also involved in the long range forecasting research. Each year, these institutes provide experimental forecasts to IMD prior to issuing of operational forecast. For the 2010 southwest monsoon season, experimental forecasts were provided by 4 institutes. The details of the forecasts for season rainfall over the country as a whole received from 4 different institutes are given in the Table 8. For the April forecast (first stage), experimental forecasts based on statistical/ empirical models from 2 institutes (IITM and SAC) and that based on dynamical models from three institutes (IITM, NCMRWF, & C-DAC) were received. For June forecast, updated forecasts based on dynamical models were provided by these three institutes. However, update forecasts based on the statistical models were not available. The statistical models used by IITM for April forecast were Global SST model (Sahai *et al*. 2008), 2-parameter MR Model (Dugam and Kakade 2004), Model based on kinetic energy (K.E.) of mid latitude waves (Bawiskar *et al*. 2005) and 4-Parameter MR Model (Munot and Kumar, 2007). For the same purpose, SAC used empirical model based on Genetic Algorithm (Kishtawal *et al*. 2003). For the April and June experimental dynamical model forecasts, IITM and C-DAC used recently established coupled forecasting system (CFS). The experimental forecasts from NCMRWF was based on Seasonal Prediction Model (InGLM1) forced by predicted sea surface temperatures.

As seen in the Table 8, the experimental forecasts issued by various national institutes showed large divergence. The experimental forecasts (all April forecasts) based on 5 statistical models varied from 91 to 112% of LPA. The NCMRWF forecast for April was normal (100% of LPA), which was downgraded to 96% of LPA when updated. The April CFS forecast from IITM and C-DAC were 97% of LPA & 105% of LPA respectively. The updated CFS forecasts from both IITM & C-DAC were upgraded to 110% of LPA and 112% of LPA respectively. Thus, the updated forecasts from dynamical models varied from 96% to 112% of LPA.

7. Conclusions

At present, to satisfy the user demands, IMD issues various operational monthly and seasonal long range forecasts for the southwest monsoon rainfall over India using a set of state-of-art statistical models. IMD issues rainfall forecasts for monthly (for July, August & September), second half of the monsoon season (August + September) and season (June - September) over the country as a whole and for season rainfall over four geographical regions (Northwest India, Central India, Northeast India and South Peninsula) with useful skill. For the 2010 southwest monsoons season, most of the long range forecasts made using the present statistical forecasting system were correct.

The long operational forecasting experience in India suggest that skillful forecasts based on statistical models have been possible only up to the level of geographical regions each of which consisted of a group of meteorological sub-divisions. For smaller areas such as meteorological sub-divisions/or districts, statistical methods have not been so successful mainly due the large rainfall variability at these spatial scales and unavailability of useful predictors for the model development. In spite of the inherent limitations of the statistical approach, statistical models have better skill than the dynamical models for the LRF of ISMR. Dynamical models have the capability to generate forecast at smaller spatial scale and to provide forecast at required time interval. However, various studies (Sperber and Palmer, 1996; Gadgil and Sajani 1998, Rajeevan 2001, Wang *et al*. 2005, Pattanaik and Arun Kumar 2010) show that at present neither Atmospheric General Circulation Models (AGCMs) nor the Coupled ocean-atmosphere General Circulation Models (CGCMs) have the required skill to simulate various features of the summer monsoon such as mean, the intra-seasonal variability (ISV) and interannual variability (IAV) with reasonable accuracy which are essential for these models to be useful for monsoon studies (WCRP, 1992 & 1993). The attempt to develop location specific forecasts based on statistical rescaling or recalibration of AGCM/CGCM model simulations/ forecasts have also not been very successful as the dynamical models have yet to make realistic simulate/forecasts rainfall and other climate parameters over India. Dynamical models are likely to go through several years of development efforts before they can completely replace statistical models. There is urgent need to develop a dynamical model suitable for LRF of Indian summer monsoon rainfall. Recently the Ministry of Earth Sciences (MoES), Government of India has taken important steps to set up a National Mission on Monsoon with an aim to improve the monsoon prediction skill of the dynamical models in India, which need concentrated and continuous research efforts. For this, both talented man power from multi disciplines such as mathematics, computer, physics, chemistry, statistics, meteorology etc. and high computational power are necessary. National mission will work on both these aspects. With the development of better dynamical models, user demand for location specific forecasts (forecast at meteorological sub-division, zone within the sub-division or district level) also should be possible.

Another aspect that needs to be addressed in the long range forecasting is the estimation of the uncertainty in the forecast. All forecasts are inherently uncertain and it is important that this uncertainty is estimated and communicated to forecast users so that they can make optimal decisions. The present operational long range forecasting system issues various forecasts (such as the season/monthly rainfall over the country as a whole, season rainfall over the four geographical regions etc.) in the form of specific value of the predictand (season/monthly rainfall), which are essentially deterministic in nature. Though the model error provided together with deterministic forecast (*e.g.*, ± 4% is the model error for June forecast of season rainfall over the country as a whole) indicates some amount of forecast uncertainty, such deterministic forecasts in effect assign probability of 1 for the event (rainfall) to be within the range of model error (model forecast ± model error) and rules out any chance ('0' probability) for the event to occur outside this range. However, the future state of a complex system such as climate cannot be predicted with certainty and it is essential to quantify uncertainty associated with all possible future outcomes. This is where the probabilistic forecasts are better than deterministic forecasts. The probabilistic forecasts do attempt to quantify the uncertainty by making clear probability statements about the chance of occurrence of all future outcomes. As the probability forecasts allow different decision-makers (forecast users) to make their own optimal decisions, they are also very useful for quantitative assessment of risk. There is some inherent difficulty with the statistical models in providing good estimate of forecast uncertainty. An attempt has already been made to develop probabilistic models based on the forecasts from the ensemble forecasting system (see section 4.1) to issue a 5 category probabilistic forecasts for the season rainfall over the country as a whole. The models have also given some encouraging results. However, the model only includes the uncertainty related to different combinations of important climate forcing (predictors) that were assumed to decide the final out come of the monsoon rainfall. More research is necessary to include the uncertainty related to other aspects such as uncertainty related to observation (error in the measurements and instrumental biases), data sampling (*e.g.*, training period of the model) etc. in the model. The development of coupled dynamical models with improved forecast skill over Indian region under proposed National Mission on monsoon provides another option to generate probabilistic long range forecasts. However, introduction of probabilistic forecasts have also some difficulties. Understanding and perception of probability forecasts and risk varies enormously from user to user. It may also be difficult to quantify the uncertainty reliably when the source (climate process that is linked to the predictand) of uncertainty in the climate system is not clearly understood or unknown.

Acknowledgements

Just prior to issuing the operational long range forecasts for the rainfall during the southwest monsoon every year, IMD receives experimental forecasts and inputs from various climate research institutes within the country. IMD uses these inputs and forecasts as guidance material for finalizing the operational long range forecasts issued officially. The experimental forecasts for the 2010 southwest monsoon season rainfall over the country as a whole presented in this study were provided by various scientists from IITM, Pune, NCMRWF, Noida, C-DAC, Pune and SAC, Ahmedabad. The authors express sincere thanks to all of them for their valuable inputs. Authors also thank Dr. Rajeevan, NARL, Gadanki for going through the manuscript and providing useful suggestions for its overall improvement.

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