Monsoon prediction – Why yet another failure?

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The country experienced a deficit of 13% in the summer monsoon of 2004. As in 2002, this deficit was not predicted either by the operational empirical models at India Meteorological Department (IMD) or by the dynamical models at national and international centres. Our analysis of the predictions generated by the operational models at IMD from 1932 onwards suggests that the forecast skill has not improved over the seven decades despite continued changes in the operational models. Clearly, new approaches need to be explored with empirical models. The simulation of year-to-year variation of the monsoon is still a challenging problem for models of the atmosphere as well as the coupled ocean–atmosphere system. We expect dynamical models to generate better prediction only after this problem is successfully addressed.

THE major drought[1-3] of 2002, with the all-India summer monsoon (June–September) rainfall (ISMR) being 19% less than the long-term average, led to considerable concern in the meteorological community since none of the predictions had suggested a large deficit in the ISMR. This was irrespective of whether the predictions were based on empirical models used in the country for generating operational/experimental forecasts, or generated in the different centres in the world using the atmospheric general circulation models[1]. Fortunately, the unanticipated failure of the Indian monsoon in the summer of 2002, was followed by the summer monsoon of 2003 for which the ISMR was 2% more than the average[4]. However, the relief was short-lived since the summer monsoon of 2004 has again been a drought (defined as a summer monsoon season for which the deficit in ISMR is larger than 10% of the long-term average), with the ISMR being 87% of the average. As in 2002, neither the forecast of the India Meteorological Department (IMD) for the ISMR nor the predictions from the international centres using atmospheric general circulation models (GCMs), suggested that there would be a drought. Clearly, it is far more important to generate accurate predictions of droughts/excess rainfall seasons than of fluctuations within 10% of the average.

The variation of the summer monsoon rainfall from year to year is not coherent over the Indian region. Generally, while some regions experience above-average rainfall, others suffer from deficit. Thus the anomalies (difference from the long-term average) of the summer monsoon rainfall are positive over some of the meteorological subdivisions and negative for others, particularly in the so-called normal years (i.e. with the magnitude of the ISMR anomaly

<10% of the average). During droughts, rainfall over the vast majority of the subdivisions is deficit. This is illustrated in Figure 1 in which anomalies of the summer monsoon rainfall for the meteorological subdivisions (expressed as a percentage of the long-term average) for the droughts of 2002 and 2004 and the 2003 normal monsoon season are shown.

The variation of the all-India rainfall is also generally not coherent within the monsoon season. Thus, in 2002 there was an unprecedented deficit of 49% in the all-India average rainfall in July, while the rainfall was close to the average during all the other months. In 2004, the all-India rainfall was close to the average in June and August, but well below the average in July and September (June: 100%, July: 81%, August: 95% and September: 71%). This year, predictions were also made for the rainfall patterns of July and August over the Indian region, by one group in the country using an atmospheric GCM. However (as shown later in the article), the observed rainfall patterns differed markedly from the predicted ones.

The variation of the all-India rainfall during the 2004 monsoon season on the weekly scale (Figure 2 a) shows that while the rainfall activity over the country during the third and fourth weeks of June was above normal, it was suppressed for five weeks from late June to late July leading to a cumulative rainfall deficit of 15% by 28 July. With the revival of the monsoon rainfall in August, the situation improved with the cumulative seasonal rainfall increasing to 94% by 25 August. However, deficient rainfall throughout September led to the seasonal rainfall deficiency of 13%. Just as the rainfall within a season varies from week to week, there are fluctuations of the rainfall within a week also. On the daily scale the all-India rainfall fluctuates between active spells and relatively dry spells (Figure 2 b).

Clearly, it is important to predict not only the total rainfall for the season, but also the variation within the season. Similarly, while the average rainfall for the country as a whole is important because it determines, to a large

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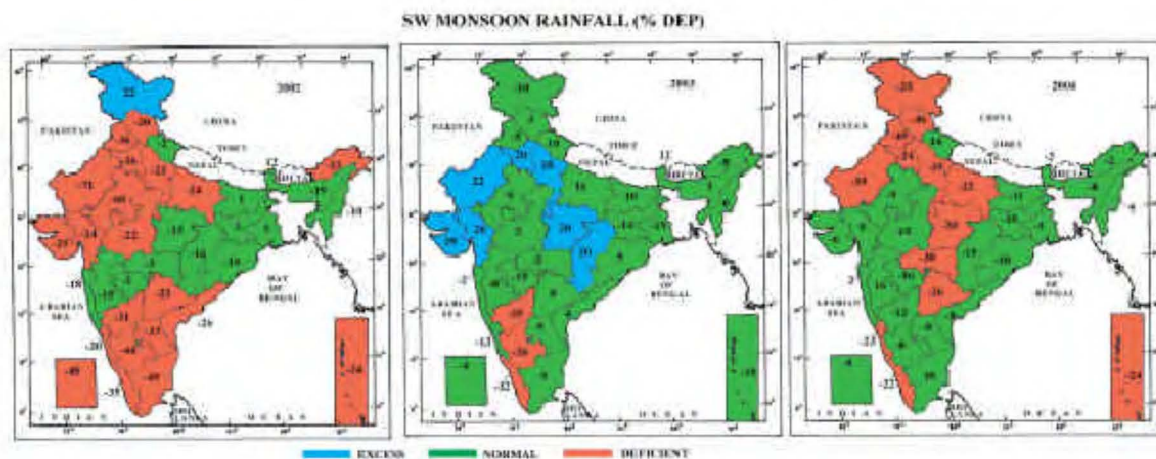*For correspondence. (e-mail: sulo@caos.iisc.ernet.in)

Figure 1. Comparison of seasonal rainfall distribution of 2002, 2003 and 2004.
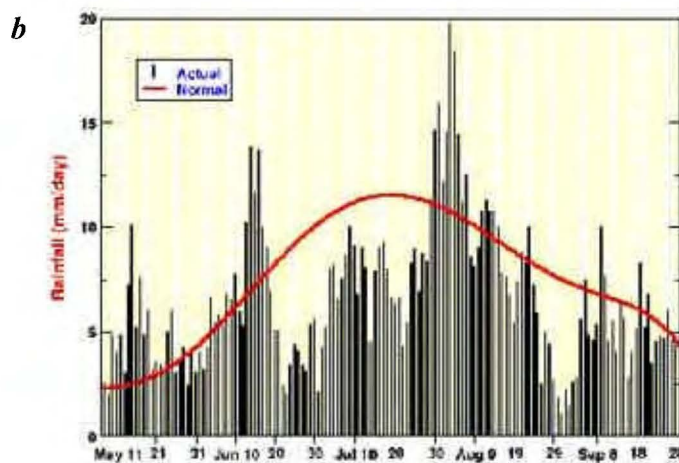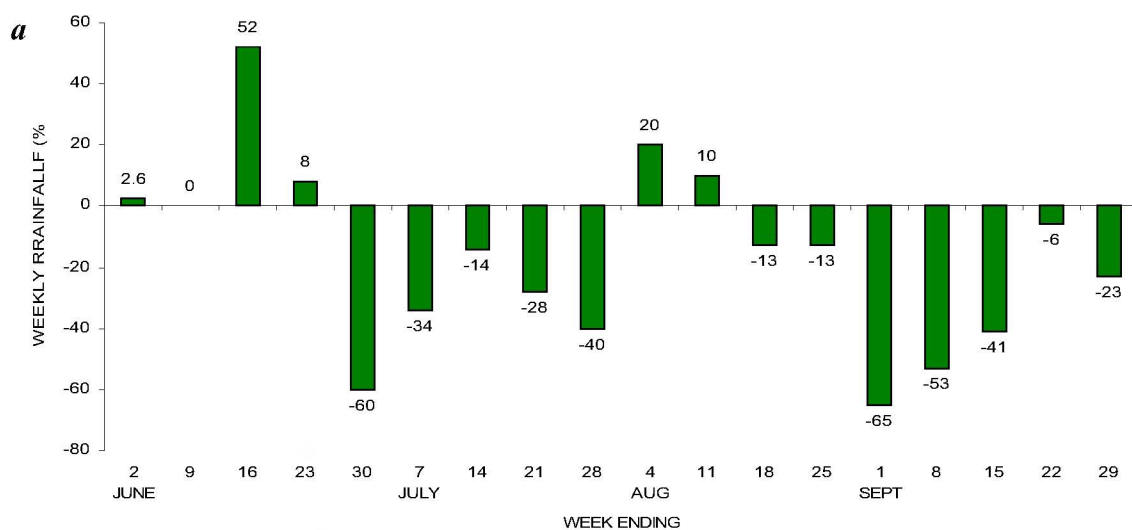

Figure 2. *a*, Variation of all-India rainfall as percentage departure on weekly scale for the season of 2004. *b*, Variation of all-India rainfall on daily scale for the season of 2004. (Source: Monsoon online at www.tropmet.res.in).

extent, the national agricultural production, irrigation potential etc., it is the variation of rainfall over different regions which has a direct impact on the livelihood of the rural populations. Not surprisingly, there is great demand for accurate predictions of the monsoon rainfall on spatial scales ranging from that of the country as a whole to district/

taluk-level and temporal scales from the total seasonal rainfall to that over a month, a nakshatra (13–14-day period based on the solar calendar used by most Indian farmers)[5], a week or shorter periods.

The need for accurate rainfall predictions has always been acutely felt by the government in the wake of major droughts with adverse impact on the economy. Thus after the great 1877 famine, H. F. Blanford, the then meteorological reporter, was called upon to make a tentative forecast for the monsoon of 1878. More recently, after witnessing the enormous impact of the long and intense dry spell that occurred in July 2002, the Ministry of Agriculture, Government of India, funded a major programme for generating predictions for the occurrence of such dry spells, about 20–25 days in advance, i.e. far beyond the limits of predictability of the chaotic atmosphere[6]. In the wake of the deficit rainfall in July this year, it was widely reported in the press that the Central Government was planning to allocate substantial funds to make possible generation of forecasts down to the scale of districts, with minimal margins of error. Given this favourable funding environment, different suggestions have been made by some groups/institutions for using the additional funds for more observations, for a network of specially designed computers, etc. In order to identify strategies of research and development and new observations for enhancement of the skill of predictions of the kind envisaged and to assess whether the proposed measures are likely to lead to improvement in the skill of predictions, it is essential to examine why the predictions have not been good enough so far. In this article, we endeavour to share with the readers, our understanding of why the predictions have failed so often and how we could achieve success in addressing this challenging problem in the near future. For want of space, we consider here only the rainfall variation on monthly/seasonal scales, although variation on shorter timescales is also important.

The skill of the atmospheric models for forecasts in the tropics is expected to be reasonable for seasonal/monthly timescales, because the variation is influenced by the boundary conditions, such as the sea surface temperature (SST) or snow cover[7]. At the outset, we consider the predictions for the rainfall over the Indian region during the summer monsoon of 2004 with empirical models and with dynamical models by international and national centres. We then assess the skill of the operational forecasts for seasonal rainfall from 1932 onwards, generated from the empirical models used operationally by the IMD (see later in the article). How good the predictions of the monsoon rainfall using dynamical models are, necessarily depends on their skill in simulating the year-to-year variation of ISMR. We describe such simulations with the state-of-the-art atmospheric GCMs and models of the coupled atmosphere–ocean system (see later in the article) and assess the chance of improving the skill of predictions with regional atmospheric models, or use models with higher resolution as has been suggested. Finally, we summarize what we understand about the year-

to-year variation of the monsoon rainfall, identify problems that have to be addressed for improving the skill of the predictions of seasonal rainfall and suggest strategies for meeting this challenge.

Predictions for the monsoon of 2004

Two distinct approaches have been adopted for generating predictions for seasonal rainfall over the Indian region. In the traditional approach, empirical models based on analysis of historical data of the variability of the monsoon and its relationship to a variety of atmospheric and oceanic variables over different parts of the world prior to the summer monsoon season are used. In the second approach, predictions are generated by physical models based on the equations governing the physics of the atmosphere from an initial state prior to the season. We consider predictions generated by both the approaches for 2004.

Empirical models

During 1988 to 2002, the IMD issued a forecast for ISMR using a power regression model[8] based on the relationship of the ISMR with 16 predictors, which are based on different facets of the state of the atmosphere and ocean over different parts of the globe. The forecast failure in 2002 prompted IMD to critically examine the 16-parameter model and introduce several new models[4], which gave correct forecast in 2003. However, the new models failed in 2004, with the predicted ISMR of 100% of the average being much higher than the observed ISMR of 87% of the average. Iyengar and Raghukanth[9] at the Indian Institute of Science (IISc), Bangalore, had predicted a deficit of 5.75% on the basis of a new model developed by them. This model is also based on the observed time series of ISMR. Kishtwal et al.[10] predicted a 2% deficit using a new empirical model that they developed based on a genetic algorithm, which also makes use of only the observed rainfall time series. Thus, among the forecasts based on empirical models, the forecast by Iyengar and Raghukanth came closest to the observed in sign and magnitude of the anomaly, but none could predict accurately the large deficit of the 2004 monsoon rainfall. In the next section, we assess the skill of the empirical models used operationally by IMD over several decades, to ascertain whether we can expect better predictions from such models for seasons such as 2002 and 2004.

Dynamical models

Some major climate prediction centres like International Research Institute for Climate Prediction (IRI) and the European Centre for Medium Range Weather Forecasts (ECMWF) prepare global seasonal predictions (for June–
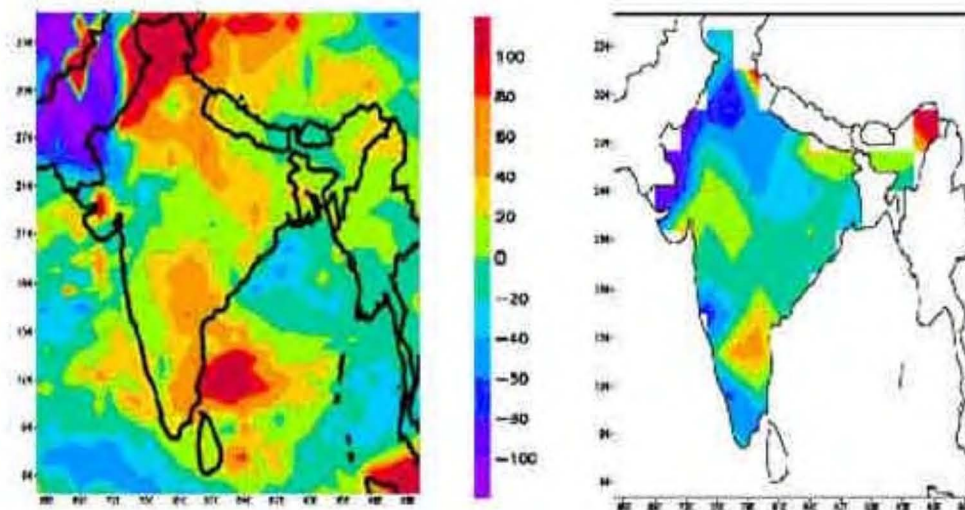
Figure 3. CMMACS predictions for July 2004 (left) and the corresponding realized rainfall (right) in percentage departure.
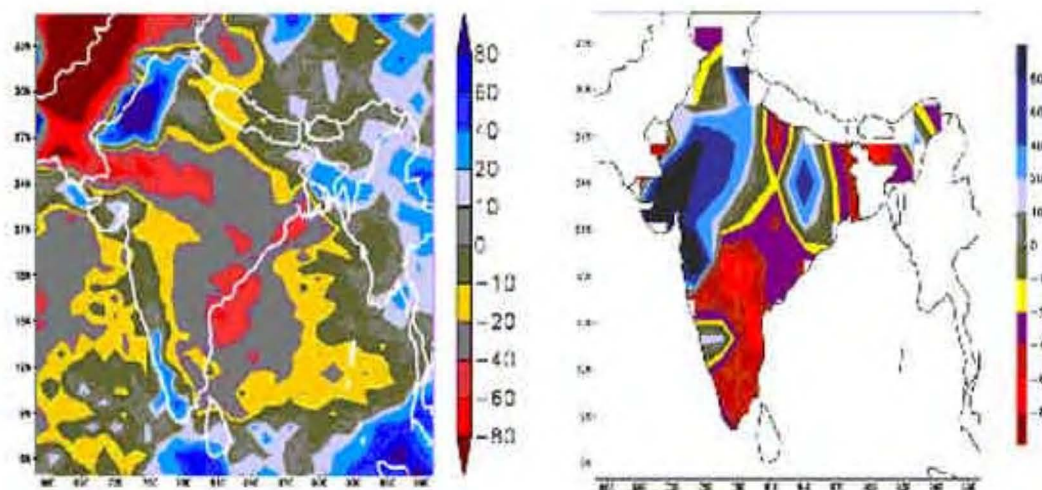

Figure 4. CMMACS predictions for August 2004 (left) and the corresponding realized rainfall (right) in percentage departure.

August and July–September) using GCMs. Some institutions in India such as the Indian Institute of Tropical Meteorology (IITM) Pune, Space Applications Centre, Ahmedabad and Centre for Mathematical Modelling and Computer Simulation (CMMACS), Bangalore also generate experimental dynamical predictions of rainfall on monthly and/or seasonal scales for the summer monsoon season.

Predictions of monthly rainfall are made by CMMACS using a redesigned version of the variable-resolution AGCM developed at LMD, France. The experimental predictions made by CMMACS of the predicted anomalies (given as percentage departures from the average of the simulated rainfall) for July and August 2004, which were available in advance on the website (http://www.cmmacs.ernet.in) before the period for which rainfall is predicted, are shown in Figures 3 and 4. For comparison with these and other predictions, we have prepared monthly gridded rainfall data at a 2.5 degree resolution using about 300 stations

which were available on real time. Anomaly was calculated by subtracting the average of the rainfall for the period 1951–2000. The observed patterns of anomalies from these data (also given as percentage departures from the average observed rainfall) are also shown in Figures 3 and 4. This comparison of the predicted and observed rainfall shows that the prediction errors are very large. For July 2004, the CMMACS prediction was above normal rainfall over most of Indian region, which was in sharp contrast to that observed. For August 2004, the forecast suggested below normal rainfall over central parts of India, Orissa, south Rajasthan and Gujarat, whereas the observed rainfall was above normal.

Rainfall predictions made by ECMWF and IRI for the June–July–August (JJA) season of 2004 are shown in Figure 5 along with the observed rainfall during the same period. It is seen that over most of the region, the observed rainfall anomaly was negative, with the largest anomaly
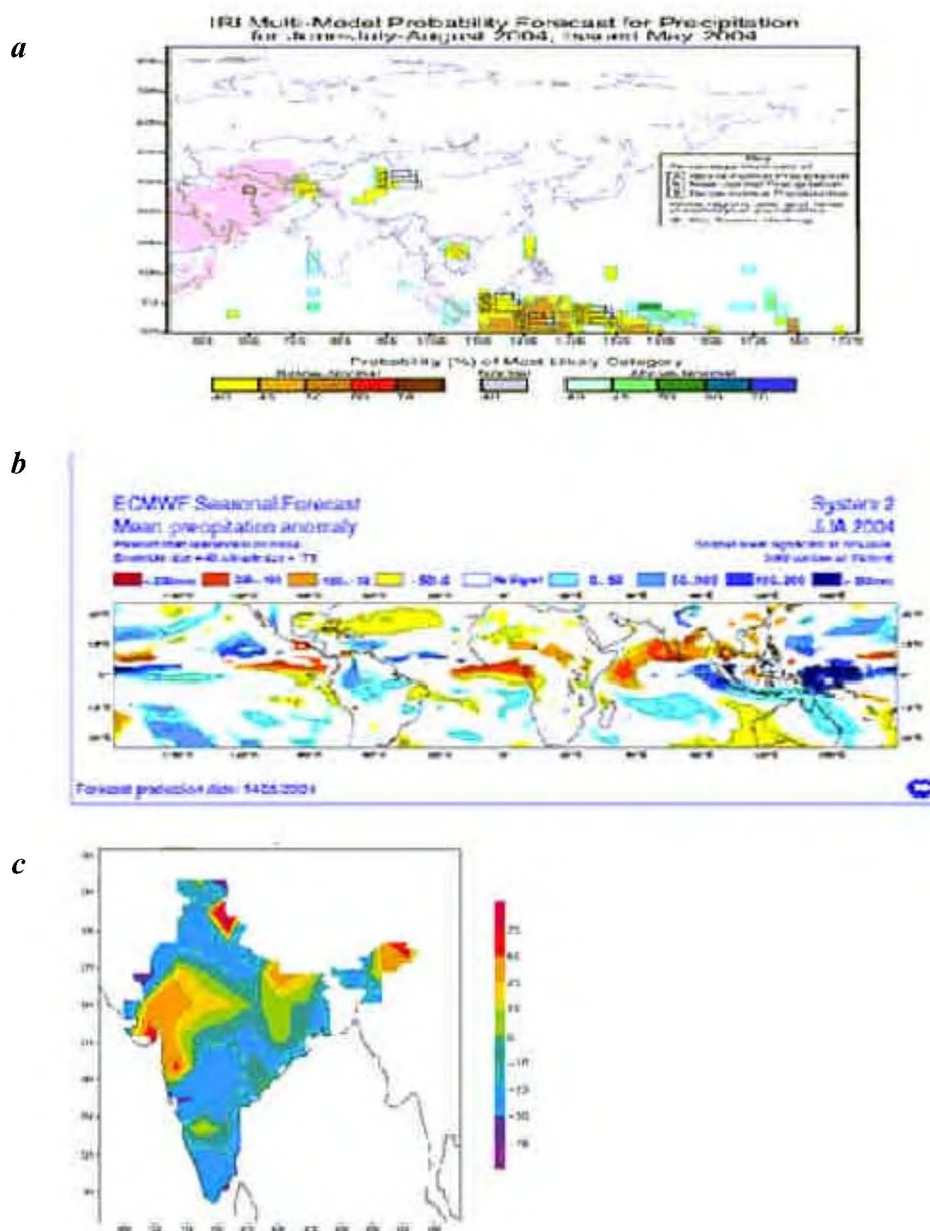
a

b

c

Figure 5. Dynamical predictions of (*a*) IRI, (*b*) ECMWF for June–July–August 2004 and (*c*) observed rainfall as percentage departure for the same period.

over northwest India. Above normal rainfall was observed only over the Gujarat region, south Rajasthan, Bihar and the adjoining region. However, ECMWF predictions suggest near normal rainfall over northwest India. Below normal rainfall was predicted only over the southern peninsula and along the west coast. The IRI predictions suggested no significant rainfall anomalies during the JJA season over the Indian region. Thus, none of these dynamical models could predict the rainfall anomaly pattern of June–August 2004 accurately. We need to understand why the models failed in 2002 and 2004, before we can consider how the predictions could be improved.

Predictions with operational models of IMD

Forecasting of monsoon rainfall has been attempted for over a hundred years in India. In 1871 the Madras famine commission recommended that, 'so far as it may be possible, with the advance of knowledge to form a forecast of the future, such aids should be made use of, though with due caution', and official monsoon forecasts began to be issued from 1886. IMD has always been the responsible agency for the operational long-range forecasts of monsoon rainfall, which have been based on empirical models from early 1900s. Here, we briefly discuss the evolution

of the models used for generating the forecasts over this period, but do not describe the models in detail since several reviews are available[11-15]. We then assess the predictions derived from these models during 1932–2004.

The first long-range forecast in 1886 was based on the relationship between Himalayan snow cover and monsoon rainfall, discovered by Blanford[16] in 1884. Forecasts during the initial years were subjective and qualitative. It was Sir Gilbert Walker, who for the first time (1909) introduced an objective technique based on correlation and regression analysis[17,18]. While investigating the links of the Indian monsoon with atmospheric conditions over the rest of the globe, Walker discovered the Southern Oscillation, which is a see-saw of pressure between Darwin, Australia and Tahiti in the Pacific Ocean. This discovery was to play a major role in the phenomenal advances in the understanding and prediction of the interannual variability of the tropical ocean–atmosphere system witnessed over the last decade. The first model used by Walker in 1909 for prediction of ISMR was a linear regression model based on four predictors (Himalayan snow accumulation at the end of May, South American pressure during March–May, Mauritius pressure of May and Zanzibar rain in April and May). However, assessment of the predictions by this model by Montogomery[19] up to 1936 showed that, in spite of its early encouraging performance, the formula had broken down completely in the 15 years from 1921. In the early 1920s, recognizing that the Indian region is not homogeneous with coherent variation of rainfall and hence too large to be considered as a unit, Walker identified homogeneous regions called NW India and Peninsula (Figure 6) on the
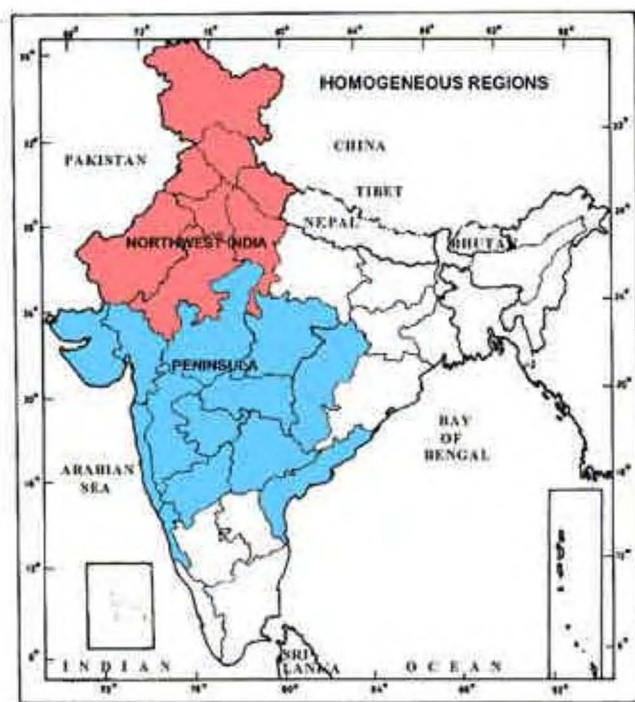

Figure 6. Map of homogenous regions.

basis of the correlation with the predictors used. He then developed models for predicting rainfall separately for these regions[11]. From 1924 to 1987, forecasts were issued only for these two regions[20,21]. In fact, as the sample of years increased with time, the correlation coefficient with several parameters became poor and for some of them even changed sign; hence many revisions were made on the model by changing the predictors.

From 1988 to 2002, the IMD reverted to issuing a forecast for the country as a whole (including the NE regions) instead of forecasts for the two homogenous regions of India. Quantitative forecasts were based on the 16-parameter power regression model and qualitative ones on the parametric models[8]. The forecast failure in 2002 prompted IMD to critically examine these two models and introduce several new models[4]. However, in spite of the new models, the forecast for 2004 monsoon failed once again.

It is important to note that during 1932–1987, although the quantitative predictions have been generated from the operational model for every year, the forecasts issued were often in terms of expected range or even more qualitative. In order to assess the performance of the empirical models (rather than the forecasts issued), we compare the predictions generated for the seasonal rainfall of NW India and Peninsula during 1932–87 and for the all-India rainfall during 1988–2004 from the models used operationally by IMD with the observed rainfall. The mean of the predicted and observed June–September rainfall is comparable (56 and 54 cm respectively, for NW India and 87 and 89 cm respectively, for Peninsula). However, the standard deviation of the predictions is much smaller than that for the observations (7.3 and 10.6 cm respectively, for NW India and 7.7 and 13.4 cm respectively, for Peninsula). The time series of observed and predicted rainfall and the magnitude of the error (predicted–observed rainfall) are depicted in Figure 7 a and b. It is seen that while for a few years such as 1979, 1982 and 1988, the predictions are close to the observed, generally the error is large. The variation of the predicted rainfall and the error for each season with the observed rainfall (Figure 8) shows that the predictions are therefore generally closer to the average than the observed values. In fact, if the predictions were always for the rainfall to equal the average rainfall, then the error would be the negative of the anomaly of the observed rainfall. It is seen that the predictions are randomly scattered about the line representing such a prediction for average rainfall.

Consider next the extent to which the models are at least able to predict the sign of the anomaly. We define seasons with rainfall below (above) the average by more than one standard deviation as droughts (excess rainfall seasons). Of the 13 (10) droughts (excess rainfall seasons) that occurred over the Peninsula, only in four the predicted rainfall was deficit (excess), while of the 8 (10) droughts (excess rainfall seasons) that occurred over NW India, only in 7 (3) the predicted rainfall was deficit (excess). Not surprisingly, the association coefficient (Pearson product moment correla-
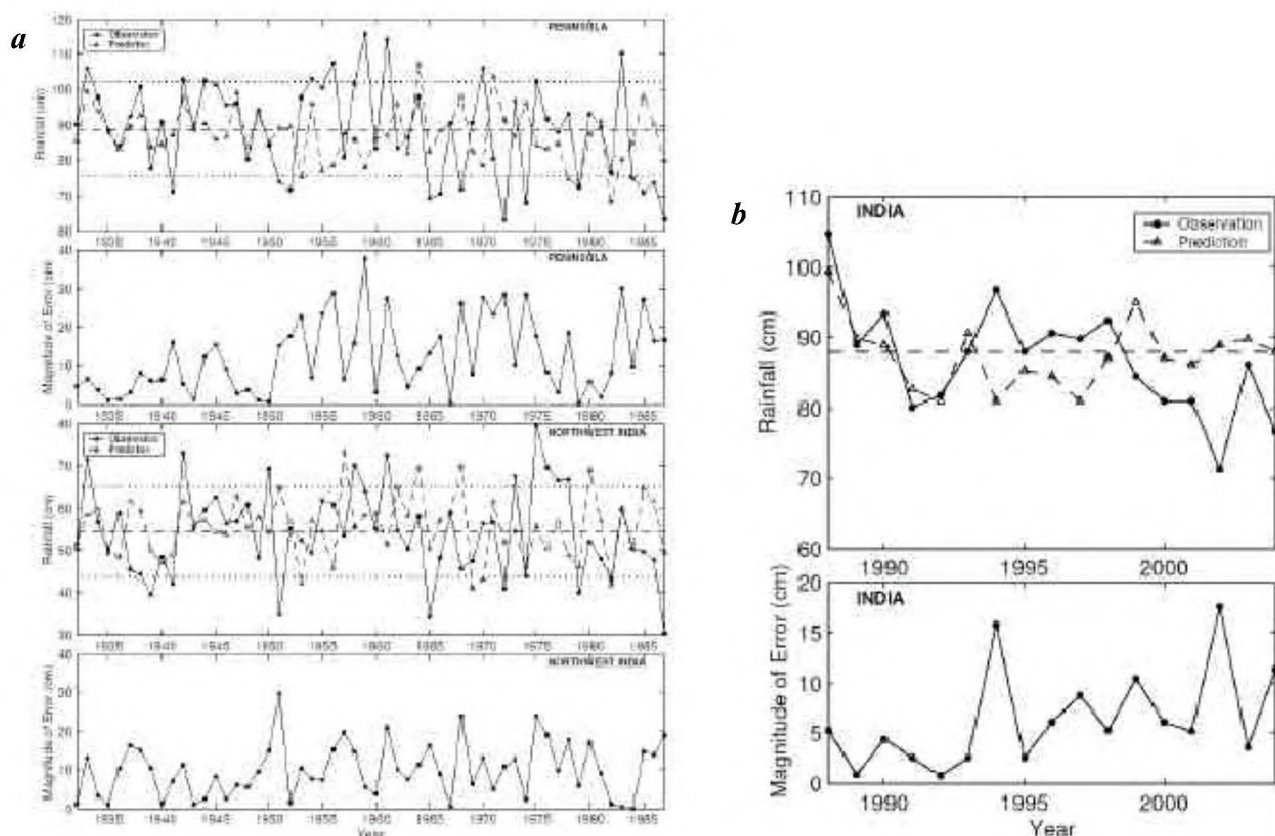
Figure 7. Variation of observed and predicted rainfall and absolute error for NW India and Peninsula (*a*) and all-India rainfall during 1988–2004 (*b*).

Table 1. Magnitude of average and maximum forecast error (in cm) for different decades

Year	Peninsula		Northwest	
	Average error	Maximum error	Average error	Maximum error
1932–1940	4.5	8.1	8.0	16.3
1941–1950	6.8	16.0	6.9	15.0
1951–1960	17.8	37.8	11.6	30.0
1961–1970	14.7	27.7	12.0	24.1
1971–1980	14.4	28.4	12.5	24.1
1981–1987	15.8	30.2	8.4	19.1

Year	All-India	
	Average error	Maximum error
1988–1990	3.5	5.3
1991–2000	6.1	15.8
2001–2004	9.5	17.6

tion coefficient) for NW India, Peninsula and also for all-India (1988–2004) was statistically not significant, suggesting that the empirical operational models could not even predict the sign of the anomaly accurately. The variation of magnitude of the error with time (Figure 7, Table 1) shows that there has not been any improvement over the years, in spite of the continuing attempts to revise the operational models based on rigorous and objective statistical methods.

Why have the dynamical models failed so far?

We suggest that this is because the atmospheric models have not evolved to a stage where they can simulate the year-to-year variation of the Indian monsoon realistically. This is supported by an analysis of the simulation for the years 1979–95 by 20 state-of-the-art atmospheric GCMs organized under the Atmospheric Model Intercomparison Project (AMIP)[22]. One of the problems in using atmospheric models for prediction is that the sea surface temperature (SST) has to be prescribed for the period of prediction. The AMIP simulations were made with the SST specified from observations and are therefore expected to have better skill than predictions made with predicted SST.

The observed and simulated[23] anomaly of ISMR for the droughts in the latter period (1979, 1982, 1987) and seasons with excess rainfall (1983, 1988, 1994) are shown in Figure 9. It is seen that while all but one model have simulated the correct sign of the anomaly for the excess monsoon of 1988, only one model did so for that of 1994. Similarly, while a majority of the models (all but three) simulated a deficit
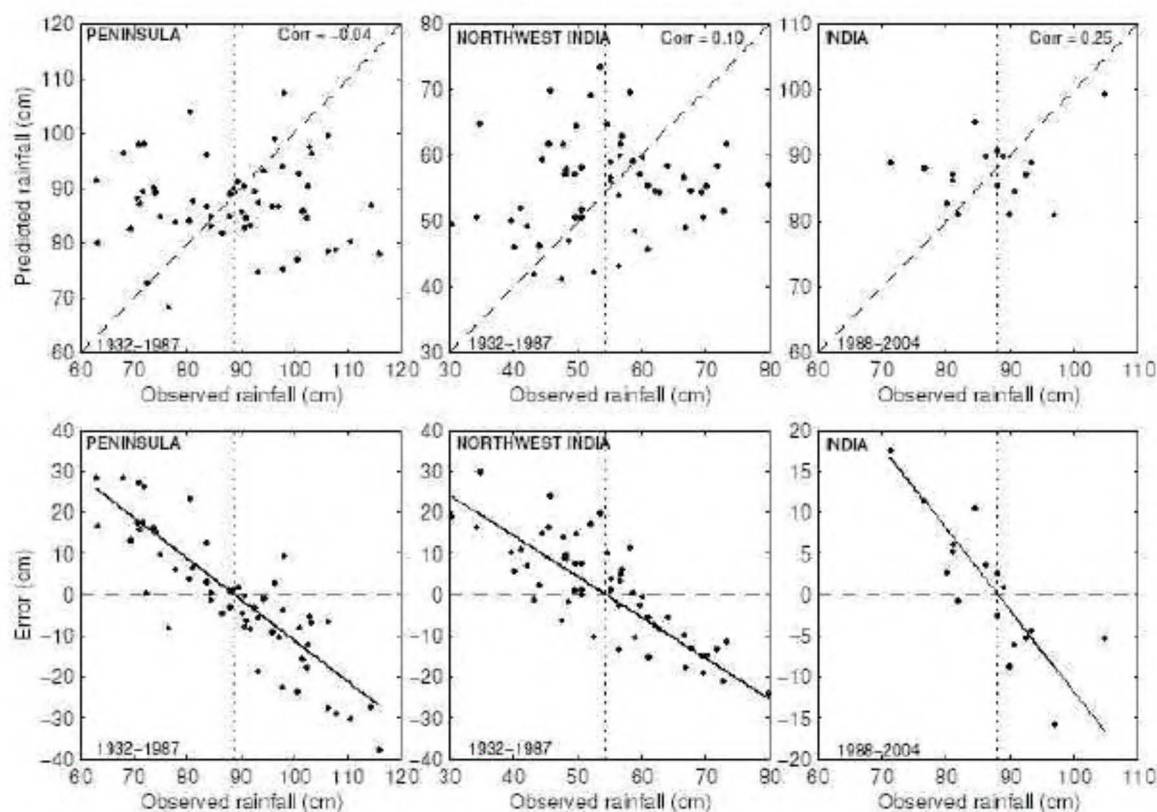
Figure 8. Predicted versus observed (top) and error versus observed rainfall. The line represents a perfect prediction (top) and the negative of the observed anomaly (mean-observed) versus observed (bottom). If the prediction was always given as the mean, the error would fall on this line. As it is, the points are scattered around the line.
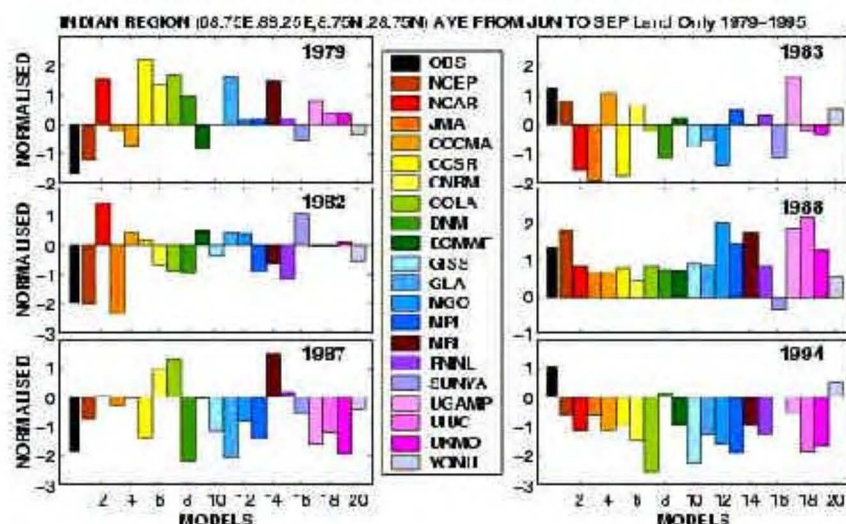

Figure 9. Normalized precipitation (June–September) anomalies in AMIP II models for the Indian region for 1979, 1982, 1983, 1987, 1988 and 1994 seasons.

(with several of them showing a large deficit) for the drought of 1987, most of the models simulations for the drought of 1979 were for excess rainfall, with only one simulating a large deficit.

Thus, on the whole, the skill of the atmospheric GCMs in simulating the year-to-year variation of the ISMR and particularly the extremes, is rather poor even when the SST is specified from observations. We now assess the extent to which models of the coupled atmosphere–ocean system are able to simulate the year-to-year variation of the Indian monsoon rainfall.

We illustrate the performance of coupled models by presenting the results of the comparison of the simulations by the UK Met Office coupled model under a project on
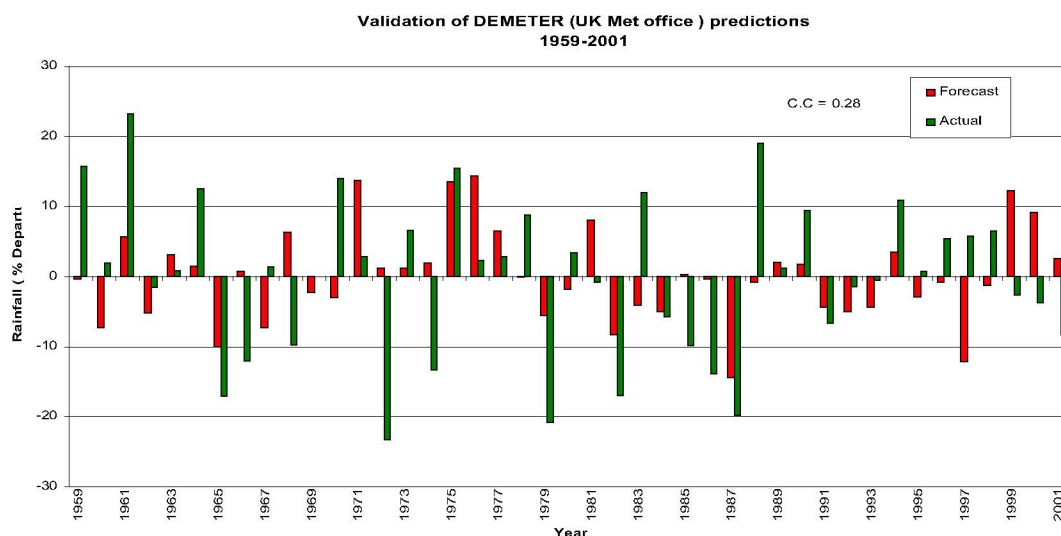
Figure 10. Comparison of DEMETER (UK Met Office model) hindcasts and actual monsoon seasonal (June–September) rainfall (1959–2001).
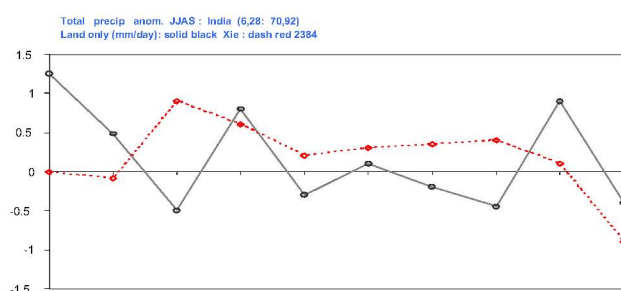

Figure 11. Results of ERA simulations of JJAS rainfall over India.

'Development of a European Multimodel Ensemble System for Seasonal to Interannual Prediction' (DEMETER)[24] of the summer monsoon rainfall over the Indian region for the period 1959–2001 with observations (Figure 10). The correlation between the simulated and observed rainfall for the 43-year period is poor (coefficient = 0.28). The pattern correlation (not shown) suggests positive correlations are observed only over the central parts of India, but they are statistically not significant. The model simulation showed the anomaly of the correct sign in four out of these eight drought years. Amongst these four years, the magnitude of the simulated anomaly was reasonable only for 1965 and 1987. For the major drought year of 1972, the model simulated a slight positive anomaly. In 1997, a major El Nino year, the model suggested deficient monsoon (second largest deficit), but the observed rainfall was above normal.

Seasons of excess rainfall have also not been well simulated. The model could not capture the strongest monsoon in the last 150 years of observations, viz. during 1961. The excess rainfall monsoons of 1983 and 1988 have also not been captured, with simulations showing negative anoma-

lies in both cases. In 1994, even though the model showed correct sign, the error was large. For the period beyond 1995, the signs of the simulated anomalies are consistently opposite to those of the observed anomalies. Thus at the present juncture, neither the atmospheric nor the coupled ocean–atmospheric models are able to simulate correctly the interannual variation of the summer monsoon rainfall over the Indian region.

How can we improve predictions from physical models?

It has been suggested that the problems in simulating the year-to-year variation of the Indian monsoon could be partly because of the coarse resolution used in most GCMs. If this is the case, then the problem could be easily solved by increasing the resolution of GCMs. Another strategy often recommended is the use of high resolution regional models in conjunction with GCMs. Before adopting either of these strategies, it is worth considering the experience so far.

The results of a recent study of simulations with a high-resolution GCM are not encouraging, especially for the Indian monsoon region. The simulation by Brankovic and Molteni[25] with the ECMWF model at a high resolution (TL 159 with 40 levels in the vertical), of the interannual variation of June–July–August–September (JJAS) rainfall (Figure 11) is not realistic. For example, the simulated rainfall for the monsoon of 1982 (a major drought year) was higher than that of 1983 (an excess rainfall season). Similarly, the simulated rainfall of 1987 (observed monsoon failure) exceeded that simulated for 1988 (a season with excess rainfall).

At present there is no basis to assume that the higher resolution obtainable in a regional climate model will improve

the seasonal forecasts. We are not aware of any systematic assessment of the performance of regional climate models in seasonal forecasting over the Indian region. Furthermore, some experts believe that regional climate models are not likely to do much better than the GCMs they are run in conjunction with. Discussing regional climate simulations, Kalnay[26], one of the leading forecasters in the world says, '...the initial regional information (in a regional climate model) is swept out of the domain in the first day or two and all additional information comes from the global model integration... the regional models acts as a "magnifying glass" to the simulations of the GCMs...'. This being so, as GCMs themselves have serious problems in simulating the Indian monsoon, it is clear that using regional models operationally for generating forecasts cannot be considered as a viable option at this juncture.

Way forward

It is clear that no 'quick fix' solutions are available to tackle the problem of predicting the summer monsoon rainfall over the Indian region. From the experience with the empirical models at IMD, it is clear that over the years, changing parameters used in regression equations have not led to a decrease in the error of the predicted rainfall. However, after 1980s, due to availability of large amount of global climate datasets, our understanding of monsoon variability and its teleconnections has improved. But this does not seem to have led to improvement of the accuracy of monsoon prediction. A part of the problem may be the way we model the relationship between the predictors and rainfall in empirical models. In general, the relationship of the rainfall to the predictors is highly nonlinear. For example, if we consider the variation of the all-India monsoon seasonal rainfall with winter Eurasian snow cover (Figure 12), it is seen that when the snow cover is much less than average (i.e. anomaly is negative and less than -1.0), above normal monsoon rainfall is almost certain. However, excess Eurasian snow cover does not always suggest deficient rainfall, but can be associated with the excess years too.
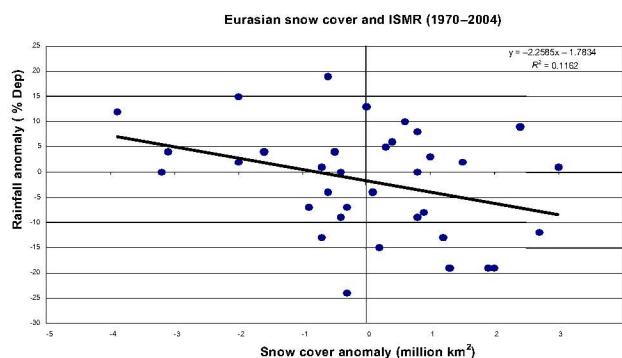

Eurasian snow cover and ISMR (1970–2004)

$y = -2.2585x - 1.7834$
$R^2 = 0.1162$

Figure 12. Relationship between winter snow cover and ISMR anomaly.

Thus a simple linear fit of the kind shown is not likely to give good predictions. In the 16-parameter model, nonlinearity was introduced in terms of power regression technique. However, the model was over-fitted due to larger number of unknown coefficients compared to the number of datapoints used, causing unrealistic nonlinearity in the model. The performance of the 16-parameter model for 15 years (1988–2002) has not justified the methodology adopted.

Recently, at IISc, Iyengar and Raghukanth[9] developed a new model for prediction of ISMR (and regional-scale average rainfall as well) based only on the observed time series up to that year. This involves decomposition of rainfall time series into six empirical time series called intrinsic mode functions and treating these mode functions separately. They demonstrated that this model was capable of predicting the drought of 2002 using only antecedent data. They predicted ISMR for the 2004 monsoon season to be 80.34 cm (a deficit of 5.75%), with a standard deviation of 3.3 cm. Thus the sign of the anomaly of ISMR turned out to be right although the magnitude was underestimated. This new approach is promising as it separates the nonlinearity of the rainfall time series. Whether it is superior to the empirical models used operationally at IMD needs to be ascertained with more years of independent verification.

The empirical approach has to be adopted until the dynamical models improve to a level at which they can simulate and hence predict the interannual variation of the Indian monsoon. Although this has not been possible so far, we believe that it should be achieved in future. It is important to note that the breakthroughs in seasonal forecasting over the tropics have come from the understanding of the physics of El Nino–Southern Oscillation (ENSO) and subsequent development of atmospheric models to achieve a realistic simulation of ENSO. In fact, the interannual variation of ISMR is known to be linked to the ENSO[27–29] over the Pacific Ocean, with an increased propensity of droughts during El Nino or the warm phase of this oscillation and of excess rainfall during the opposite phase, i.e. La Nina[30–32]. The realistic simulation of the 1987 drought in an El Nino year and of the 1988 excess monsoon season in the La Nina year by most of the AMIP models, suggests that the models have evolved to a level at which the impact of ENSO on the Indian monsoon is well simulated. However, AMIP models could not simulate some anomalous years like 1997, 1994 and 1979 correctly. During the strongest El Nino of the century in 1997, ISMR was above normal; in 1994, a non-La Nina year, the ISMR was well above normal. In 1979, a non-El Nino year, a severe drought was experienced. The monsoon of 2002 being a major drought although the El Nino was weak, turned out to be a wake-up call, suggesting that there was much more to monsoon variability than could be attributed only to ENSO.

Recent studies[33,34] triggered by the drought of monsoon 2002 showed that in addition to ENSO, the phase of the equatorial Indian Ocean Oscillation (EQUINOO), which is the atmospheric component of the Indian Ocean Dipole

Mode, also plays an important role in the interannual variation of ISMR. In fact, every drought (and excess rainfall year) during 1958–2004 is associated with an unfavourable (favourable) phase of ENSO and/or EQUINOO or both (Figure 13 *a*). It is seen that the excess rainfall season of 1994 is associated with favourable phase of EQUINOO, whereas the drought of 1979 with an unfavourable phase. Although over the years the models have evolved to simulate reasonably the link of the Indian monsoon to ENSO, they are not able to simulate the link with the EQUINOO. It is seen from Figure 13 *b* that for many seasons with extreme rainfall, i.e. excess or drought including 2004, the phase of the EQUINOO is important.

Since EQUINOO, which occurs in closer proximity to the Indian region than the ENSO, plays an important role in the extremes (droughts or excess rainfall seasons) of the Indian monsoon, we believe that development of models to achieve realistic simulations of EQUINOO and its links with the Indian monsoon are essential for improvement of seasonal forecasts of the monsoons. This in turn requires concerted efforts to gain a deep understanding of EQUINOO physics and improve its simulation in the models. We can expect a realistic simulation and hence prediction of the interannual variation of the Indian monsoon only when it is possible to simulate the impact of the events over the equatorial Indian Ocean as well as the Pacific Ocean.
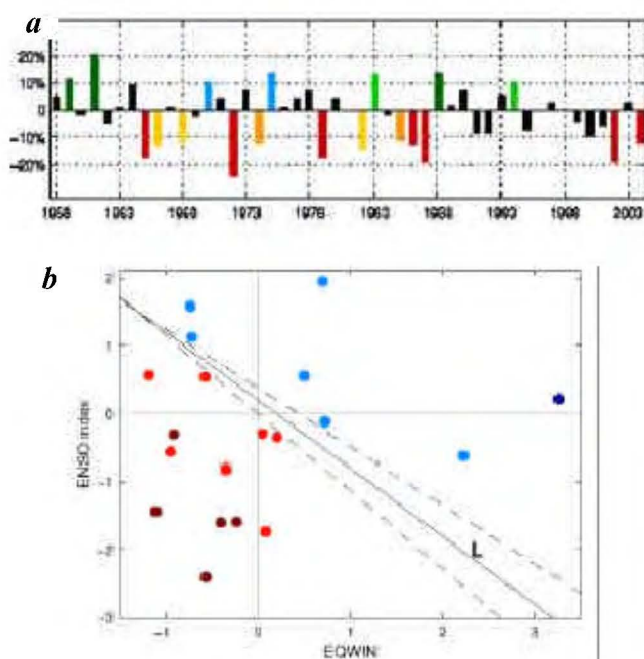

Figure 13. *a*, Percentage departure of ISMR from long-term mean. Colour code: Yellow, ENSO unfavourable; orange, EQWIN unfavourable; red, both unfavourable; blue, ENSO favourable; green, EQWIN favourable, and dark green, both favourable. *b*, Scatter plot of Nino 3.4 versus EQWIN for June–September 1958–2004. ISMR anomaly is indicated with different symbols representing large dark green (red) closed circles for ISMR above (below) 1.5 (–1.5) standard deviation; Green (red) closed circles for ISMR between 1 (–1) and 1.5 (–1.5) standard deviation. Red star represent drought of 2004.

Summary and concluding remarks

Our analysis of the predictions generated by the empirical models used operationally by IMD since 1932, suggests that the performance of these models based on the relationship of the monsoon rainfall to atmospheric/oceanic conditions over different parts of the globe has not been satisfactory. They have also not improved over the eight decades, despite several changes in the operational models and better understanding of monsoon variability. Thus, while the contribution of Sir Gilbert Walker's discovery of the Southern Oscillation to the present-day understanding of tropical variability is monumental, it appears that following in his footsteps and continuing to use the kind of models he formulated for monsoon forecasting, has been far from successful. Whether new approaches which take into account the inherent nonlinearity in the relationships will yield better results, have to be explored. Also we need to explore precursors for the events in the equatorial Indian Ocean (like EQUNIOO) to use as predictors in the empirical models along with other ENSO-related predictors.

We have seen that the skill of atmospheric and coupled models in predicting the Indian monsoon rainfall is also not satisfactory, and the problem is particularly acute as these models fail to predict the extremes, i.e. droughts and excess rainfall seasons. It has been sometimes argued that using coupled models and/or high resolution atmospheric models or regional models for forecasts could be a panacea for improving the monsoon forecasts. However, at the present juncture, neither the performance of coupled models nor of high-resolution models is particularly encouraging. Also, tailor-made computers can only contribute towards enhancing to some extent, the computational capacity to address this massive challenge. Clearly, there are no 'quick fix' solutions.

This is not surprising since understanding, simulating and hence predicting the variability of the Indian monsoon is clearly the next frontier in tropical variability after the elucidation of ENSO physics. The advances in the understanding of ENSO physics in the last two decades, led to development of atmospheric models to a level at which they could simulate the phenomenon and its impacts on the climate of different regions realistically. We have seen that the drought of 1987 and the excess rainfall year of 1988 of the Indian monsoon associated with El Nino and La Nina respectively, were reasonably well simulated by almost all the models in the AMIP.

With concerted effort in elucidating the physics of variability of the monsoon and its links with events over the Pacific Ocean and Indian Ocean (ENSO and EQUINOO), considerable progress can be achieved in the next 5–10 years. This expectation is based on the enormous progress achieved on all fronts in our country in last three decades. Scientists have made major contributions to elucidating the nature of the variability of the monsoon from sub-seasonal to interannual timescales, of the links to convection and rainfall over the Indian Ocean and Pacific Ocean. The observational

network over the surrounding oceans has been extended with special platforms such as data buoys, ARGO floats, etc. to complement the ever-increasing observations by satellites over the land and oceans. Special observational programmes such as the Bay of Bengal Monsoon Experiment conducted under the Indian Climate Research Programme, have provided new insights into the coupling with the oceans. With a substantial increase in computational resources, considerable expertise has been developed in atmospheric and oceanic GCMs as well as coupled models.

It is clear that the Indian meteorological community has to rise to the occasion to meet the demands from user agencies for the forecast of monsoon rainfall. However, the challenges are daunting. Since the empirical models have inherent limitations in meeting some of these requirements, dynamical model is the alternate option. But we need to improve dynamical models to simulate monsoons realistically. For atmospheric models, this implies systematic improvements in their ability to model clouds, radiation and its interaction with clouds, surface fluxes, air–sea interaction and numerical methods. For the oceanic component, this implies better ability to ingest oceanic observations and improve the capability to simulate SSTs and the thermodynamics of the upper ocean. The capacity to address these challenges has already been built up with support from the Government through generous and judicious funding. We are optimistic that reasonable predictions of the Indian summer monsoon will be generated in not-too-distant a future.

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