Predicting the extremes of Indian summer monsoon rainfall with coupled ocean–atmosphere models

Ravi S. Nanjundiah[1], P. A. Francis[2], Mohit Ved[3] and Sulochana Gadgil[1,*]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore 560 012, India
[2]Indian National Centre for Ocean Information Services, Hyderabad 500 090, India
[3]Centre for Development of Advanced Computing (CDAC), CDAC Knowledge Park, No. 1, Old Madras Road, Bangalore 560 038, India

An analysis of the retrospective predictions by seven coupled ocean–atmosphere models from major forecasting centres of Europe and USA, aimed at assessing their ability in predicting the interannual variation of the Indian summer monsoon rainfall (ISMR), particularly the extremes (i.e. droughts and excess rainfall seasons) is presented in this article. On the whole, the skill in prediction of extremes is not bad since most of the models are able to predict the sign of the ISMR anomaly for a majority of the extremes. There is a remarkable coherence between the models in successes and failures of the predictions, with all the models generating loud false alarms for the normal monsoon season of 1997 and the excess monsoon season of 1983. It is well known that the El Niño and Southern Oscillation (ENSO) and the Equatorial Indian Ocean Oscillation (EQUINOO) play an important role in the interannual variation of ISMR and particularly the extremes. The prediction of the phases of these modes and their link with the monsoon has also been assessed. It is found that models are able to simulate ENSO–monsoon link realistically, whereas the EQUINOO–ISMR link is simulated realistically by only one model – the ECMWF model. Furthermore, it is found that in most models this link is opposite to the observed, with the predicted ISMR being negatively (instead of positively) correlated with the rainfall over the western equatorial Indian Ocean and positively (instead of negatively) correlated with the rainfall over the eastern equatorial Indian Ocean. Analysis of the seasons for which the predictions of almost all the models have large errors has suggested the facets of ENSO and EQUINOO and the links with the monsoon that need to be improved for improving monsoon predictions by these models.

Keywords: ENSEMBLES project, EQUINOO–ISMR linkage, ocean–atmospheric models, rainfall, summer monsoon.

Introduction

'I seek the blessings of Lord Indra to bestow on us timely and bountiful monsoons.'

Pranab Mukherjee, budget speech in the Lok Sabha, February 2011.

THIS opening remark by the then Finance Minister in his presentation of the budget for 2011–12 in parliament, drives home the point that the monsoon continues to have a substantial impact on the Indian agricultural production and economy, even after six decades of development. The situation does not appear to have changed substantially since 1953 when Normand[1] remarked, 'While industry and trade certainly play a larger part in the economy than they did, failures of the monsoon rains, as in the drought years of 1877, 1899 and 1918, would still embarrass the budget of the Central Government and thoroughly upset the budgets of the Provincial Governments in the famine areas.' Thus, understanding and prediction of the variability of the monsoon rainfall over the Indian region continues to be extremely important to this day. The Finance Minister's prayer was for good rainfall over the Indian region during the forthcoming summer monsoon season of June–September, i.e. the Indian summer monsoon rainfall (ISMR). The variation of ISMR from 1960 to 2011 is shown in Figure 1. Of particular concern are the extremes of monsoon rainfall, i.e. droughts and excess rainfall seasons. Seasons with negative ISMR anomaly larger than one standard deviation are defined as droughts and those with positive ISMR anomaly larger than one standard deviation as excess rainfall seasons. It is seen that droughts occurred frequently during 1965–87 and after a lull during 1988–2001, the frequency has been high in the last decade with droughts in 2002, 2004 and 2009.

A quantitative assessment of the impact of monsoon on foodgrain production (FGP) in the country and the Gross Domestic Product (GDP) by Gadgil and Gadgil[2] has shown that despite a substantial decrease in the contribution of agriculture to GDP from about 50% to 20% during 1951–2004, the impact of droughts has remained 2–5% of the GDP throughout. They have also shown that droughts

*For correspondence. (e-mail: sulugadgil@gmail.com)

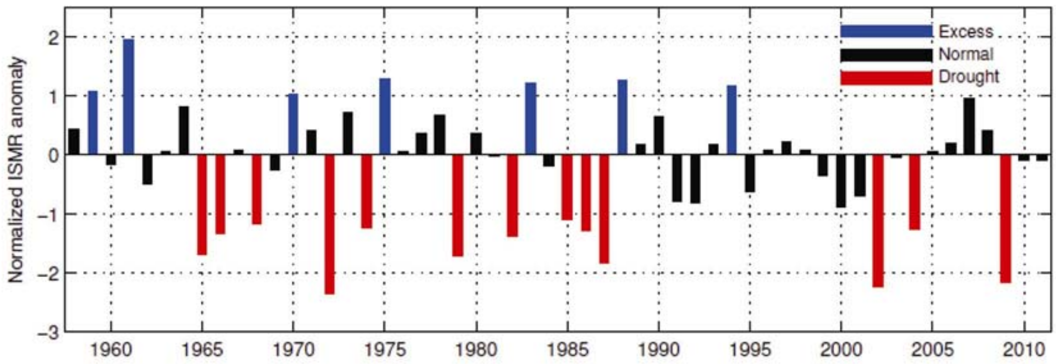

Figure 1. Variation of the anomaly of Indian summer monsoon rainfall (ISMR), normalized by the standard deviation, during 1960–2011. Excess rainfall seasons, represented as blue bars, are defined as seasons with the normalized ISMR anomaly > 1 and droughts, represented as red bars, are defined as seasons with the normalized ISMR anomaly < – 1.

in the current decade had as much impact on FGP as they had in the 1960s. An unexpected result from this study is that the impact of monsoon on FGP and GDP is highly nonlinear, with the negative impact of negative ISMR anomaly being much larger than the positive impact of a positive ISMR anomaly of the same magnitude. They have suggested that while the yields of rainfed regions are substantially reduced during droughts, there is hardly any enhancement of the yields in years of normal and good rainfall because the requisite investment in fertilizers and pesticides is not made by the farmers. Farmers adopt this strategy because such an investment is not cost-effective in years of poor rainfall. If reliable forecasts of the non-occurrence of droughts were available, the farmers could enhance the yields substantially in a majority of the years with the existing knowhow and technology. Clearly, prediction of the occurrence and non-occurrence of extremes of ISMR should be an important focus of seasonal prediction. In fact, the importance of the prediction of extremes, particularly droughts, has been recognized for over five decades. In Normand's[1] words 'The most important need in monsoon forecasting is to pick out with a reasonable degree of success the years of low rainfall, the possible drought years … Until years of scarcity can be forecast with greater certainty, the forecasts can give little help to the public at large.'

Recent studies have shown that there has been improvement in the skill of predictions of ISMR with coupled models. While the correlation of the multi-model ensemble (MME) prediction with the observed ISMR for the models in the DEMETER project[3] for 1960–2001 was 0.22 (ref. 4), the correlation for the MME from six models of the ENSEMBLES project which are updated versions of the models involved in the DEMETER project, for 1960–2005 is 0.45 (ref. 5). Note that even with the increased correlation, only about 20% of the variance is explained. Furthermore, the track record of the predictions for droughts has not improved, with the prediction for 2009 failing as did those for 2002 and 2004 (refs 6 and 7). The models also generate false alarms, as in the case of the normal monsoon season of 1997 when a drought was predicted by all the models. Clearly further improvement, particularly in the skill of extremes, is a must.

In this article, we consider the prediction of the interannual variation of ISMR, focusing on the extremes and assess the predictions generated by several coupled atmosphere–ocean models to gain an insight into how the skill can be improved. We believe that the time is opportune for such an exercise, as an ambitious 'monsoon mission' has recently been launched by the Ministry of Earth Sciences (MoES), Government of India (GoI)[8], with the aim of substantially improving the skill of forecasts over different timescales, including seasonal forecasts. We present an analysis of the retrospective predictions of five of the six models of ENSEMBLES, the CFS2 model of the National Centre for Environmental Prediction (NCEP), USA (which has been identified as the model to be improved under the monsoon mission) as well as an earlier version of the NCEP model, viz. CFS1 (refs 9 and 10). In the next section we summarize the present understanding of the interannual variation of the ISMR. In the following sections, the model runs and data analysed are described and the results of the analysis of retrospective predictions of the interannual variation of the monsoon are presented. The nature of the predicted teleconnections is then elucidated and the prediction of ISMR for some special seasons are discussed. The last section comprises a discussion of the interpretation of the results and implications for the way forward in our endeavour to improve the skill of the models in monsoon prediction.

Interannual variation of the monsoon – present understanding

It is well known that there is a strong link between the interannual variation of ISMR and the El Niño and Southern Oscillation (ENSO)[11–13]. We use an ENSO index, which is defined as the negative of sea surface temperature (SST) anomaly of the Niño 3.4 region (120–170°W, 5°S–5°N), normalized by its standard deviation. Positive values of the ENSO index imply a phase of ENSO favourable for the monsoon. For the study of the ENSO–monsoon relationship, we identify El Niño events when June–September mean ENSO index is less than –1.0 and La Niña events when June–September mean ENSO index is greater than 1.0. The relationship of ISMR with the ENSO index is shown in Figure 2 for the period 1958–2004, in which the droughts and excess rainfall seasons of ISMR can also be distinguished. It is seen that ISMR is well correlated with the ENSO index with a correlation coefficient of 0.54, which is significant at 99%. When the ENSO index is favourable (> 0.7), there are no droughts and when it is unfavourable (< –0.6) there are no excess monsoon seasons. However, for intermediate values of the ENSO index, there are several droughts and excess rainfall seasons. If we consider the interannual variation of the monsoon since 1980, consistent with the links of the monsoon with ENSO, the El Niño events of 1982 and 1987 were associated with droughts and the La Niña event of 1988 with excess rainfall (Figure 2). It turned out that for 14 consecutive years beginning with 1988, there were no droughts; furthermore, during the strongest El Niño event of the century in 1997, the ISMR was higher than the long-term mean (Figure 1) and Krishna Kumar *et al.*[14] suggested that the relationship between the Indian monsoon and ENSO had weakened in the recent decades. Then came the drought of 2002, which occurred in association with a much weaker El Niño than that of 1997 and neither the statistical nor the dynamical models could predict it.

The intriguing monsoon seasons of 1997 and 2002 triggered studies which suggested a link to events over the equatorial Indian Ocean[15,16]. Suppression of convection over the Eastern Equatorial Indian Ocean (90–110°E, 10°S–EQ, henceforth EEIO) tends to be associated with enhancement of convection over the Western Equatorial Indian Ocean (50–70°E, 10°S–10°N, henceforth WEIO) and vice versa. Equatorial Indian Ocean Oscillation (EQUINOO) is the oscillation of a state with enhanced convection over WEIO and reduced convection over EEIO (positive phase), and another with anomalies of the opposite signs (negative phase). The positive phase of EQUINOO is associated with easterly anomalies in the equatorial zonal wind, whereas the negative phase (i.e. with enhanced (suppressed) convection over the EEIO (WEIO)), is associated with westerly anomalies of the zonal wind at the equator. We use an index of the EQUINOO based on the anomaly of the zonal component of the surface wind over the central equatorial region (CEIO, 60–90°E, 2.5°S–2.5°N), which is highly correlated with the difference between OLR of WEIO and EEIO (correlation coefficient is 0.79, which has a confidence level of 99%). The zonal wind index (henceforth EQWIN) is taken as the negative of the anomaly so that positive values of EQWIN are favourable for the monsoon[16]. The nature of the impact of ENSO and EQUINOO on the convection over the Indian region, surrounding seas and the equatorial Indian Ocean is seen in Figure 3 *a*. While a favourable ENSO is associated with enhanced convection over the entire region, a positive phase of EQUINOO (i.e. with enhanced convection over WEIO and suppressed convection over EEIO) is associated with enhanced convection over the Indian region. The correlation of ISMR with Outgoing Longwave Radiation (OLR) (Figure 3 *b*) shows that the teleconnections of the monsoon with ENSO and EQUINOO are clearly manifested as atmospheric bridges. Note that the magnitude of the correlation of ISMR with the convection over WEIO is comparable to that over the central Pacific corresponding to the link with ENSO.

In Figure 4, all the extremes of ISMR in the period 1958–2004 are shown in the phase plane of the June–September averages of the ENSO index and EQWIN. The most striking feature of the distribution of the extreme years is the clear separation between years with excess and deficit, with each of the surplus (deficit) years located above (below) a certain line in the phase plane of the two indices (line L in Figure 4). This distribution in the phase plane suggests that an appropriate index would be a composite index, which is a linear combination of the ENSO index and EQWIN. When the value of this index is high (i.e. point above the line L), not only is there no chance of droughts but also no chance of moderate deficits. For low values of the index (i.e. below the line L), there is no chance of excess rainfall seasons but a small chance of moderate above-normal rainfall[16].

EQUINOO has been considered to be the atmospheric component of the Indian Ocean dipole (IOD)/zonal

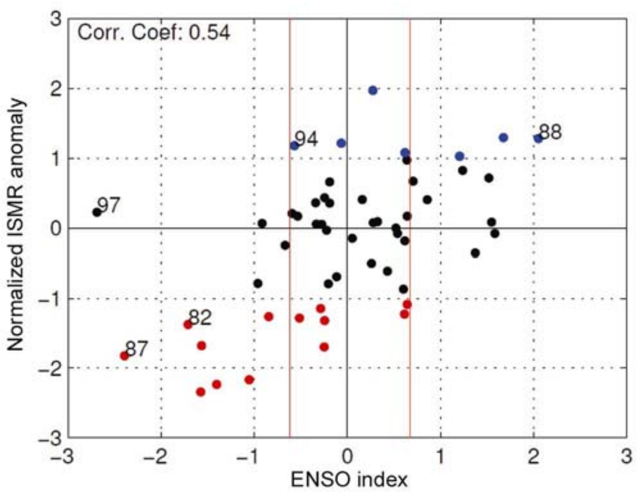

Figure 2. Normalized ISMR anomaly values for the period 1958–2011 plotted against the June–September values of the ENSO index. Red dots represent droughts and blue dots represent excess rainfall seasons.

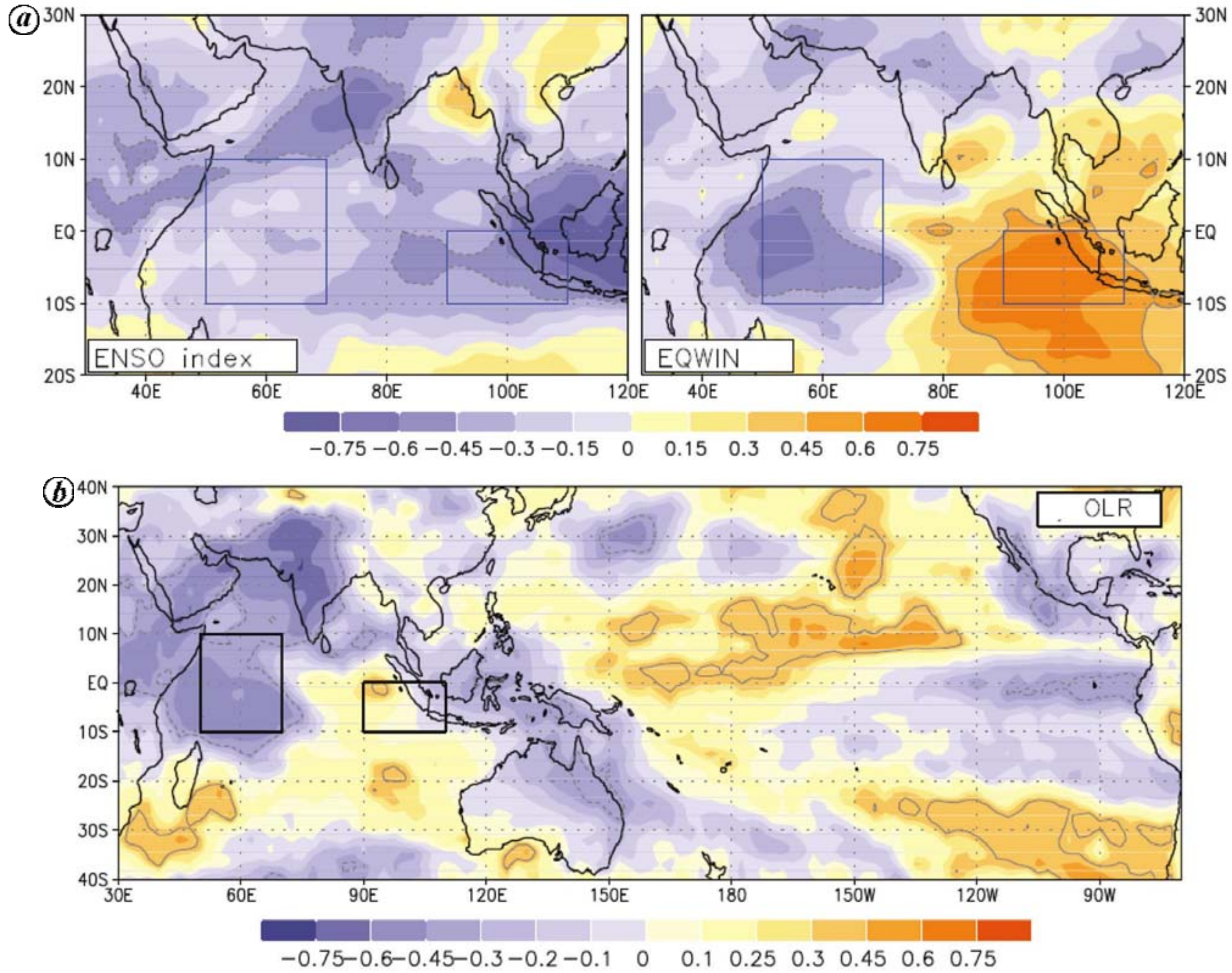

Figure 3. ***a***, Correlation of the June–September OLR at every grid point over 30–120°E and 20°S–30°N with the seasonal ENSO index (left) and EQWIN (right). Data for the period 1979–2011 are considered for computing the correlation coefficient. Contours show the confidence level at 95%. ***b***, Correlation of ISMR with the June–September OLR at every grid point over 30°E–70°W and 40°S–40°N. Data for the period 1979–2011 are considered for computing the correlation coefficient. Contours show the confidence level at 95%.

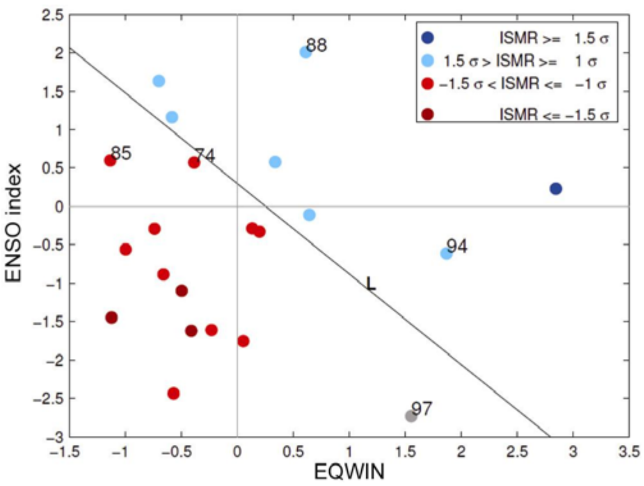

Figure 4. Extremes of ISMR as defined in Figure 1 (red for droughts and blue for excess rainfall seasons) in the phase plane of the seasonal EQWIN and ENSO index.

mode[17,18]. However, the coupling between EQUINOO and the ocean component is weaker than that between the atmosphere and ocean components of ENSO. The study by Ihara *et al.*[19] on the relationship of the variation of the monsoon with ENSO, EQUINOO and IOD, using data for a much longer period (from 1881 to 1998) than that used by Gadgil *et al.*[16], also suggests that the variation of ISMR is better described by use of indices of ENSO and EQUINOO. If it is possible to predict ENSO and EQUINOO for the forthcoming monsoon season, it will be possible to generate a reliable one-sided prediction, i.e. non-occurrence of one of the extremes (i.e. either droughts or excess rainfall season).

Note that during the strong El Niño of 1997, a strong positive phase of EQUINOO occurred, and as a result of this tug-of-war, the monsoon rainfall was close to normal. While the excess monsoon season of 1988 was associated with favourable phase of both the modes, that of 1994 was associated with a favourable EQUINOO and an unfavourable ENSO. Analysis of an international Atmospheric Model Intercomparison Project (AMIP)[20] showed that almost all Atmospheric General Circulation Models (AGCMs) could simulate at least the correct sign of the ISMR anomaly (whether deficit or excess) for the droughts or excess monsoon seasons associated with ENSO[6]. However, almost all the AGCMs simulated deficit ISMR for the excess monsoon season of 1994 (ref. 6). Wang *et al.*[21] analysed ensemble simulations of Asian–Australian monsoon (A–AM) anomalies in 11 AGCMs for the unprecedented El Niño period of September 1996–August 1998. They showed that: (i) the simulations of anomalous Indian/Asian summer rainfall patterns were considerably poorer than in the El Niño region, and (ii) the skill in the ensemble simulations with the SNU model for 1950–98 of the Indian monsoon is significantly higher than that for the period 1996–98. They concluded that 'During 1997/98 El Niño, the models experienced unusual difficulty in reproducing correct Indian summer monsoon anomalies.'

There have been a large number of studies investigating whether the monsoon–ENSO link is realistically simulated in models. Annamalai *et al.*[22] showed that the ENSO–monsoon link is realistically simulated by IPCC AR4 coupled simulations. Rajeevan and Nanjundiah[23] showed that while the ENSO–monsoon link is realistic the EQUINOO–ISMR link is either non-existent or of the wrong sign in AR4 simulations. We assess the skill of predictions of ISMR by the models as well as the prediction of the two important modes and the teleconnections of ISMR with these modes. For this we also consider the prediction of the special cases of ISMR of 1994 and 1997, which have proved to be a challenge for AGCMs.

Data

We have analysed the retrospective predictions of precipitation rate and the SST from five different ocean–atmopshere coupled general circulation models – HadGEM2 model of the UK Met Office (UKMO), MeteoFrance (MF), the European Centre for Medium-range Weather Forecasts (ECMWF), the Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), and the Euro-Mediterranean Centre for Climate Change (CMCC-INGV), Bologna – which were part of the European Union funded ENSEMBLES project[24]. Data are downloaded from http://www.ecmwf.int/research/EU_projects/ENSEMBLES/ for the period 1961–2005. Analysis of the retrospective predictions of the precipitation rate and SST by two versions of the coupled forecast system – CFS1 and CFS2 of NCEP[9,10], downloaded from http://cfs.ncep.noaa.gov/menu/download/, is also presented. For validation of the forecasts, we use monthly mean data from Climate prediction centre Merged Precipitation Analysis (CMAP)[25], Global Precipitaion Climatology Project (GPCP)[26], HadISST[27] from UK Met-Office and NOAA optimal interpolated SST from NCEP (http://www.cdc.noaa.gov/). ISMR is computed from the monthly mean all India rainfall data[28] hosted by Indian Institute of Tropical Meteorology (IITM, http://tropmet.res.in) Pune.

Retrospective predictions of the interannual variation of ISMR

The mean JJAS rainfall patterns from the five models from the ENSEMBLES project and the observations are shown in Figure 5 *a* and those from CFS1 and CFS2 in Figure 5 *b*. On the whole, the basic features of the mean rainfall pattern over the Indian region and equatorial Indian Ocean are reasonably well captured by the models. However, for some models such as MeteoFrance and UKMO, rainfall over the Indian region is highly underestimated. The major rain-belt in the mean rainfall pattern of the MeteoFrance over 60–90°E and UKMO model over 50–80°E is over the equatorial Indian Ocean rather than over the Indian region. Also, for the UKMO model, the rainfall pattern over the equatorial Indian Ocean has maximum rain over the western part and hardly any over the eastern part (which is opposite of what is observed) and the pattern correlation coefficient of the mean JJAS rainfall pattern with the observed (CMAP) rainfall over 60–100°E, 10°S–30°N is the lowest (Table 1). The mean rainfall pattern over this region is simulated rather well by CFS2 and ECMWF models (Table 1).

The simplest and most commonly used measure of the skill of prediction of the interannual variation, is the correlation coefficient between the predicted and observed features of interest, i.e. ISMR in this case. The correlation coefficients between the predicted and observed ISMR by the different models are given in Table 1. A surprising result is the lack of a relationship of the correlation coefficient between observed and predicted ISMR to the fidelity, i.e. the pattern correlation of the mean rainfall. Thus while the model with the highest correlation between predicted and observed ISMR (UKMO) is the poorest in simulation of the mean pattern, the second best correlated model CFS2, simulates the mean pattern very well.

If we consider all the extremes observed in the period over which the retrospective predictions are available, the skill of prediction of the ISMR extremes seems to be reasonable for several models. Consider first the predictions by five models from ENSEMBLES for 1960–2005. Of the nine droughts during 1961–2005, negative ISMR anomaly was predicted for eight seasons by two models (ECMWF, UKMO) and for seven seasons by the other three models. For the seven excess monsoon seasons, positive ISMR anomaly was predicted in six seasons by three

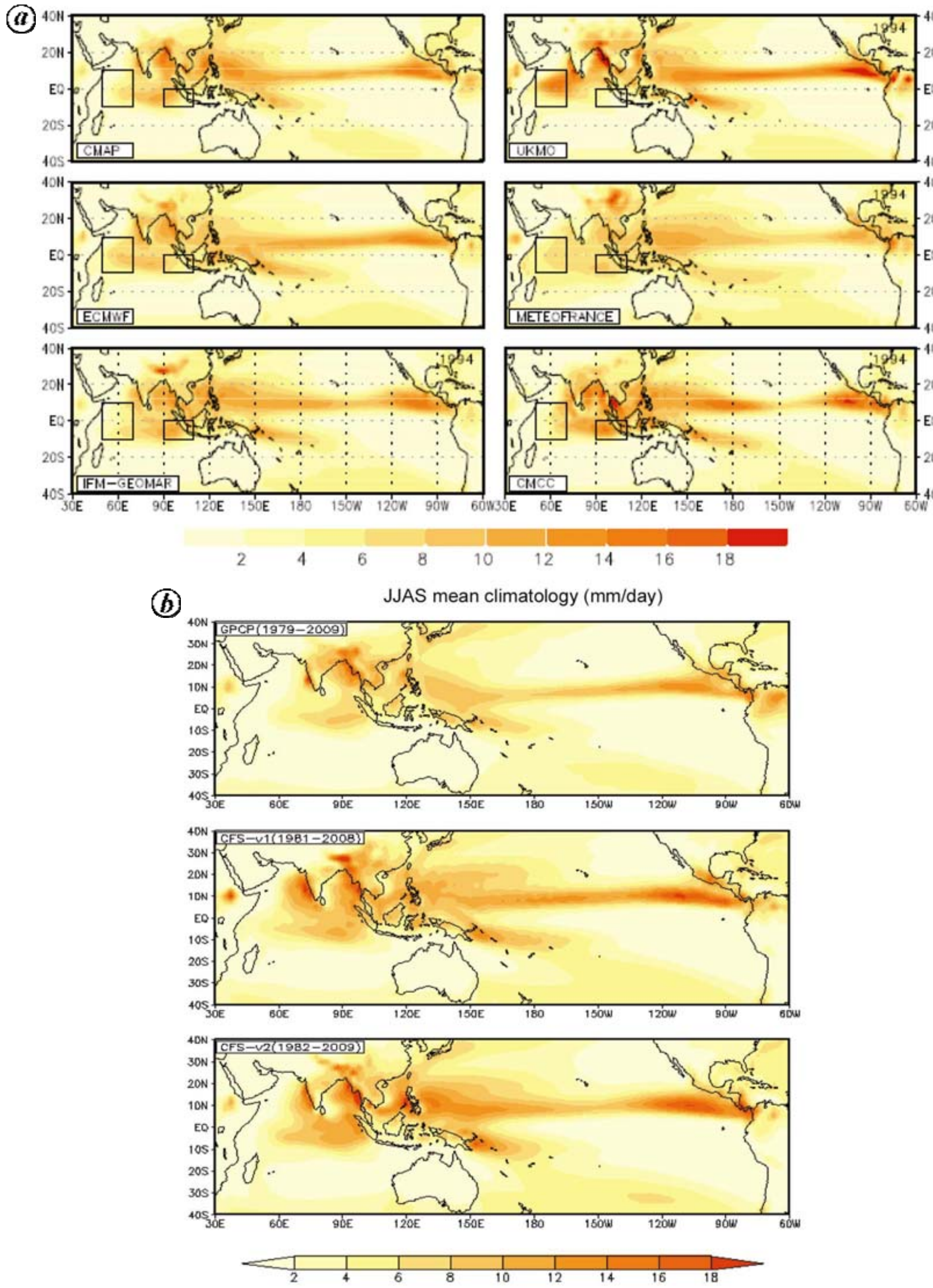

Figure 5. ***a***, Mean JJAS rainfall patterns from observations (CMAP) and those simulated by five models which participated in the ENSEMBLES project. ***b***, Mean June–September rainfall (mm/day) patterns observed (GPCP) and simulated by CFS1 and CFS2.

models, viz. ECMWF, UKMO, MeteoFrance (exception being 1983), but in only four seasons by the other two. For 1982–2009, CFS1 and CFS2 predicted negative ISMR anomaly for five out of six droughts (exceptions being the large positive ISMR anomaly predicted for 2009 by CFS1 and a small positive ISMR anomaly for 1982 by CFS2). Whereas CFS1 predicted positive anomaly for four out of five excess rainfall seasons (exception being 1983), CFS2 predicted positive anomaly for three out of five excess rainfall seasons in this period (exceptions being 1983 and 1994).

For a few extremes of monsoon rainfall and the special season of 1997, the observed ISMR anomaly and that predicted by five models of ENSEMBLES, are shown in

Table 1. Correlation coefficient between observed and predicted rainfall (June–September)

	Pattern correlation coefficient between simulated and CMAP (GPCP) mean rainfall for all available years between 1979 and 2009	Correlation coefficient between predicted and observed ISMR	
Model	Region: 60–100°E, 10°S–30°N	All available years	All available years, excluding 1983 and 1997
UKMO*	0.56 (0.57)	0.43	0.53
MeteoFrance*	0.60 (0.58)	0.36	0.47
CMCC*	0.71 (0.57)	0.33	0.47
IFM*	0.65 (0.47)	0.30	0.41
ECMWF*	0.79 (0.76)	0.29	0.40
CFS1**	0.66 (0.60)	0.14	0.33
CFS2**	0.81 (0.74)	0.41	0.57

*Period: 1960–2005; **Period: 1982–2009.

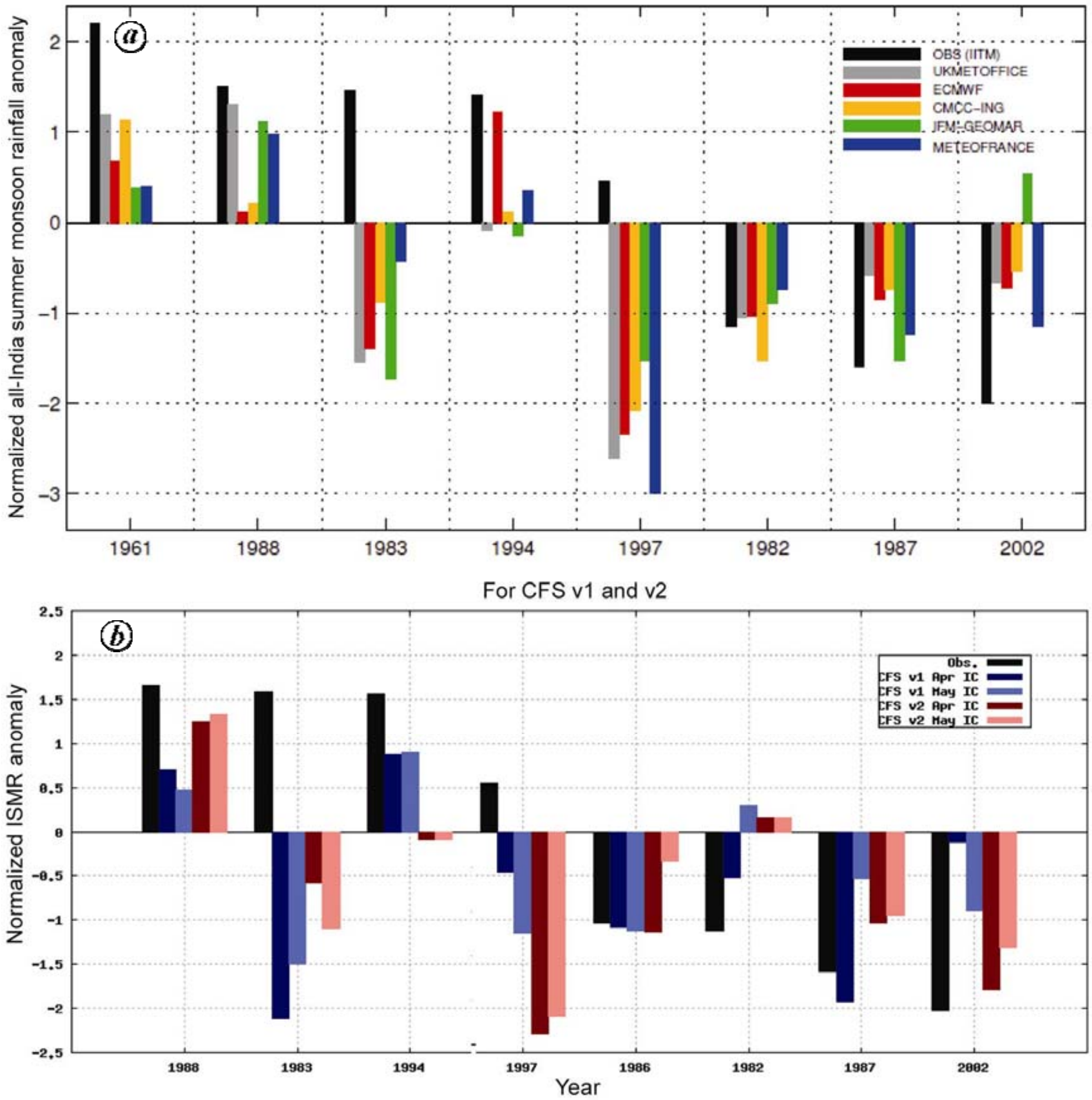

Figure 6. ***a***, Observed normalized ISMR anomaly and that predicted by five models of ENSEMBLE project for a few selected years, viz. 1961, 1988, 1983, 1994, 1997, 1982, 1987 and 2002. ***b***, Observed normalized ISMR anomaly and that predicted by CFS1 and CFS2 with April and May initial conditions for a few selected years, viz. 1988, 1983, 1994, 1997, 1986, 1982, 1987 and 2002.

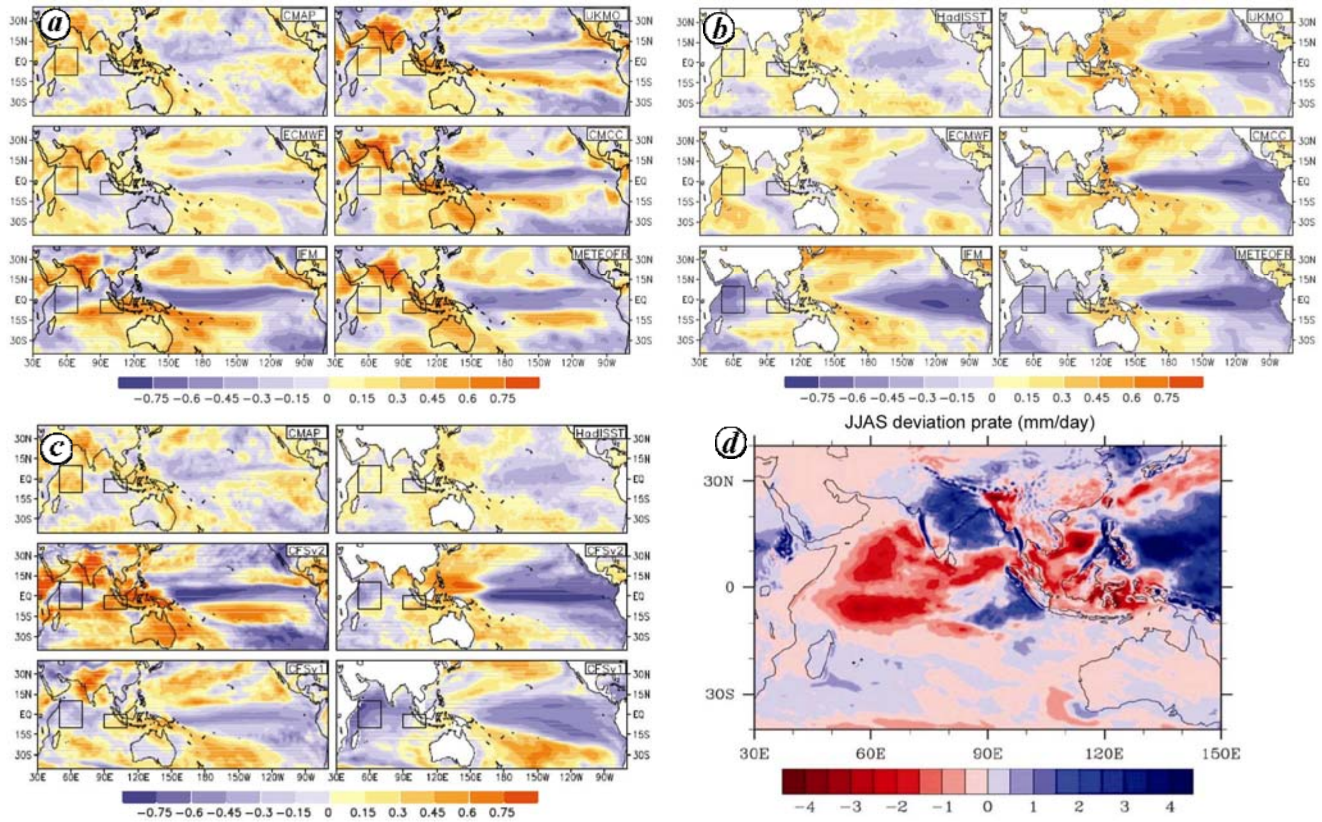

Figure 7. ***a***, Correlation between the model ISMR and the model rainfall at every grid point for the five models which participated in the ENSEMBLE project. Correlation between observed ISMR (IITM) and observed rainfall (CMAP) at each grid point is shown in the top left panel. All the available data for the period 1979–2009 are considered here to compute the correlation coefficient. ***b***, Correlation between the model ISMR and the model SST at every grid point for the models that participated in the ENSEMBLES project. Correlation between observed ISMR (IITM) and observed SST (HadISST) at each grid point is shown in the top left panel. All the available data for the period 1979–2009 are considered here to compute the correlation coefficient. ***c***, (Left panels) Correlation between the model ISMR and model rainfall at every grid point for CFS1 and CFS2. (Top left panel) Correlation between observed ISMR (IITM) and observed rainfall (CMAP) at each grid point. (Right panels) Correlation between model ISMR and model SST at every grid point for the CFS1 and CFS2. (Top right panel) Correlation between observed ISMR (IITM) and observed SST (HadISST) at each grid point. All the available data for the period 1979–2009 are considered here to compute the correlation coefficient. ***d***, Precipitaion anomaly pattern predicted for the monsoon season of 2012 by the Indian Institute of Tropical Meteorology using a high-resolution version of CFSv2.

Figure 6 *a* and for CFS1 and CFS2, for April and May initial conditions, in Figure 6 *b*. The most remarkable feature of Figure 6 is the coherence in the signs of the ISMR anomalies predicted by the different models for several years[29]. Thus all models predict negative anomaly for the drought of 1987, and positive anomaly for the excess monsoon season of 1988. All but one predict negative ISMR anomaly for the droughts of 1982 and 2002. However, all the models predict deficit ISMR or droughts for the excess monsoon season of 1983 and the normal monsoon of 1997. Thus, while there has been some improvement in the prediction of the correct sign of the ISMR anomaly for the excess monsoon season of 1994 from the simulation of that season by AGCMs forced with observed SST, with two of the seven models predicting a substantive positive ISMR anomaly, the prediction of the season of 1997 (identified as problematic by Wang *et al.*[21]) continues to be a challenge for coupled models as well. Since all the models predict deficit ISMR or droughts for the excess monsoon season of 1983 and the normal monsoon of 1997, there is a marked improvement in the correlation coefficients of the predicted with observed ISMR, if these two years are dropped from reckoning (Table 1). Clearly, even if the emphasis is only on the improvement of the correlation between the predicted and observed ISMR, an appropriate strategy would be to first focus on improving the prediction of these seasons by identification of the special features/facets of these seasons which most of the models are unable to capture and attempt to improve the predictions of these features/facets.

Predictions of the monsoon and its teleconnections

The coherence in the successful predictions for 1987 and 1988, and failures for the special seasons of 1997 and

Table 2. Correlation of ISMR with ENSO index and rainfall over WEIO

Model	Correlation coefficient between predicted and observed ENSO indices	Correlation coefficient between ISMR and ENSO index	Correlation coefficient between ISMR and rainfall over WEIO
UKMO*	0.82	0.66	–0.03
MeteoFrance*	0.75	0.75	–0.06
CMCC*	0.72	0.74	–0.13
IFM*	0.73	0.63	–0.25
ECMWF*	0.83	0.29	0.32
CFS1**	0.69	0.44	–0.3
CFS2**	0.65	0.78	–0.32
Observed		0.54†	0.51‡

*Period: 1960–2005; **Period 1982–2009; †Period: 1960–2009; ‡Period: 1979–2009.

1983 (false alarms), despite the differences in parameterization, etc. can arise from success/failure to predict a critical phenomenon across the board. We have seen that two modes, viz. ENSO and EQUINOO play an important role in determining the extremes of ISMR. It is therefore pertinent to consider the observed teleconnections of the monsoon to the rainfall over and the SST of the Indian and Pacific Oceans, and compare them with the teleconnections of the predicted ISMR with the predicted rainfall over this region and predicted SST of these oceans. The correlation of the observed/predicted ISMR with the observed/predicted rainfall over and observed/predicted SST of the Indo-Pacific region for the set of models from ENSEMBLES is shown in Figure 7 *a* and *b* and for CFS1 and CFS2 in Figure 7 *c*.

The ENSO-monsoon teleconnection

Consider first the correlation of the observed ISMR with the observed (CMAP) rainfall over the Indo-Pacific region shown in Figure 7 *a*. A prominent feature is the negative correlation with rainfall over the equatorial Pacific (primarily over western and central regions), which represents the monsoon–ENSO link. Note that although the correlation between the observed ISMR and observed SST (Figure 7 *b*) is negative over a zonal band eastward of about 150°E extending right up to the South American coast, the region over which the correlation between ISMR and rainfall is negative is primarily to the west of 120°W. From the South American coast up to 120°W, the region over which correlation of the rainfall with the predicted ISMR is negative is restricted to a zonal band of narrow latitudinal extent around 5°N. It is seen from Figure 7 *a* and *c* that the ISMR predicted by most of the models has a negative correlation with the rainfall over the equatorial western and central Pacific as observed, but the magnitude of the correlation coefficient is higher than that observed. The latitudinal extent of this band of negative correlation hardly changes across the Pacific, so the teleconnection with the rainfall over 120–90°W, 0–15°S is of opposite sign to that observed. The pattern of correlation with ENSO, therefore, does not appear to be completely realistic. The predicted ENSO index is generally highly correlated with the observed ENSO index, with the correlation coefficient ranging from 0.65 to 0.83 (Table 2). The correlation of the predicted ISMR with the predicted ENSO index is higher than the observed correlation coefficient for all the models, except the ECMWF model for which the correlation coefficient is only 0.29.

The EQUINOO–ISMR linkage

The other prominent feature of the correlation of the observed ISMR with rainfall shown in Figure 7 *a* is the link with EQUINOO, manifested as a positive correlation with rainfall over the WEIO and a negative correlation over the EEIO. This implies that a positive phase of EQUINOO is favourable for ISMR. Note that the magnitude of the positive correlation with rainfall over WEIO is larger than that of the negative correlation with rainfall over EEIO. Correlation of the observed ISMR is positive with SST of WEIO and negative with SST of EEIO (Figure 7 *b*), implying that the positive phase of IOD is favourable for ISMR. However, the correlation coefficients of ISMR with SST are smaller in magnitude than those of ISMR with rainfall. We find that the correlation of the predicted ISMR with the predicted rainfall over WEIO is of the correct sign and comparable with the observed correlation only for the ECMWF model (Table 2, Figure 7 *a* and *c*). For all the other models, the ISMR is negatively (instead of positively) correlated with the rainfall over WEIO (Table 2, Figure 7 *a* and *c*). Also, the correlation between ISMR and rainfall over EEIO is negative (as observed) only for the ECMWF model (Figure 7 *a* and *c*). The correlation coefficients of all the other models are positive, ranging from 0.21 for CFS1 to 0.71 for CFS2. Thus only the ECMWF model has realistic teleconnections with EQUINOO and IOD, i.e. positive (negative) correlation between ISMR and rainfall over and SST of WEIO (EEIO). The UKMO model has weak positive correlations with rainfall over and SST of WEIO as well as EEIO. For all the other ENSEMBLES models, as well as CFS1 and CFS2, the correlation of ISMR with rainfall over and SST of EEIO (WEIO) is positive (negative), i.e. of opposite sign to that observed (Figures 7 *a* and *c*). The prediction for the summer monsoon of 2012 generated by a high-resolution version of CFS2 at IITM (Figure 7 *d*) is perhaps a manifestation of the erroneous link of the predicted ISMR to the predicted EQUINOO in CFS2. Thus if we consider the teleconnection of the Indian monsoon with the equatorial Indian Ocean and the atmosphere above the equatorial Indian Ocean, it is well captured only by the ECMWF model. Hence although the strength of the monsoon–ENSO link is weaker than that observed in this model (as pointed out by DelSole and Shukla[30]), in our view, because of its success in capturing the link with EQUINOO, a detailed analysis of its retrospective forecasts could provide valuable insights into how the other models can be improved to incorporate this important feature.

Teleconnections and predictions

Consider next the implications of the nature of the teleconnections for prediction of the extremes of the monsoon. Note that the drought seasons of 1982, 1987 and 2002 for which almost all the models predicted deficit ISMR, were characterized with the occurrence of an El Niño, and excess of 1988 with La Niña. Since the models are generally able to predict the strong phases of ENSO and all predict a realistic monsoon–ENSO teleconnection (although stronger than that observed for most models and weaker for ECMWF), they are generally able to predict accurately the sign of the ISMR anomaly for extremes which are associated with ENSO. The seasons of 1997 and 1983 for which all models generated false alarms and also the excess monsoon season of 1994, for which only two models predicted a substantive positive ISMR anomaly, were characterized by a strong positive EQUINOO phase (Figure 8). The strong positive EQUINOO phase in 1994 and 1997 was associated with strong positive IOD events[31–33]. There was a strong El Niño in 1997 and weaker El Niños in 1994 and 1983 (Figure 8). Thus for all these seasons, the phase of ENSO was unfavourable for ISMR and that of EQUINOO was favourable. While the strong positive phase of EQUINOO played a critical role overcoming the negative impact of the strong El Niño of 1997, it overwhelmed the impact of the relatively weak El Niño events of 1994 and 1983 and led to excess rainfall in these seasons. We consider next the prediction of the two modes and the ISMR for these seasons by the different models.

Consider first the case of 1994 for which the ECMWF model predicted an excess and several models, including CFS2 predicted the rainfall to be close to normal. In fact, all the models predicted a positive phase of IOD and EQUINOO for JJAS 1994, as observed. However, they all predicted a suppression of rainfall in the equatorial belt over the Pacific the region where the rainfall is negatively correlated with the predicted ISMR (e.g. Figure 9 for ECMWF and CFS2), i.e. a favourable ENSO phase (instead of the observed unfavourable phase) for the Indian monsoon. This error implied that for the ECMWF model, both the modes were favourable and the result was excess rainfall over India. However, for other models, a positive phase of EQUINOO is unfavourable for ISMR. With the two modes opposing one another, for most of the models (such as CFS2) the ISMR is close to normal (Figures 6 and 9). Clearly, for improving the hindcast of the excess monsoon season of 1994, it is necessary to achieve a realistic simulation of the monsoon–EQUINOO link.

In the case of 1997, all the models predicted a strong El Niño as observed. Rajeevan *et al.*[5] have shown that in 1997, the MME of ENSEMBLES predicted a much stronger El Niño over the central Pacific (which is expected to have a larger negative impact on the Indian monsoon). Thus the failure of the predictions in 1997 has been attributed to the failure in accurate prediction of the spatial pattern and intensity of the anomalies associated with the El Niño of 1997. They also showed that the MME did not predict the positive IOD event in 1997. We find that the ECMWF and UKMO models predicted SST anomalies of the opposite sign to that observed over WEIO and EEIO[29], implying a negative phase of IOD and simulated very weak rainfall anomalies. The CFS1 and CSFS2 models predicted positive phase of EQUINOO (Figure 9 for the CFS2 model), which was somewhat weaker than that observed; MeteoFrance, IFM and CMCC predicted positive EQUINOO, but much weaker than that observed. This implied that the EQUINOO phase predicted by the models was either very weak or unfavourable in 1997. The prediction of large deficits/droughts of ISMR in 1997 is consistent with both the modes being unfavourable. Given that the CFS2 model could predict accurately the signs of the rainfall anomalies over the equatorial Indian Ocean, the critical factor for improving the hindcast of the 1997 season, is the improvement of the prediction of the monsoon–EQUINOO link.

It is intriguing that the ECMWF model, which predicted a positive phase of the IOD for the event of 1994, could not predict the major IOD event of 1997. It is important to understand why the 1997 event was not triggered in the model. All hypotheses for the initiation and evolution of positive IOD events[34–37] involve a suppression of convection over the EEIO as the precursor to the triggering of positive IOD events. A suppression of convection over EEIO can occur due to the strong convection over the central Pacific associated with El Niño[34] or due to the enhancement of convection over the South China Sea in association with an EL Niño[35] or due to severe cyclones over the Bay of Bengal in April–May[36]. Francis *et al.*[36] suggested that a suppression of convection over EEIO, leads to an enhancement of convection over WEIO

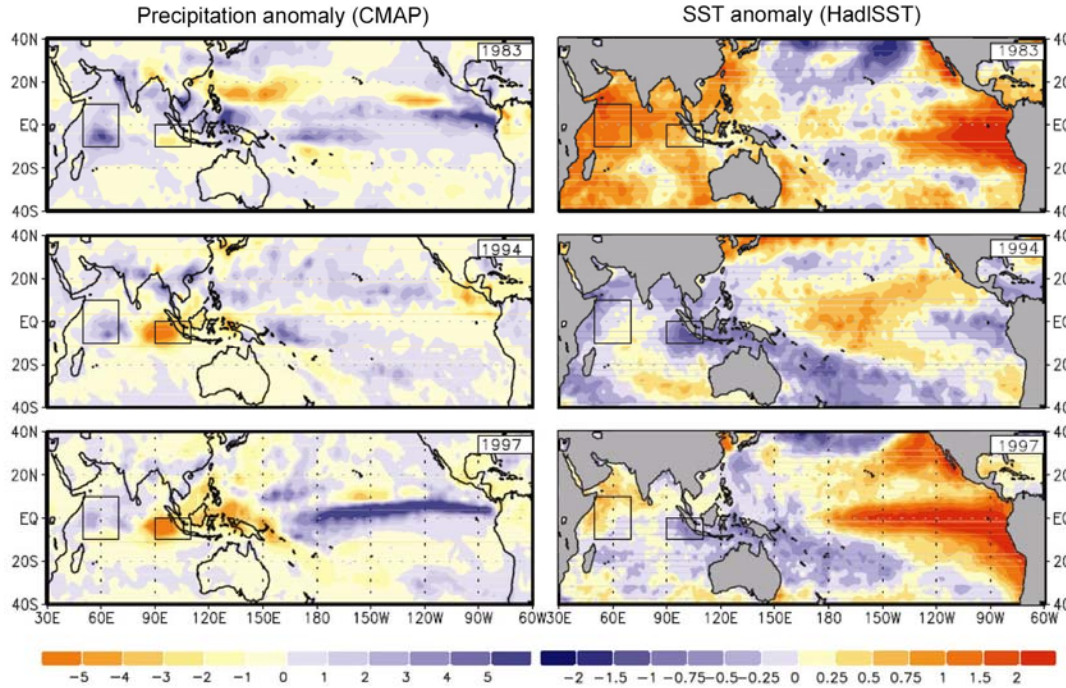

Figure 8. Observed June–September mean rainfall (left panels) and SST (right panels) anomaly patterns for 1983, 1994 and 1997.

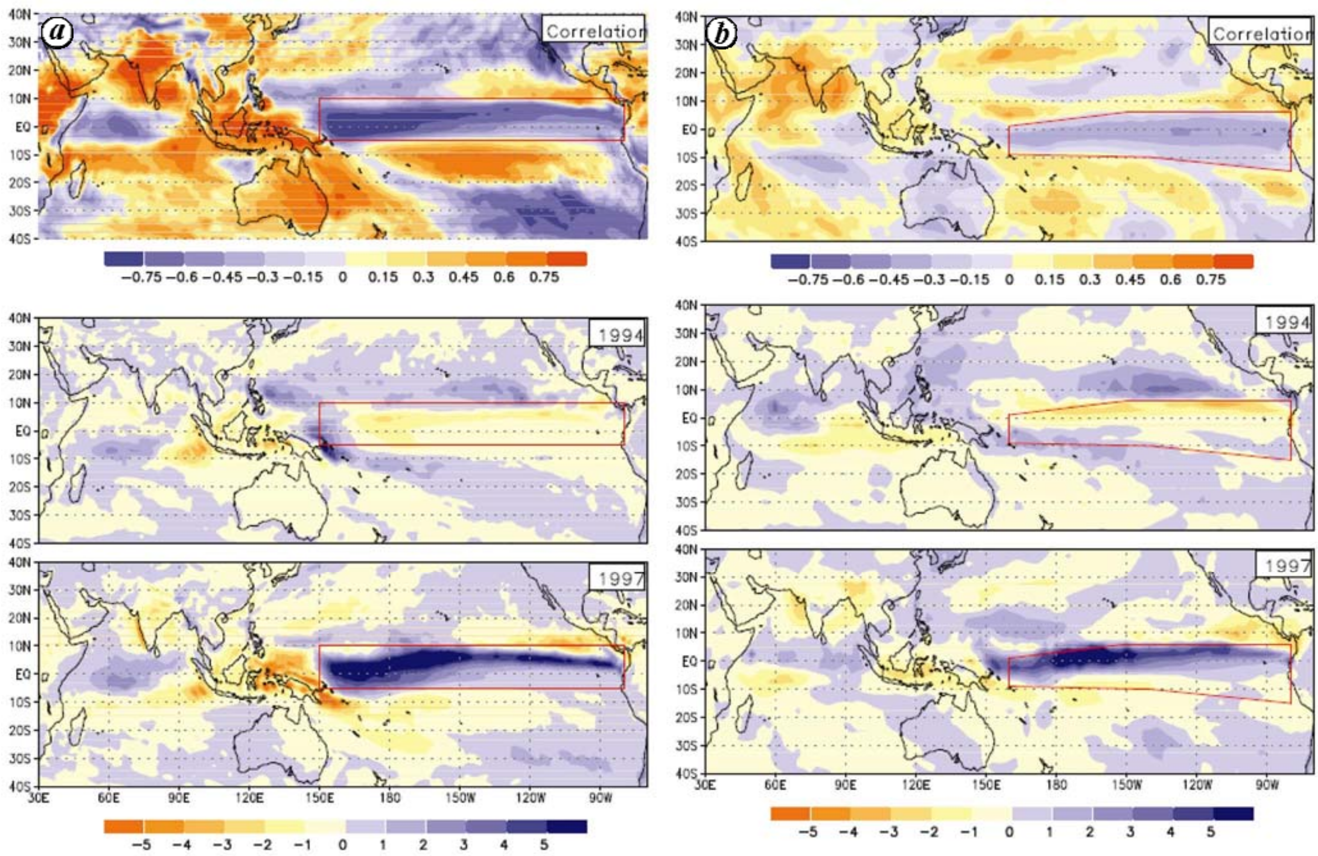

Figure 9. ***a*** (Top panel) Correlation between model ISMR and model rainfall at every grid point for CFS2 model (top panel). June–September mean rainfall anomaly patterns for 1994 (middle panel) and 1997 (bottom panel) simulated by CFS2 model. ***b***, same as (***a***), but for ECMWF model simulations.

and hence a positive EQUINOO phase and intensification of the easterly anomaly of the zonal wind. The evolution of the 1997 El Niño event commenced in the boreal spring, and the convection over EEIO was suppressed and a strong positive EQUINOO phase prevailed throughout the summer monsoon season. If the evolution of the El Niño had been accurately predicted by the model, we expect that the convection over EEIO would have remained suppressed throughout the season. Thus it appears that the positive EQUINOO phase was not predicted by the model because of errors in the prediction of the evolution of the El Niño of 1997.

For the season of 1983, the El Niño signal is evident over the Pacific in the observations (Figure 8) and was captured by all the models. The SST anomaly was positive over both WEIO and EEIO, being larger for WEIO, and a strong positive phase of EQUINOO was observed (Figure 8). Rajeevan *et al.*[5] showed that in the season of 1983, the warm SST anomalies over the central Pacific were predicted by MME to persist throughout the season, whereas in observation they disappeared half way through the season. They attributed the failure of the prediction of ISMR in 1983 to the failure in predicting the retreat of the El Niño of 1982–83 from the central Pacific accurately. We find that all the models predicted a weak negative phase of EQUINOO (instead of the observed positive phase). Thus the EQUINOO phase was favourable for all the models (except for ECMWF because it has a realistic teleconnection). However, all the models predicted large deficits in ISMR, presumably due to the impact of the El Niño.

Discussion

Prediction of the Indian monsoon rainfall on a seasonal scale is an important but challenging problem for dynamical models. Here we have analysed five models from ENSEMBLES project and two versions of the NCEP climate forecast model, to assess their ability to predict ISMR with specific reference to extremes of ISMR. Given the immense societal impact of the extremes of the ISMR, and particularly droughts, we believe that only when it becomes possible to generate reasonably accurate and reliable predictions of these extremes, can it be claimed that a substantial improvement of a model or a set of models has been achieved.

On the whole, the skill of the coupled models studied here in predicting the extremes, appears to be reasonable, with the models being able to predict at least the sign of the ISMR anomaly for a majority of the ISMR extremes. However, all the models predict a large deficit/drought for the excess monsoon season of 1983 and the normal monsoon season of 1997, implying loud false alarms for these seasons. The inability of models which have different model physics, dynamics and methods of initialization to predict these seasons, clearly indicates a basic shortcoming in their prediction of a major feature/phenomenon, which is important in these seasons. If after identification of such a feature/phenomenon, its prediction and hence the monsoon prediction of these seasons could be improved, correlation between the predicted and observed ISMR would be substantially enhanced, as seen when these years are dropped from reckoning (Table 1). Given the important roles of ENSO and EQUINOO in the interannual variation of the Indian monsoon and particularly the extremes, we have tried to ascertain whether the errors in monsoon prediction are associated with these in the prediction of one or both of these phenomena and their links to the monsoon.

Earlier studies with AGCMs forced by observed SST had also shown such coherence in the successes/failures in the simulation of ISMR for some seasons. Thus almost all the models predicted large deficits for the excess monsoon season of 1994 (ref. 6), which was characterized by a weak El Niño and the normal monsoon year of 1997 which was characterized by a very strong El Niño[21]. Both these seasons were characterized by a strong positive phase of the EQUINOO. It was suggested[6] that the failure in the simulation of the 1994 and 1997 could arise from one or more of the following factors – (i) inability to simulate the positive phase of EQUINOO, (ii) inability of the models to simulate the monsoon–EQUINOO link and (iii) unrealistically high sensitivity to ENSO forcing. The results of a national project on intercomparison of atmospheric models for seasonal prediction of the Indian monsoon (SPIM) suggested that the major factor was the unrealistically strong response of the models to ENSO[38]. It is interesting that large errors occur in the prediction of ISMR for 1997, as also for all the coupled models considered here. However, the prediction of 1994 seems to have improved with two models predicting substantive positive anomalies of ISMR.

We find that generally the coupled models predict the strong phases of ENSO reasonably well. In the case of 1994, which was characterized by a weak El Niño, all the models predicted a favourable phase (in place of the observed unfavourable phase) of ENSO. All the models predicted a positive phase of EQUINOO (as observed) for 1994. However, they were less successful in prediction of strong phases of positive EQUINOO in 1983 and 1997. On the whole, the ability of models to simulate ENSO–monsoon linkage is quite reasonable though most models overestimate the strength of this relationship and over the eastern regions of equatorial Pacific, the correlations are of the wrong sign. The most surprising result of this study is that the EQUINOO–ISMR link is opposite to the observations in most of the models. Only the ECMWF model is able to simulate both these linkages reasonably realistically. Hence with both the modes being favourable, the ECMWF model predicted excess ISMR for 1994. However, since in the other models the monsoon–

EQUINOO link is of the opposite sign to that observed, the two modes for 1994 opposed one another in these models, and ISMR was close to normal in most of them. Thus, large deficits in rainfall were not predicted for the ISMR of 1994 (as in the case of AGCMs driven with the observed SST for this case) primarily because of errors in the predicted ENSO phase, which was favourable in all the models. Had the prediction of the ENSO phase been accurate, realistic results would have been possible only with a realistic monsoon–EQUINOO link. The errors in prediction of ISMR in 1997 have been attributed to the errors in the prediction of rainfall anomalies over the central Pacific and those in 1983 to errors in the prediction of the retreat of the 1982–83 El Niño from the central Pacific[5]. We suggest that the inability of most of the models to predict the strong positive EQUINOO phase in these seasons combined with the inability of all the models (except ECMWF) to predict the monsoon–EQUINOO link also contributed to the failure of the predictions for these seasons. For models such as CFS2, which predicted realistically the positive EQUINOO phase in 1997, the simulation of a monsoon–EQUINOO link of the wrong sign would have contributed to the large error in the prediction of ISMR in that season.

Thus it appears that improvement of the prediction of the phases of EQUINOO, the simulation of the monsoon–EQUINOO link and of some aspects of ENSO is a prerequisite for better predictions of the Indian monsoon. As far as ENSO is concerned, the predictions of the occurrence of weak El Niño events (such as 1994), the anomaly patterns over the Pacific associated with strong El Niño events (such as 1997), and the transition phase involving the retreat of El Niño from the central Pacific (as in 1983) have to be improved. A bigger challenge is in the prediction of strong phases of EQUINOO (e.g. 1983, 1997) and the prediction of triggering and evolution of positive IOD events (such as 1997). Perhaps the biggest challenge is to improve the prediction of the monsoon–EQUINOO link in the models. It should be noted that marked improvements of the simulation of the ENSO–monsoon link in AGCMs occurred as a result of systematic experimentation with models to improve the simulations of the drought of 1987 associated with El Niño and the excess monsoon season of 1988 associated with a La Niña under the MONEG (Monsoon Numerical Experimental Group) programme of WCRP. A systematic experimentation with models to improve the hindcasts of selected years such as 1994, 1983 and 1997 can contribute towards improvement in the prediction of the monsoon–EQUINOO link.

The inability of most of the models to predict EQUINOO and simulate realistically its link with ISMR needs to be understood with extensive analysis of simulations both with AGCMs and Coupled General Circulation Models (CGCMs). The experience with AMIP and SPIM suggests that the problem is non-trivial and the success in simulating the monsoon–EQUINOO relationship could be related to sensitivity of the models to other factors such as the ENSO forcing[38]. The gradient of SST between WEIO and EEIO is known to play an important role in determining the phase of EQUINOO even in the absence of IOD events and hence for a realistic prediction of the phase of the EQUINOO, a realistic prediction of the evolution of SST over the equatorial Indian Ocean is required[39]. While the variation of SST of EEIO is determined by atmospheric forcing as well as ocean dynamics, that of WEIO is primarily driven by atmospheric fluxes[40]. Studies such as that of Bollasina and Nigam[41] have indicated that there could be problems in ocean–atmosphere coupling and fluxes over the Indian Ocean. Studies have also shown that simulation of SST–rainfall relationship with CGCMs tends to be realistic due to compensation of errors in coupled models–lower simulated SSTs compensate higher rainfall and the simulation tends to be realistic[23,42,43]. Such errors can also have an impact on the evolution of the SST gradients and hence EQUINOO. Systematic studies with AGCMs, OGCMs and CGCMs aimed at unravelling the complex feedbacks between the monsoon and the coupled atmosphere–equatorial Indian Ocean system could pave the way for improving the ability of the models in predicting the monsoon.

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