

# Seasonal prediction of the Indian monsoon

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**Under the project ‘Seasonal Prediction of the Indian Monsoon’ (SPIM), the prediction of Indian summer monsoon rainfall by five atmospheric general circulation models (AGCMs) during 1985–2004 was assessed. The project was a collaborative effort of the coordinators and scientists from the different modelling groups across the country. All the runs were made at the Centre for Development of Advanced Computing (CDAC) at Bangalore on the PARAM Padma supercomputing system. Two sets of simulations were made for this purpose. In the first set, the AGCMs were forced by the observed sea surface temperature (SST) for May–September during 1985–2004. In the second set, runs were made for 1987, 1988, 1994, 1997 and 2002 forced by SST which was obtained by assuming that the April anomalies persist during May–September. The results of the first set of runs show, as expected from earlier studies, that none of the models were able to simulate the correct sign of the anomaly of the Indian summer monsoon rainfall for all the years. However, among the five models, one simulated the correct sign in the largest number of years and the second model showed maximum skill in the simulation of the extremes (i.e. droughts or excess rainfall years).**

The first set of runs showed some common bias which could arise either from an excessive sensitivity of the models to El Niño Southern Oscillation (ENSO) or an inability of the models to simulate the link of the Indian monsoon rainfall to Equatorial Indian Ocean Oscillation (EQUINOO), or both. Analysis of the second set of runs showed that with a weaker ENSO forcing, some models could simulate the link with EQUINOO, suggesting that the errors in the monsoon simulations with observed SST by these models could be attributed to unrealistically high sensitivity to ENSO.

**Keywords:** Atmospheric models, Indian summer monsoon, seasonal prediction, simulation.

A national project on ‘Seasonal Prediction of the Indian Monsoon’ (SPIM) was triggered by a guest editorial in *Current Science*<sup>1</sup>. The project involved a comparison of the skill of the atmospheric models used in the country for prediction of the summer monsoon, in simulation of the year-to-year variation of the summer monsoon rainfall over the Indian region for 1985–2004. In this article, we present in brief, the major results of this project. The time

is opportune for presenting the results of this first national project on simulation of the Indian summer monsoon by atmospheric models, as the Ministry of Earth Sciences, Government of India has just decided to launch a national ‘Monsoon mission’ for improving the forecasts with dynamical models<sup>2</sup>, which is a logical follow-up of the SPIM project.

SPIM was conceived in response to the need for an objective assessment of the skill of the atmospheric models in the country, in the simulation and prediction of the Indian summer monsoon rainfall (ISMR). In early June 2005, as soon as it became clear that there would be some delay in the onset of the monsoon over Kerala, an extensive discussion began in the media of the two publicly available forecasts for the forthcoming monsoon. Of these two forecasts made in April, one was the ‘official’ forecast released by the India Meteorological Department (IMD) and the other an ‘experimental forecast’ by the Centre for Mathematical Modelling and Computer Simulation (CMMACS; CSIR), Bangalore. IMD had predicted normal seasonal (June–September) rainfall (i.e. within one standard deviation) for the country as a whole, whereas the CMMACS forecast had suggested excess rainfall for June. The CMMACS forecast was revised on 2 June 2005. The revised forecast suggested a very large deficit in rainfall in June (of 34%), a deficit of 12% in July, and an excess of 13% for August from the average monthly values. The Secretary General of the Confederation of Indian Farmers’ Association, pointed out that ‘such forecasts by two government departments lead to confusion amongst farmers down the line’.

Amidst the confusion created by the conflicting predictions in 2005, in mid-June came a report that the Department of Science and Technology (DST), New Delhi had stated that only IMD had the mandate to make public the long-range monsoon forecast. This in turn triggered a debate on whether this is a violation of the right of scientists to disseminate information on monsoon forecasts derived from various models. This raised the question of whether it is reasonable to allow dissemination of information on the prediction of the monsoon by the different models to the lay public. In this regard, it is important to first consider the quality of predictions that are generated. This is because announcing predictions of drought about the forthcoming season, based on models that have not been shown to generate reliable predictions of the monsoon, is as unacceptable as arbitrary suppression of information about research results.

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Predictions of the monsoon with models of the atmosphere and coupled ocean–atmosphere system based on physics (as distinct from the statistical models used for a long time) have become possible in the last two decades because of the rapid developments in meteorology and high performance computers. The problem is that, despite major advances in atmospheric sciences, simulation and prediction of the Indian monsoon remains a tough challenge. For example, almost no model of the atmosphere or coupled ocean–atmosphere system could predict the recent droughts of 2002, 2004 and 2009 (refs 3 and 4). Predictions based on such models are readily available from the major international centres. Some experimental forecasts with atmospheric models have also been generated at CMMACS; the Indian Institute of Tropical Meteorology (IITM), Pune; Space Applications Centre, Ahmedabad (in collaboration with the National Centre for Medium Range Weather Forecasting (NCMRWF), Delhi), and IMD (in collaboration with the Indian Institute of Science (IISc), Bangalore). Of these, only the CMMACS forecast (referred to above) was posted on the web and made available to the public. However, critical information on the expected error levels in the predictions by this and other models is not available. In order to ensure accountability and transparency, it is necessary to stipulate that forecasts from models can be made public, if and only if, information about the performance of the model based on objectively assessed error levels is included.

The performance and reliability of such atmospheric models need to be assessed by running them for several years with identical initial and boundary conditions from data available for each monsoon season. The error level of each atmospheric model can be objectively assessed by analysis of these retrospective forecasts. Such an exercise would lead to a more focused research effort in developing better models for monsoon prediction. Furthermore, it would also suggest the appropriate weightage for each model in a multi-model forecast.

Gadgil and Srinivasan<sup>1</sup> suggested that organizing such an intercomparison should be given a high priority by DST. In fact, the SPIM project, the results of which are briefly discussed in this article, is a manifestation of the high priority given by DST to such a study. At the end of the monsoon season of 2005, it became clear that there were indeed very large errors in the predictions generated by the CMMACS model (Table 1). It can be seen that for July and August the predicted anomaly of monthly rain-

fall was of opposite sign to that observed, and the magnitude of the error in prediction was more than twice the standard deviation of the monthly rainfall. Thus the need to assess the reliability of the different models used for prediction cannot be overemphasized.

For generating predictions with atmospheric models, conditions at the surface (land or ocean) have to be specified. The main determinant of seasonal atmospheric predictability is the slowly varying boundary conditions at the earth's surface. In particular, an important component of the variability of the tropical atmosphere arises from the variation of the sea surface temperature (SST). Hence it has been possible to simulate the atmospheric component of the El Niño Southern Oscillation (ENSO) with atmospheric models run with observed SST as a boundary condition. Charney and Shukla<sup>5</sup> suggested that the large-scale seasonal mean monsoon rainfall over India is largely determined by the boundary conditions at the surface. There have been several studies of intercomparison of atmospheric general circulation models (AGCMs) in simulating the interannual variation of the Indian monsoon<sup>3,6,7</sup>. These studies involved analysis of the simulations by 20 state-of-the-art AGCMs organized under the Atmospheric Model Intercomparison Project (AMIP)<sup>8</sup> for the years 1979–1988 (AMIP-1) and 1979–1995 (AMIP-2), with SST specified as the observed SST. The simulations generated with the observed SST are expected to have the maximum possible skill for each AGCM, since it implies a perfect specification of the boundary condition.

Here we present in brief, some of the results of our analysis of the simulations of ISMR for the summer monsoon (June–September) seasons of 1985–2004, with several AGCMs used in the country for predictions on the monthly/seasonal scale, under the SPIM project. A more detailed report with an extensive discussion of all the results and implications has also been prepared<sup>9</sup>. The project involved two phases. In phase I, the models were run with the observed SST for May–September for 1985–2004. These runs were used for assessing the potential of the models for simulation of the monsoon for the seasons of 1985–2004. For generating predictions with these models, it is necessary to specify predicted SST as the boundary condition. In phase II, the models were run only for five selected years, viz. 1987, 1988, 1994, 1997 and 2002, with predicted SST. The SST was predicted by a simple algorithm to get an idea of how the simulations differ when the SST specified is not the observed SST.

**Table 1.** Comparison of the anomaly of the observed monthly rainfall during June–August 2005 with that predicted by CMMACS

Rainfall predicted for	Observed standard deviation/mean (%)	Predicted rainfall anomaly (% of the mean)	Observed rainfall anomaly (% of the mean)	Error (% of the mean)
June	22.5	–34	–12	–22
July	13.5	–12	+14	–26
Aug	16	+13	–24	+37

The project was a collaborative effort of the coordinators and scientists from the different modelling groups across the country. All the runs were made at CDAC on the PARAM Padma supercomputing system. The contribution of the different modelling groups was critical for the porting of the models by the CDAC team. The first results of the analysis of phase I runs of three models (SFM, COLA and PUM) along with the results of the validation runs for these models were presented to the Secretary, DST, in March 2006, as an input for the seasonal forecast of 2006. Subsequently, several presentations of the results were made until the end of the project. It is important to note that the entire analysis of the runs was done at IISc. As such, the responsibility for the inferences about the performance of the models presented in this article rests solely with us.

The scientists involved in generating the predictions at CMMACS did not want to get their model run on the CDAC computer and hence did not participate in the SPIM project. It is, therefore, not possible to determine whether the magnitude of the errors in the prediction of the monsoon of 2005 (Table 1) is representative of a simulation for several years. Despite considerable efforts, it was not possible to make the runs for the model provided by the Indian Institute of Technology (IIT), Delhi. So the results of the simulations of five models at different institutions in the country, which generate prediction of rainfall over the Indian region on the monthly and seasonal scales are presented here (Table 2). A description of the models run for the project is given in the detailed report<sup>9</sup>, along with a discussion of the computational aspects of the project and its implementation at CDAC.

### Background: understanding interannual variation of the summer monsoon

There is a strong link between the interannual variation of ISMR and ENSO with an increased propensity of droughts during El Niño and excess rainfall during La Nina (refs 10–12 and several subsequent studies). A study by Ihara *et al.*<sup>13</sup> of the monsoon–ENSO relationship for 1880–1998 has shown that the correlation is highly significant and explains over 32% of the variance of

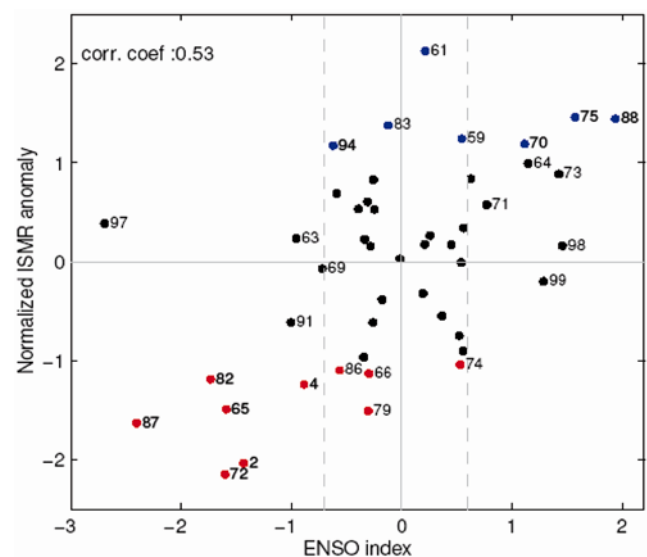
ISMR. Thus during the period 1985–2004, El Niño events of 1982, 1987, 2002 and 2004 were associated with droughts and the La Nina event of 1988 with excess monsoon rainfall. Analysis of AMIP runs for several models showed that all of them simulate the correct sign of the ISMR anomaly for the excess monsoon associated with La Nina of 1988, and most of them simulated the negative anomaly for the droughts of 1982 and 1987 associated with El Niño<sup>3</sup>. Clearly the first and foremost requirement of the atmospheric models used for prediction of ISMR is the realistic simulation of its association with ENSO.

For depicting the relationship between ISMR and ENSO, we used an ENSO index based on the SST anomaly of the Nino 3.4 region (120°–170°W, 5°S–5°N), as the magnitude of the correlation coefficient of ISMR with SST over this region is higher than that over the other Nino regions<sup>13</sup>. The ENSO index is defined as the negative of the Nino 3.4 SST anomaly (normalized by the standard deviation), so that positive values of the ENSO index imply a phase of ENSO favourable for the monsoon. El Niño events are associated with ENSO index less than –1.0 and La Nina with ENSO index greater than 1.0. The variation of ISMR with the ENSO index during 1985–2004 is shown in Figure 1. It is seen that the worst droughts are associated with El Niño. Note that when the ENSO index is favourable (>0.6), there are no droughts and when it is unfavourable (<–0.8), there are no excess monsoon seasons.

However, the monsoon is a complex phenomenon and although the correlation is high, there is no one-to-one correspondence between El Niño (La Nina) and droughts (excess monsoon seasons). Thus there are several extreme

**Table 2.** Modelling groups and models (AGCMs)

Institution	Model used	Lead scientist
IITM	COLA model	R. Krishnan
	PUM-Hadley Centre model	A. K. Sahai
NCMRWF–SAC	NCMRWF (a version of the NCEP model)	A. K. Bohra
IMD–IISC	SFM (a very recent version of NCEP)	Ravi Nanjundiah
NAL	Varsha (modified version of the NCMRWF model)	U. N. Sinha

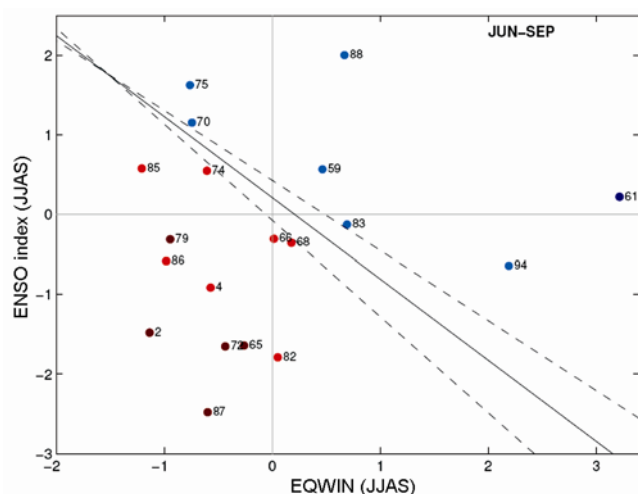


**Figure 1.** Relationship between Indian summer monsoon rainfall (ISMR) and El Niño Southern Oscillation (ENSO) index for 1958–2004. Droughts and excess rainfall seasons are shown as red and blue points respectively.

seasons when the ENSO index is within the range  $-0.8$ – $0.6$ . A striking example is the excess monsoon season of 1994 with a negative (i.e. unfavourable) ENSO index. Also, during the strongest El Niño event of the century in 1997, which was much stronger than that associated with the severe droughts of 2002, the ISMR anomaly was positive.

The experience of 1997 and 2002 indicated that the link between ISMR and ENSO had yet to be properly understood, and triggered studies which suggested that ISMR was also linked to events over the equatorial Indian Ocean<sup>14,15</sup>. With an analysis of the period 1958–2003, Gadgil *et al.*<sup>15</sup> showed that in addition to ENSO, the phase of the Equatorial Indian Ocean Oscillation (EQUINOO), which is considered to be the atmospheric component of the Indian Ocean Dipole/Zonal Mode<sup>16,17</sup>, makes a significant contribution to the interannual variation of ISMR. EQWIN, the index for EQUINOO, is based on the anomaly of the zonal component of the surface wind over the central Equatorial Indian Ocean ( $60^{\circ}$ – $90^{\circ}$ E,  $2.5^{\circ}$ S– $2.5^{\circ}$ N). EQWIN is defined as the negative of this anomaly, so that the EQUINOO phase with positive values of EQWIN is favourable for the monsoon.

The ISMR anomaly for each of the summer monsoon seasons during 1958–2004 with the magnitude of the ISMR anomaly larger than one standard deviation (i.e. extremes), is depicted in the phase plane of EQWIN and ENSO index for June–September in Figure 2. It is seen that each drought (excess rainfall season) is associated with unfavourable (favourable) phases of either ENSO or EQUINOO, or both. In 1994, ENSO was unfavourable and excess rainfall can be attributed to the favourable phase of EQUINOO. In the monsoon season of 2002,



**Figure 2.** ISMR in the phase plane of June–September average values of the ENSO index and EQWIN for all the June–September seasons between 1958 and 2004. Red (dark red) represents seasons with ISMR deficit greater than 1 (1.5) standard deviation, and blue (dark blue) represents seasons with ISMR excess of magnitude greater than 1 (1.5) standard deviation.

although the El Niño was weaker than that in 1997, EQUINOO was also unfavourable and a severe drought occurred. Thus with EQUINOO we can ‘explain’ not only the droughts that occurred in the absence of El Niño or in the presence of a weak El Niño, but also excess rainfall seasons in which ENSO was unfavourable. The worst droughts are associated with unfavourable phases of both the modes. Gadgil *et al.*<sup>15</sup> further showed that there is a strong relationship between the extremes of ISMR and a composite index of ENSO and EQUINOO with all the droughts characterized by low values of this index and all excess monsoon seasons by high values. It is surprising that for a complex phenomenon such as the Indian monsoon, the extremes can be ‘explained’ in terms of links with just two modes – ENSO and EQUINOO.

The results of Ihara *et al.*<sup>13</sup> of the association of ISMR with ENSO and EQUINOO over a much longer period, viz. for 1881–1998, are consistent with the result of Gadgil *et al.*<sup>15</sup>. Ihara *et al.*<sup>13</sup> showed that although the ISMR is not as highly correlated with EQWIN as with the ENSO index, the linear reconstruction of ISMR on the basis of a multiple regression from an ENSO index and EQWIN better specifies ISMR than regression with only the ENSO index. Thus, first and foremost, we need to assess the skill of the atmospheric models in simulating the link between ISMR and ENSO. We also need to assess how well they simulate the link with EQUINOO and finally the skill at simulating the interannual variation of the monsoon for extremes as well as seasons in which the anomaly is somewhat smaller in magnitude.

Analysis of AMIP runs showed that while most of the models could simulate the sign of the ISMR anomaly for 1988 and 1987, only one of the models could simulate the positive anomaly of ISMR associated with the excess monsoon season of 1994 (ref. 3). AMIP was followed by the CLIVAR/Monsoon GCM Intercomparison Project. None of the models participating could simulate realistically the observed response of the Indian monsoon to the 1997 El Niño event<sup>18,19</sup>. Wang *et al.*<sup>19</sup> suggest that the models experience unusual difficulties in simulating the Indian monsoon of 1997, which was the strongest El Niño of the century.

We note that the excess monsoon of 1988 for which all the models simulated the correct sign of the anomaly is a La Nina year with ENSO being highly favourable. In 1994, excess rainfall occurred despite an unfavourable phase of ENSO, in association with a positive phase of EQUINOO, and almost no model could simulate the positive sign of the ISMR anomaly. No model simulated the negative sign of the ISMR anomaly for 1985 when deficit rainfall occurred when EQUINOO was unfavourable, despite a favourable phase of ENSO (Figure 2). Thus it appears that models are able to simulate the anomalies associated with ENSO far better than those associated with EQUINOO. The success in simulating the link with

ENSO could be the result of the efforts made at incorporating the critical processes for ENSO in AGCMs and systematic studies of the simulation of the monsoon during the El Niño of 1987 and La Niña of 1988 made beginning with that of the Monsoon Numerical Experimentation Group (MONEG) of the Tropical Ocean Global Atmosphere (TOGA) program<sup>20</sup>.

### Objective, methodology and simulation of climatology

The major objective of the SPIM project was to assess the skill of AGCMs which are used for generating predictions of monthly and seasonal rainfall in the country, in simulations of the seasons during 1985–2004. It was envisaged that all the models would be run on a single computational platform, viz. the CDAC computer, so as to ensure a level playing field for the intercomparison of the skill in simulation of the interannual variation of the Indian monsoon rainfall by the different models.

As in AMIP, the first set of runs (phase 1) was made with SST specified as the observed SST for May–September of each year during 1985–2004. The second phase involves runs for five selected seasons (1987, 1988, 1994, 1997 and 2002) with SST predicted by a simple algorithm, i.e. by assuming that the SST anomalies are the same as those observed in April. For each of the phases, for each year, five runs were made with initial conditions specified from the daily observations for

26–30 April. All the runs were made on the PARAM Padma at CDAC.

In Figure 3, the mean June–September rainfall simulated by the different models has been compared with the observed rainfall (CMAP) from Xie and Arkin<sup>21</sup>. It is seen that almost all the models get reasonable rainfall over the core monsoon zone north of 20°N. However, the major rain-belt simulated by COLA is a few degrees south of that observed. Note that the NCMRWF and NAL-Varsha models simulate much less rain over the Pacific and equatorial Indian Ocean than that observed.

We compared the ensemble average of the monthly/seasonal rainfall over the Indian region for each year for each of the models with the all-India rainfall data from Parthasarathy *et al.*<sup>22</sup>. These data are based on a fixed network of 306 well-distributed stations across India. Hill stations were not included in the computation of the rainfall series. The updated time-series for the Indian region are available on the website of IITM ([www.tropmet.res.in](http://www.tropmet.res.in)). In Table 3, the mean and standard deviation of ISMR for the period 1985–2004 from the simulations by the different models have been compared with those observed.

It is seen that although the mean ISMR is close to that observed for the SFM model, it is about 20% in excess for the PUM model, about 44% excess in the NCMRWF and NAL models and 20% less for the COLA model. The standard deviation for the interannual variation is close to that observed for PUM, 50% in excess for COLA and almost three times that observed for SFM.

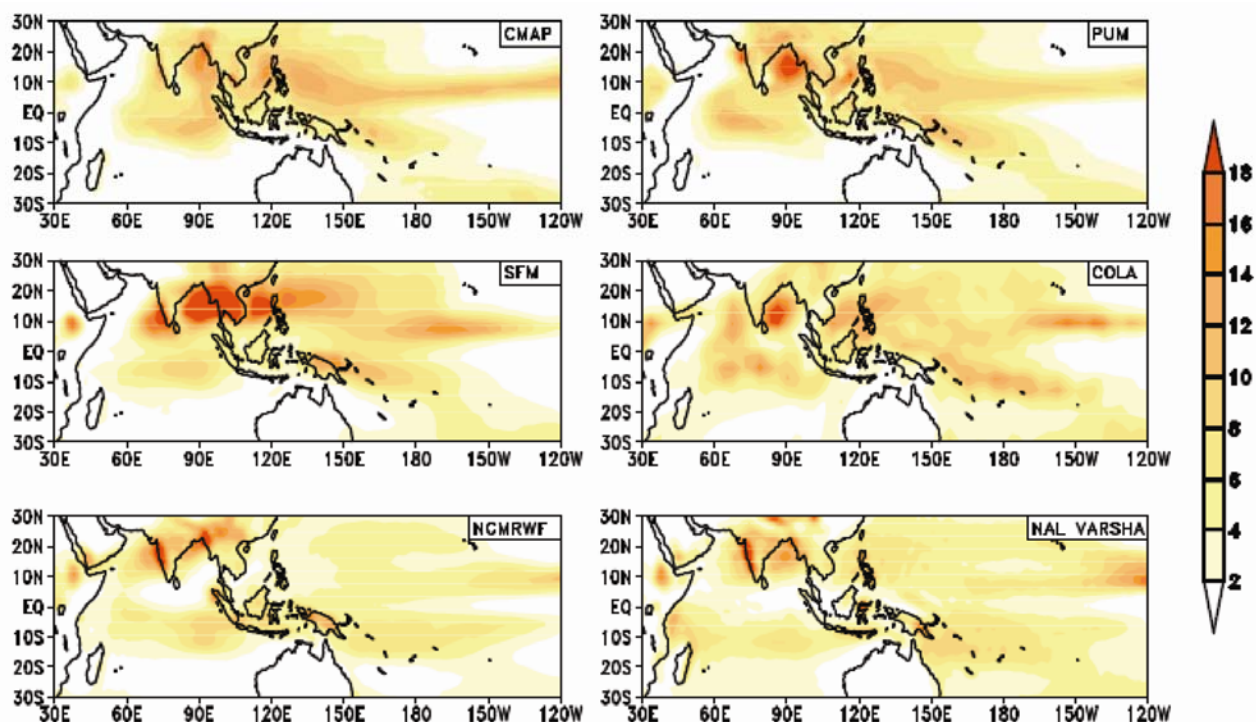
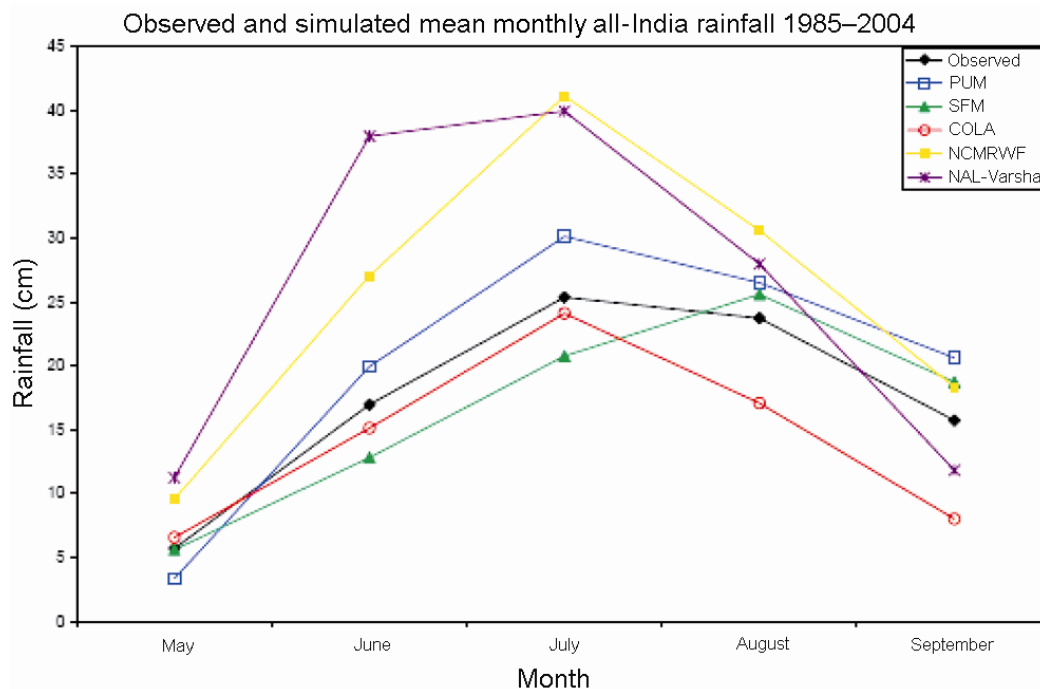


Figure 3. Mean June–September rainfall for 1985–2004 (mm/day), observed (CMAP) and simulated by different models.



**Figure 4.** Observed and simulated mean monthly precipitation for May–September.

**Table 3.** Observed and simulated mean June–September rainfall over the Indian region for 1985–2004

Period 1985–2004	Mean rainfall (cm)	Standard deviation (cm)
Observed	81.82	7.84
PUM	97.24	6.40
SFM	77.94	22.13
COLA	64.38	11.40
NCMRWF	117.15	7.40
NAL-Varsha	117.75	14.34

Although the mean ISMR for NCMRWF is almost identical to that of the NAL model, the standard deviation of the latter is almost twice that of the former. Since the NAL-Varsha model is a modified version of the NCMRWF model, it would be interesting to study what has led to the high variability. When we compare the anomalies simulated by the models with the observed anomalies, we use anomalies from the simulated mean rainfall normalized by the standard deviation of the simulated rainfall, so that these errors in the mean and standard deviation do not influence the results of comparison of the anomalies.

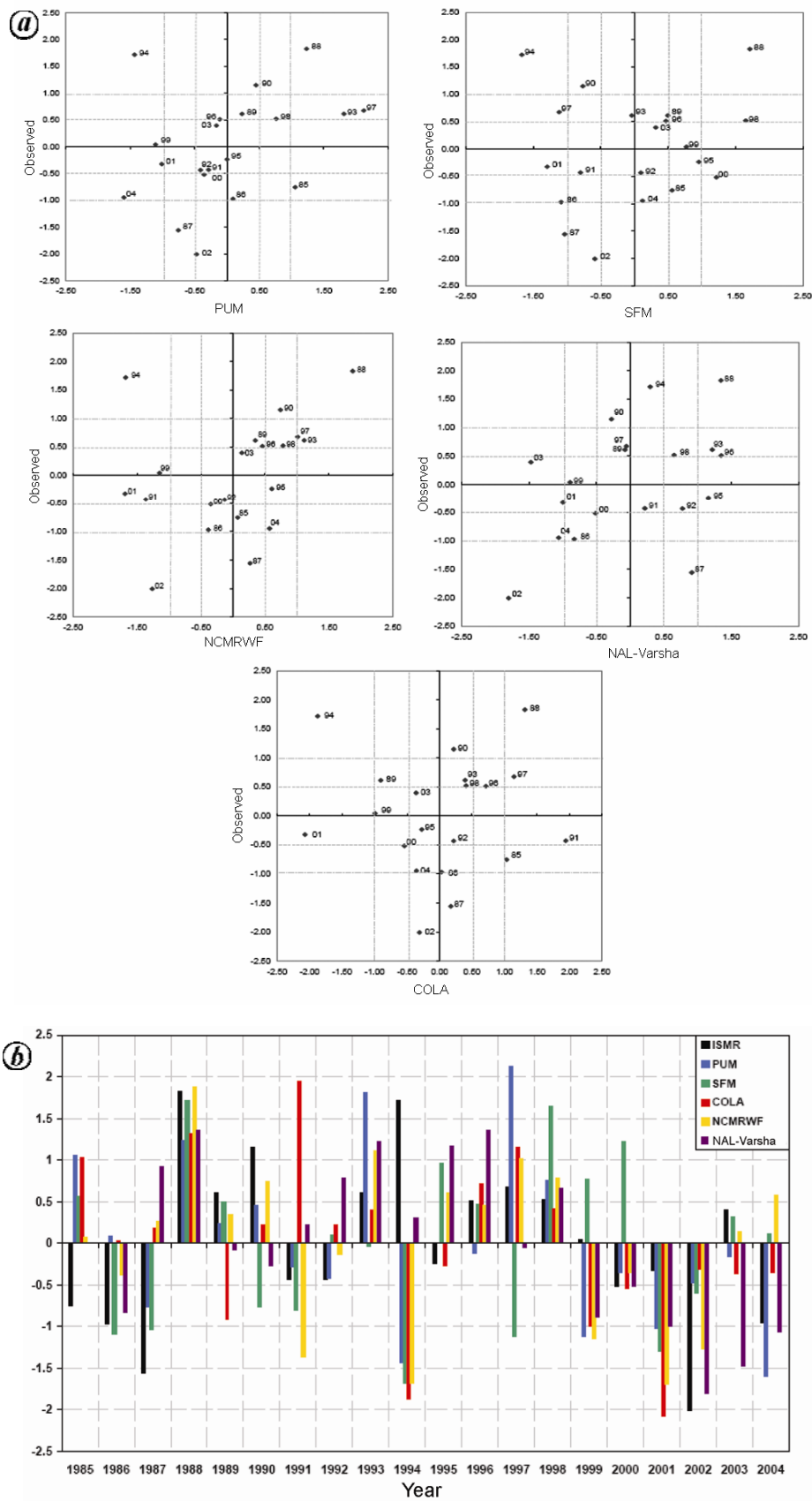
In Figure 4, the simulated mean monthly rainfall over the Indian region by the different models is shown along with the observed rainfall. In the observed rainfall pattern, the peak rainfall months of the summer monsoon are July and August, with rainfall in June and September being 60% of that in July in which the rainfall was maximum. Four of the five models simulate maximum rainfall

in July. The exception is the SFM model for which the mean August rainfall is higher than that in July. The quantum of the mean monthly rainfall during June–September simulated by PUM, COLA and SFM is rather close to that observed. The NCMRWF and NAL-Varsha models simulate much higher rainfall in June and July than that observed, with the rainfall of June being comparable with that of July for the latter model. We focus here on the simulation of the interannual variation of the ISMR.

**Simulation and observations of the interannual variation of the all-India summer monsoon rainfall for 1985–2004**

The relationship of the simulated ISMR anomalies to the observed anomalies for the small sample of years is best brought out with scatter plots of the observed versus simulated ISMR anomalies for each model (Figure 5 a). If a model could simulate the sign of the ISMR anomaly for each of the years, the points would be either in the top right (with positive anomalies) or the bottom left (with negative anomalies) quadrant. It is seen that none of the models simulates the correct sign of the ISMR anomaly for all the years, which is not surprising considering the track record of models the world over, in predicting the Indian monsoon rainfall.

For models with higher skill in simulation of the interannual variation, there are several years for which the simulated signs of the anomalies are the same as that of



**Figure 5.** *a*, Observed versus simulated anomalies of all-India June–September rainfall (ISMR) for different models for 1985–2004. *b*, Variation of the observed and simulated anomalies of all-India June–September rainfall (ISMR) for different models for 1985–2004.

the ISMR anomalies (top right and bottom left quadrants) with fewer years for which the simulated sign is opposite to the observed anomalies (the points in the 'wrong' quadrants, i.e. top left and bottom right). We tried to understand why the outliers in the wrong quadrants (which are associated with very large errors) occur and also, in some cases, whether the seasons are in the 'right' quadrants for the right reasons, so as to gain some insight into how the model could be improved.

It is seen that the seasons of 1988 and 2002 (and also 1998 and 2001) are in the correct quadrants for all the models. PUM has a minimum number of points in the 'wrong' quadrants; the two outliers in these quadrants are 1985 and 1994. Clearly the PUM model is superior to all the other models in the group considered here, in simulating the sign of the ISMR anomaly and is one of the best models for simulation of the interannual variation of the ISMR.

We have quantitatively assessed the skill only for the extremes of ISMR. We find that none of the models has high skill in simulating the extremes of ISMR. In many cases when the hit rate is high, so is the false alarm rate. The skill of SFM is the highest in simulating excess rainfall seasons as well as droughts; the NCMRWF model has comparable skill in simulating excess rainfall seasons. Thus although PUM ranks highest in simulating the sign of the ISMR anomaly during 1985–2004, SFM has the highest skill in simulating the extremes. When we interpret the results, it will become clear that amongst the models considered, these two are the best in simulating the interannual variation of the Indian summer monsoon during 1985–2004.

The anomalies of ISMR simulated by all the models for each year along with the observed ISMR anomalies for the period 1985–2004 are shown in Figure 5*b*. We were particularly interested in assessing whether the models are capable of simulating droughts and excess rainfall years. We note that all the models simulate a positive ISMR anomaly for the excess monsoon season of 1988 (which had the maximum ISMR during the period considered), and only NAL-Varsha for 1994 (with the second largest excess). These results are consistent with the analysis of AMIP simulations<sup>3</sup>. Again, although all models simulate a negative ISMR anomaly for the drought of 2002 (which had the minimum ISMR during the period considered), only two models (PUM and SFM) simulate negative rainfall anomalies for the drought of 1987 (with the second largest deficit). The ISMR anomaly simulated by the NAL-Varsha model for 1987 is not only of the wrong sign (i.e. positive instead of negative), but of large magnitude as well (close to one standard deviation).

We found that the relationship of ISMR with the ENSO index is well-simulated by the PUM model. The ISMR anomaly simulated by SFM was better correlated with the ENSO index than the observed ISMR anomaly, with the anomalies in 1994 and 1997 consistent with those of

the ENSO index (and hence of opposite sign to that observed). In fact, all the seasons with large errors in the simulation by the SFM model can be attributed to the unrealistically large correlation of the simulated anomalies with the ENSO index. This suggests that it should be possible to improve the skill of the simulations when this problem is overcome. It turns out that the results of phase 2 of this project support this suggestion.

The relationship of the ISMR anomalies simulated by the other three models (COLA, NCMRWF and NAL-Varsha) and the ENSO index is relatively weak. However, all of them simulate a positive ISMR anomaly for the excess monsoon season of 1988 associated with a La Nina. As observed, much higher rainfall over most of the Indian region is simulated for the summer monsoon of 1988 than that for the season of 1987 by the NCMRWF and the COLA models. In contradistinction to the observations, in the simulation by the NAL-Varsha model for the season of 1987, positive rainfall anomaly occurred over the entire Indian region and the strong El Niño of 1987 was associated with excess ISMR, with the magnitude of the simulated anomaly in ISMR of close to one standard deviation. Furthermore, for the season of 1988, the region over which positive anomalies of rainfall are simulated was much smaller than that for 1987, with negative anomalies over much of the peninsula.

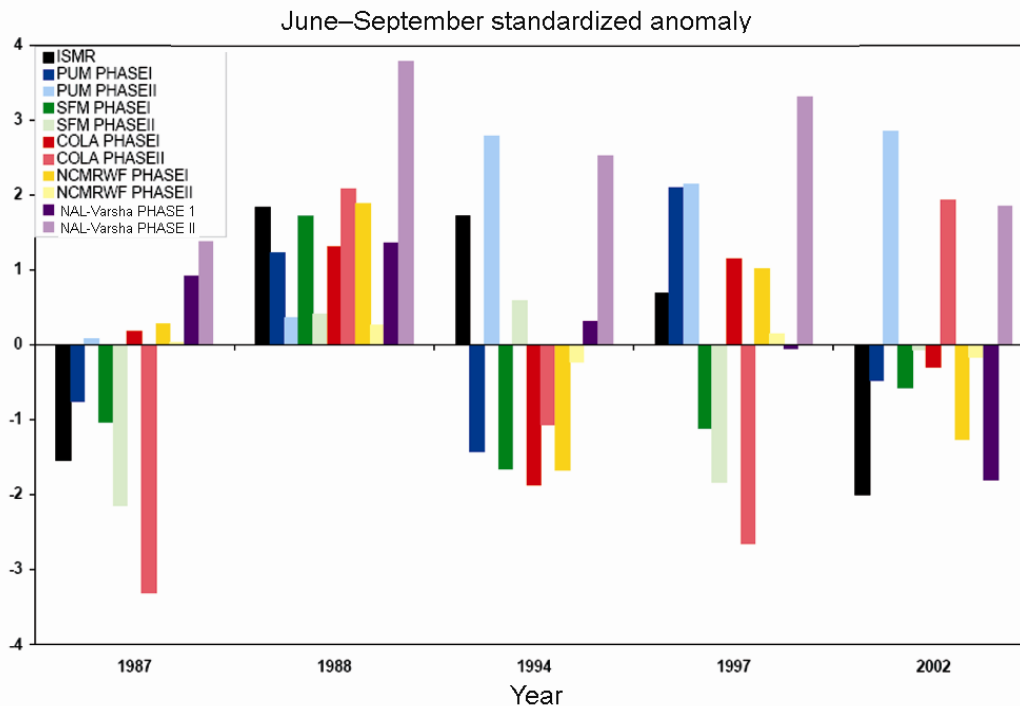
Given the weak relation with ENSO for these three models, we do not expect the outliers to be due to the influence of ENSO, as for SFM. Indeed, for only two of the five outliers of the COLA model and one of the three outliers of the NCMRWF model, the sign of the simulated ISMR is the same as that of the ENSO index. Of the five outliers of the NAL-Varsha model, the season for which a large rainfall was simulated instead of a drought, viz. 1987, has a large negative ENSO index and the seasons of 2003, 1992 and 1990 have ENSO index close to zero. Hence, only in one of the five outliers, the simulated ISMR anomaly was of the same sign as that of the ENSO index. Thus, the largest errors occurred in the response of the simulated monsoon rainfall to ENSO for the NAL-Varsha model.

It is important to understand the implications of the high/low sensitivity to ENSO in the simulation of ISMR in the different models. In phase 2 of the project, the magnitude of the ENSO index was smaller than that observed in June–September for each of the seasons considered. We therefore consider the implications in the next section in which the results of phase II are presented.

### Simulations of phase II with predicted SST for five seasons

We consider next the simulations for 1987, 1988, 1994, 1997 and 2002 made by assuming that the SST anomalies





**Figure 6.** Observed and simulated ISMR anomaly in phase 1 (observed SST) and phase 2 (predicted SST) by the models.

observed in April of each season, persist from April onwards. These years were chosen because 1987 and 1988 are classic cases of drought (excess rainfall) occurring in association with El Niño (La Niña), simulations of 1994 and 1997 with AGCMs have proved to be a major challenge and 2002 was a drought year to which unfavourable phases of ENSO and EQUINOO contributed. The simulated anomalies of ISMR for these five seasons along with the simulated anomalies of phase I and the observed anomalies are depicted in Figure 6.

Here we focus on the excess monsoon season of 1994. This is because a vast majority of AGCMs participating in AMIP and all but one model participating in this SPIM project simulated a negative ISMR anomaly for this season, when run with the observed SST as the boundary condition. Gadgil *et al.*<sup>3</sup> had attributed this failure of the models to simulate even the sign of the ISMR anomaly to the inability of most models to simulate the link with EQUINOO. We found that all the models participating in SPIM were able to simulate the positive phase of EQUINOO (with suppression of rainfall over the eastern part and enhancement over the western part of the equatorial Indian Ocean), when driven by the observed SST for 1994 (phase I). This result is consistent with the hypothesis of lack of skill of most models in simulating the link of ISMR with EQUINOO. More light will be shed on this issue when we consider the results of phase II of SPIM.

We note that the simulated anomalies of PUM and SFM for ISMR of 1994 are positive for phase II, whereas they were negative for phase I. It turns out that the

anomalies of NCMRWF and COLA are also less negative for phase II (implying a smaller error), while the magnitude of the positive ISMR anomaly increases in phase II for NAL-Varsha to be far in excess of that observed. In fact, the SST anomalies for April 1994 were not large either over the central Pacific or over the equatorial Indian Ocean; they developed during the monsoon season<sup>9</sup>. Thus the assumption that the SST anomalies persist from April implies that the magnitude of the SST anomalies over the equatorial central Pacific (and hence of the ENSO index) is smaller than that observed for each month of the summer monsoon. When run with SST specified as the observed SST (phase I), all the models simulated higher ISMR for 1988 than 1987 (although three of them had simulated a positive ISMR anomaly for the El Niño of 1987). Hence it is not surprising that with a weakening of the unfavourable ENSO forcing, the simulated ISMR increases in all the models.

It is important to note that when PUM and SFM models are forced by a weaker ENSO, they are able to simulate a realistic link with EQUINOO. Thus it appears that the PUM and SFM models are not inherently incapable of simulating the link with EQUINOO; they are able to simulate it when the strength of the ENSO forcing decreases. Hence, the failure of the models to simulate the sign of the observed ISMR anomaly in 1994 can be attributed to the unrealistically high sensitivity to ENSO, rather than to an inherent inability to simulate the link with EQUINOO. The validity of this conclusion could have been tested with a set of runs in which the Indian

Ocean SSTs are specified from observations and the Pacific SSTs from climatology. However, such an experiment was not planned as a part of the project and has to be considered in a future study.

The simulation of the correct sign of the ISMR anomaly for the season of 1994 by the NAL-Varsha model when driven by the observed SST, could be a consequence of the unrealistically low sensitivity of the model to ENSO. Since the most important link of the monsoon is with ENSO, efforts are needed with further work on the model for a better simulation of the response of rainfall over the Indian region, as well as that over the Arabian Sea and Bay of Bengal to ENSO. Since the NAL-Varsha model is a modified version of the NCMRWF model (which has a more realistic response to ENSO than the NAL-Varsha model) and SFM (which has unrealistically high sensitivity to ENSO) is a later version of the AGCM from the same stable, some guidance about how this could be achieved may be provided by detailed comparison with these two models and sensitivity studies.

### Summary and concluding remarks

In this study, simulation of the interannual variation of ISMR, by five AGCMs at different institutions in the country has been assessed. In addition, an attempt has been made to understand the possible cause of the errors in these models. Two sets of runs were made for this purpose. In the first set, AGCMs were forced by the observed SST for May–September for 1985–2004. In the second set, runs were made for 1987, 1988, 1994, 1997 and 2002 forced by SST which was obtained by assuming that the April anomalies persist during May–September. The results of the first set of runs show that, as expected from earlier studies, none of the models was able to simulate the correct sign of the anomaly of ISMR for every year. However, amongst the five models, PUM has simulated the correct sign in the maximum number of years. We found that the SFM model had the maximum skill in the simulation of the extremes (i.e. droughts or excess rainfall seasons).

The first set of runs showed some common bias in the models. Most of the models failed to simulate the sign of the ISMR anomaly for the excess monsoon season of 1994. This result was consistent with those of the analysis of the AMIP runs<sup>3</sup>. Most of the models also failed to simulate the ISMR deficit of the monsoon season of 1985. Since the excess (deficit) in 1994 (1985) occurred in association with a favourable (unfavourable) phase of the EQUINOO, despite an unfavourable (favourable) phase of the ENSO, a possible cause of these systematic biases could be the excessive sensitivity of the models to ENSO, and/or the inability of the models to simulate the link of the Indian monsoon rainfall to EQUINOO<sup>3</sup>. The sensitivity of the model that could simulate the sign of

the ISMR anomaly in 1994, viz. the NAL-Varsha model, to ENSO was unrealistically low. It simulated a large excess in ISMR for the El Niño of 1987, which was a severe drought year. In the second set of runs, when the models were forced by a weaker ENSO signal in SST over the Pacific, PUM and SFM could simulate the positive sign of the ISMR anomaly for the season of 1994. Thus it appears that the models do have the ability to simulate the link with EQUINOO, but are perhaps unrealistically sensitive to ENSO.

This project involving an intercomparison of the performance of several AGCMs in the simulation of the Indian summer monsoon for a 20-year period, was rather ambitious when conceived. It could be undertaken in 2006 only because of the unstinting support by CDAC in terms of computer resources and expertise. It led to a fruitful interaction among the different modelling groups in the country throughout the implementation phase of the project. The basic results presented here have already yielded some insight into the ‘how and why’ of the simulation of the interannual variation of monsoon rainfall by these models. Such an understanding is a necessary prerequisite for improvement of the models.

So far we have discussed the simulation of monsoon variability by atmospheric models. For generating predictions of the rainfall during the summer monsoon using such models, it is necessary to predict SST for the forthcoming season. Clearly, predictions have to be eventually generated with models of the coupled atmosphere–ocean system using initial conditions for the ocean as well as the atmosphere. However, the skill of the predictions generated at different international centres based on state-of-the-art coupled models is not satisfactory, as revealed by the recent experience of the drought of 2009. A recent analysis of several such coupled models<sup>23</sup> has shown that there are large biases in the mean monsoon rainfall simulated by the coupled models compared to the observations, with the models simulating excess rainfall over the equatorial Indian Ocean and less rainfall over the Indian monsoon zone. Most models have a systematic cold bias in the simulation of SST over the equatorial Indian Ocean and Pacific Ocean. Thus the coupled models have to be improved before they can generate accurate and reliable predictions of monsoon rainfall.

In the past few years, there has been a remarkable increase in computational resources and network connectivity in India. At present, in the country as a whole, there is considerable expertise in modelling as well. The national Monsoon Mission, which envisages harnessing of all these resources, would be a far more ambitious effort than SPIM. While SPIM involved assessment of the performance of some AGCMs in the simulation of monsoon variability, the Monsoon Mission envisages research and development of both atmospheric and coupled ocean–atmosphere models for improvement in the accuracy and reliability of prediction of the monsoon. Given the

enormous impact of monsoon on our agriculture and economy<sup>24</sup>, it is important to address this challenging problem and make the mission successful.

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