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On improving the ability of a high-resolution atmospheric general circulation model for dynamical seasonal prediction of the extreme seasons of the Indian summer monsoon

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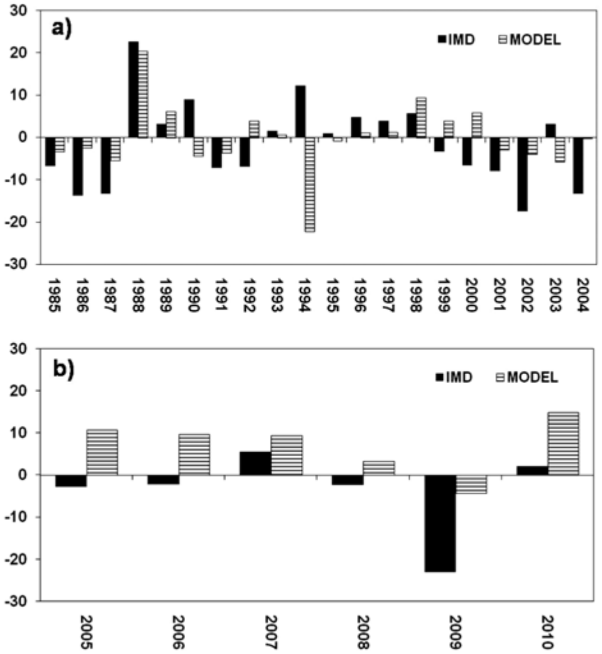
सार – इस शोध पत्र में उच्च विभेदन वाले राष्ट्रीय पर्यावरणीय पूर्वानुमान केन्द्र (एन. सी. ई. सी.) टी 170/एल 42 वायुमंडलीय सामान्य परिसंचरण निदर्श (ए. जी. सी. एम.) की क्षमता की जाँच की गई है ताकि परिसीमा स्थिति के अनुरूप एन. सी. ई. पी. युग्मित पूर्वानुमान प्रणाली (सी. एफ. एस.) एस. एस. टी. सहित पूर्वानुमान पद्धति में 6 वर्ष (2005–2010) की अवधि और परिसीमा स्थिति के रूप में प्रेक्षित भूमंडलीय समुद्र सतह तापमानों (एस. एस. टी.) सहित 20 वर्षों (1985–2004) की अवधि के हिंडकास्ट पद्धति के लिए गठित 5 सदस्यों पर आधारित ऋतुनिष्ठ भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) के दीर्घावधि – गतिकीय पूर्वानुमान के लिए इनकी उपयोगिता का पता लगाया जा सके। पाँच दिवसीय पंचक औसत वर्षा के आधार पर आई. एस. एम. आर. अनुकरणों की जाँच की गई है। इससे यह पता चलता है कि 5 सदस्यों के सामूहिक प्रभाव के औसत के आधार पर आई. एस. एम. आर. को अनुकरित करने वाले निदर्श में आई. एस. एम. आर. की चरम ऋतुओं (सूखा/अधिक आई. एस. एम. आर.) को अनुकरित करने की सीमित क्षमता होती है। तथापि, यदि भारत मौसम विज्ञान विभाग के प्रेक्षित जलवायु विज्ञान पर आधारित अपने–अपने पंचकों के लिए सहगुणांक विभिन्नता (सी. वी.) द्वारा बताए गए आरंभिक मान के लिए प्रत्यंतर द्वारा निर्धारित अथवा मौसमी जलवायु विज्ञान से आई. एस. एम. आर. की प्रतिशत विसंगति के आधार पर पूरी ऋतु के दौरान सामूहिक औसत को समरूपी सामूहिक सदस्यों तक पंचकवार नीचे (बी) और ऊपर (ए) सामान्य वर्षा की घटनाओं के पूरे प्रवाह में से किसी एक तक सीमित कर दिया जाता है तो सूखा / मानसून ऋतुओं की अधिकता का पूर्वानुमान लगाने में काफी सुधार आ सकता है। आई. एस. एम. आर. के गतिकीय मौसमी पूर्वानुमान को सुधारने के लिए हमारी नीति इस बात पर आधारित है कि अंतरा–मौसमी विविधता (आई. एस. वी.) और अंतरा–वार्षिक विविधता (आई. ए. वी.) अंतरिम रूप से संबंधित होती हैं और ग्रीष्मकालीन मानसून ऋतु के दौरान मानसून आई. एस. वी. के बृहत्त मान विक्षोभ पश्चिम दिशा की ओर बढ़ते हुए (10–20 दिन) और उत्तर की ओर बढ़ते हुए (30–60 दिन) तंत्रों द्वारा बताए गए हैं। इस प्रकार अनुकरित मौसम में बी. घटनाओं की अत्याधिक संचयी वर्षा सूखे की ऋतु के सदृश अथवा इसके विपरीत होगी। इस शोध पत्र में अनुकरित आई. एस. एम. आर. श्रेणियों के एल. नीनों–मानसून संबंधों की भी जाँच की गई है और प्रस्तावित प्रणाली विज्ञान से इनमें काफी सुधार देखा गया है। इस नीति से विशेषकर सुखे का पूर्वानुमान लगाने में सुधार देखा गया है। अध्ययन के परिणामों के आधार पर सूखा अथवा अत्यधिक आई. एस. एम. आर. श्रेणी के लिए ए घटनाओं पर अत्यधिक बी घटनाओं के आधार पर अनुकरित आई. एस. एम. आर. और इसके विपरीत स्थिति में उपयुक्त सिग्नल का उपयोग करने का प्रस्ताव है। प्रतिशत आधार पर कुल सामूहिक प्रभावों और समरूपी सामूहिक सदस्यों के सापेक्षिक अनुपात के आधार पर श्रेणी आधारित मौसमी आई. एस. एम. आर. के पूर्वानुमान के लिए संभावित वितरण का भी प्रस्ताव है। इस शोध पत्र में संयुक्त रूप से एल. नीनों – दक्षिण दोलन (एनसो) और भारतीय महासागर द्विध्रुव (आई. ओ. डी.) तंत्रों द्वारा उत्पन्न मानसून ऋतु की अधिकता पर भी विचार विमर्श किया गया है और अतः महासागर–वायुमंडल युग्मित निदर्श में पूर्वानुमान करने के लिए आई. ओ. डी. पद्धति को सुधारने पर बल दिया गया है क्योंकि 6 से 9 महीने पहले एनसो पद्धति से पुर्वानुमान लगाने के समय ऐसा हुआ है।

ABSTRACT. The paper is devoted to examine the ability of a high-resolution National Center for Environmental Prediction (NCEP) T170/L42 Atmospheric General Circulation Model (AGCM), for exploring its utility for long-range dynamical prediction of seasonal Indian summer monsoon rainfall (ISMR) based on 5-members ensemble for the hindcast mode 20-year (1985-2004) period with observed global sea surface temperatures (SSTs) as boundary condition and 6-year (2005-2010) period in the forecast-mode with NCEP Coupled Forecast System (CFS) SSTs as boundary condition. ISMR simulations are examined on five day (pentad) rainfall average basis. It is shown that the model simulated ISMR, based on 5-members ensemble average basis had limited skill in simulating extreme ISMR seasons (drought/excess ISMR). However, if the ensemble averaging is restricted to similar ensemble members either in the overall run of pentad-wise below (B) and above (A) normal rainfall events, as determined by the departure for the threshold value given by coefficient of variability (CV) for the respective pentads based on IMD observed climatology, or during the season as a whole on the basis of percentage anomaly of ISMR from the seasonal climatology, the foreshadowing of drought/excess monsoon seasons improved considerably. Our strategy of improving dynamical seasonal prediction of ISMR was based on the premise that the intra-seasonal variability (ISV) and intra-annual variability (IAV) are intimately connected and characterized by large scale perturbations westward moving (10-20 day) and northward moving (30-60 day) modes of monsoon ISV during the summer monsoon season. As such the cumulative excess of B events in the simulated season would correspond to drought season and *vice-versa*. The paper also examines El Niño-Monsoon connections of the simulated ISMR series and they appear to have improved considerably in the proposed methodology. This strategy was particularly found to improve for foreshadowing of droughts. Based on results of the study a strategy is proposed for using the matched signal for simulated ISMR based on excess B over A events and *vice-versa* for drought or excess ISMR category. The probability distribution for the forecast seasonal ISMR on category basis is also proposed to be based on the relative ratio of similar ensemble members and total ensembles on percentage basis. The paper also discusses that extreme monsoon season are produced by the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) modes in a combined manner and hence stresses to improve prediction of IOD mode in ocean-atmosphere coupled model just as it has happened for the prediction ENSO mode six to nine months in advance.

Key words – Indian summer monsoon rainfall, Climate model, Seasonal prediction.

1. Introduction

In a recent paper by Ratna *et al*. (2010), we have discussed the details of 20-year (1985-2004) of dynamical simulations of the Indian summer monsoon (ISM) circulation and Indian summer monsoon rainfall (ISMR) as well as its interannual variability (IAV) of the ISMR, using NCEP T170/L42 atmospheric general circulation model (AGCM). This study showed that the model had fidelity in simulating the climatology of the circulation features of the monsoon season as well as episodes like the onset of the monsoon over Kerala and its advance to northwest India in a realistic manner. However, the model-simulated rainfall climatology showed certain bias, like the fast build-up of the monsoon rainfall in the month of June compared to slow build-up in the observations, slightly lower average monthly rainfall for July and August by about 12 to 20% respectively and the faster decline of rainfall from August to September compared to corresponding monthly observations. However, the IAV of the seasonal and monthly rainfall were quite comparable to the observations. A major problem in the simulations was with regard to the IAV of the model simulated ISMR, averaged over the land grid point for the country as a whole, in relation to the observed El Niño-Monsoon connections. Even though in the 20-year simulations the model was forced with the observed global sea surface temperatures (SSTs) and climatological sea ice conditions from May to September, it could not produce the drought monsoon seasons for the years 1986, 2002 and 2004 though the major drought of 1987 was predicted. Three years 1986, 2002 and 2004 were warm El Niño years but all-members ensemble average simulated ISMR for these three years was -2.5, -4.0, and -0.3 percent respectively from the model climatology. Thus, the model indicated only slight negative ISMR anomaly for each of the three years and its simulations for all the three years could be categorized under normal ISMR category (10% of long-term normal) only. The model also simulated excess rainfall over India for the La Nina year of 1988 in agreement with the observations in category term. For the monsoon of 1998 season, the model simulated near-excess ISMR (+9.5% of the normal) whereas the observed rainfall was in excess by only 5.7% (normal category). However, the model simulation was totally unsatisfactory for the observed excess season of 1994 as it simulated ISMR as a drought season under previous year (1993)



Figs. 1(a&b). Percentage departure of model simulated ensemble mean rainfall and IMD observed rainfall from respective climatologies. (a) Observed SST is used for 1985-2004 (b) predicted SST used for 2005-2010 persistent El Niño SSTs in the equatorial Pacific Ocean whereas in observations the rainfall was in the excess category (12.2%). Figs. 1 (a&b) show the model and observed rainfall in the form of percentage departure from the simulated model climatology (model anomaly) and IMD's long-term climatology (observation). The recent drought associated with El Niño year 2009 also could not be simulated by the model as the ensemble average seasonal rainfall departure was simulated as -4% of the model climatology (normal category) where as the observed ISMR was -22% of the long-term normal (severe drought). In summary, the model-based ensemble average of ISMR performance was satisfactory for El Niño year of 1987 and La Nina year of 1988 but its performance was not very satisfactory for foreshadowing the three drought monsoon years which were related to warm El Niño events of 1986, 2002 and 2004. Also, the model results were quite in opposition with respect to sign of the observed ISMR for 1990, 1992, 1994, 2000. Of these four years only 1994 season was excess ISMR in observed series but was simulated as drought in the forecast series. This non-performance of the all-members ensemble average based simulations in extreme ISMR years (1986, 1994, 2002, 2004 and 2009) is a perplexing problem as the real test of the model has to be with regard to its prediction capability for the drought/excess monsoon years under forced El Niño/La Nina type boundary conditions.

Of special interest with regard to long-range forecast (LRF) of the monsoon has been the snow-monsoon connections in terms of aerial coverage of snow cover and snow depth (Blanford, 1884; Hahn and Shukla, 1976; Kriplani *et al*., 2007) and the Southern Oscillation (Walker, 1920) - the El Niño warming in the equatorial Pacific Ocean (Sikka 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). The pioneering work of Charney and Shukla (1980) had provided the paradigm for the dynamical long-range prediction of seasonal rainfall in the tropics on continental/sub-continental scale (large temporal and aerial average) based on the boundary conditions such as snow, soil moisture and SST. Possible dependence of ISMR on the winter/spring snowfall over Himalaya/Eurasian, Tibetan, and East Asian has been examined in dynamical sensitivity experiments by several workers (a short review is given in Sikka, 2010). Since the last 2-3 decades El Niño-Southern Oscillation (ENSO) phenomenon has been recognized as the most dominant modulator of IAV of the global and regional climate system in the tropics (Keshavamurty, 1982; Wallace *et al*., 1998; Su *et al*., 2001; Lau and Nath, 2003; Huang and Kinter, 2002; Annamalai and Liu, 2005) as a sequel of the international Tropical Ocean Global Atmosphere (TOGA) Program, undertaken during 1985-1994.

Several attempts have been made by different research groups to simulate the IAV of the ISMR with the observed or forecast global SSTs as boundary forcing but have met with limited success (Palmer *et al*., 1992; Fennesy *et al*., 1994; Goswami, 1998; Ashrit *et al*., 2001; Sperber *et al*., 2001; Wang *et al*., 2005; Krishna Kumar *et al*., 2005; Sajani *et al*., 2007; Rajendran *et al*., 2008). Studies by Gadgil and Sajani (1998), Kang *et al.* (2002), Sahai *et al.* (2003) and others, using Atmospheric Model Inter-comparison Project (AMIP) simulations for diagnosing the skill of AGCMs for simulating IAV of ISMR, have shown that even though the AGCMs are capable of simulating circulation features of summer monsoon rather well, they showed limited success in simulating monsoon drought/excess years as forced by global SST conditions. However, in AMIP runs the excess ISMR for 1988 was well simulated by several models under La Nina conditions. Recently, Joseph *et al.* (2010) have also shown that the coupled ocean-atmosphere general circulation model (CGCM) runs under the Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER) Program (Palmer *et al*., 2004) of the European Centre for Medium-Range Weather Forecasts (ECMWF) also had limited success in forecasting ISMR in extreme seasons. Similarly the performance of Coupled Forecast System (CFS) of National Center for Environmental Prediction (NCEP) for foreshadowing of extreme ISMR seasons, as determined by Pattanaik and Kumar (2010) and Pattanaik *et al.* (2010), was also not satisfactory. Wajsowicz (2005) has stated that the potential predictability of tropical Indian Ocean SST anomalies is limited in CGCMs. Studies by some other investigators have also found that while the AGCMs showed great skill in simulating the El Niño-related rainfall over the equatorial central Pacific Ocean region, they have limited skill or even no skill at all with regard to simulating Indian summer monsoon droughts/excess realistically. Slingo and Annamalai (2000) have made a detailed study of the warm El Niño of 1997, which was warmest of the century and yet it did not produce a drought in the ISMR which was 2% of the normal (normal category). Obviously there are other factors which impact adversely on the ISMR. Shukla *et al.* (2000) have reviewed dynamical seasonal predictability and also found limited success in predictability of ISMR. The observed El Niño-monsoon connections are not well simulated by the AGCMs even in hindcast with the observed SST conditions, based on all-members ensemble average rainfall simulations. To sum up in many dynamical studies on the prediction of ISMR by AGCMs and CGCMs, the El Niño-Monsoon connections could not be found to be robust in the simulated all-members ensemble average ISMR of the models. This could be even due to limited number of ensemble members used in some of these studies as Branković and Palmer (1997) have related the atmospheric seasonal predictability with the ensemble size. The inability of the models to simulate extreme ISMR seasons is also thought to be due to the land-locked area of the ISMR over which region land-atmosphere-ocean-biosphere interactions play crucial roles in modulating ISMR. As such it is recognised that the internal atmospheric variability during the monsoon season plays crucial role in modulating ISMR along with the SST boundary conditions (Webster *et al*., 1998; Goswami and Ajaymohan, 2001; Goswami *et al*., 2006). SST related boundary forcing versus internal variability of the ISMR has been a puzzling problem and as such the LRF of the ISMR still remains as one of the most challenging problems (Wang *et al*., 2005). Also, Saji *et al.* (1999), Behera *et al.* (1999) and others have suggested that development of Indian Ocean Dipole (IOD) event in the eastern equatorial Indian Ocean (EEIO) modulates ISMR. Gadgil *et al.* (2004 & 2007) have shown that besides the El Niño, the Equatorial Indian Ocean Oscillation (EQUINOO) mode contributes to the IAV of the ISMR in extreme years and as such the El Niño-Monsoon connections may get modulated in those years when the EQUINOO/IOD mode is working in opposition to the El Niño mode. As already mentioned the IAV of the ISMR is strongly linked with its ISV as organised convection in ISM occurs from super cloud clusters (~ 4000 km), large cloud clusters (~ 2000 km) and mesoscale cloud clusters (300-600 km) scales in the horizontal and low frequency (10-60 day), synoptic (3-5 day) and meso (~1 day) scales. The overlapping envelope for the organised convection (rainfall) is provided by the low frequency ISV in which organised convection moves from western Pacific to Bay of Bengal (BoB) on 10-20 day scale and from near equatorial to the north BoB and north Arabian Sea (AS) on 30-60 day scale. Rainfall during ISM season is also organised in spells of good and deficient rainfall on the country scale and spells and modulated by synoptic and low frequency scales. Spell-wise analysis of ISMR in any major drought/excess year would show that more spells of deficient/excess ISMR occurs in a drought/excess season. Krishnamurthy and Shukla (2007) have also emphasized that the performance of seasonal ISMR depends on the quasi-incidence of persistent rain spells for excess years and their absence in drought years and these are modulated by atmospheric patterns relating to Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) mode, which are caused by the coupled ocean-atmosphere processes.

Our motivation for this study stems from our desire to demonstrate that limited ability of the AGCMs to simulate extreme ISMR seasons could result from the technique of all-members ensemble averaging adopted for reaching a quantitative (deterministic) forecast of the ISMR on the seasonal scale. We propose a methodology for improving the foreshadowing of extreme ISMR events by selecting similarity among the individual ensemble members as determined by robustness in a cumulative way for the season or by identifying cumulative reproducibility of below normal or above normal rain spells among individual members. We show that the model simulation might compare more favorably with the observations even in extreme monsoon seasons, provided the averaging of ensemble members is made by quite-similar ensemble members matching. We propose the ensemble matching in counting the spells of below normal (B) and above normal (A) categories of pentad rainfall spells in model simulations on cumulative basis for the season as a whole. Measurement of similarity results from analysis of pentad rainfall. This would result in determining similar and reproducible ensemble members based on which the ensemble average could be prepared for a deterministic forecast. Alternatively the similarity among individual ensemble members could be identified based on the anomaly of simulated ISMR from observed anomaly, obtained by averaging of similar ensemble members. We show that there may be individual members in the suite of ensemble, which might indicate deficient/normal or excess monsoons but in the all-members ensemble averaging the signal is smoothed out. In the observations an excess or deficit monsoon season is produced by three to five pentads of excessively high or low rainfall on two or three occasions in the season. A somewhat persistent nature of sub-seasonal scale of the monsoon activity results in an extreme season. Thus it is the intra-seasonal variability (ISV) which is strongly linked to IAV in making an excess or a deficit ISMR season. To our understanding ISMR simulations, with the dynamical models, have not been examined with regard to the sub-seasonal fluctuations of the monsoon rainfall that occur in excess or deficit monsoon years. We have detail data for 20 years (1985-2004) hindcast seasonal simulation followed by six years (2005-2010) of forecast mode simulations. We used these data to address the question of the unsatisfactory performance of the model used by us (T170L42) with regard to the extreme monsoon seasons. Our objective in this study is to examine the 5-day (pentad) average rainfall for each of the simulated monsoon season from the beginning of June to the end of September (1 June to 28 September covering 24 pentads) and compare these pentad rainfall fluctuations in the model with regard to the corresponding long-term observed pentad rainfall series. Since the model is used for simulating the seasonal ISMR only (not for pentad-wise rainfall), we determine the number of pentads in the season as a whole (cumulatively) in which the percentage deviation of pentad rainfall from long-term observed climatology was below the respective pentad coefficient

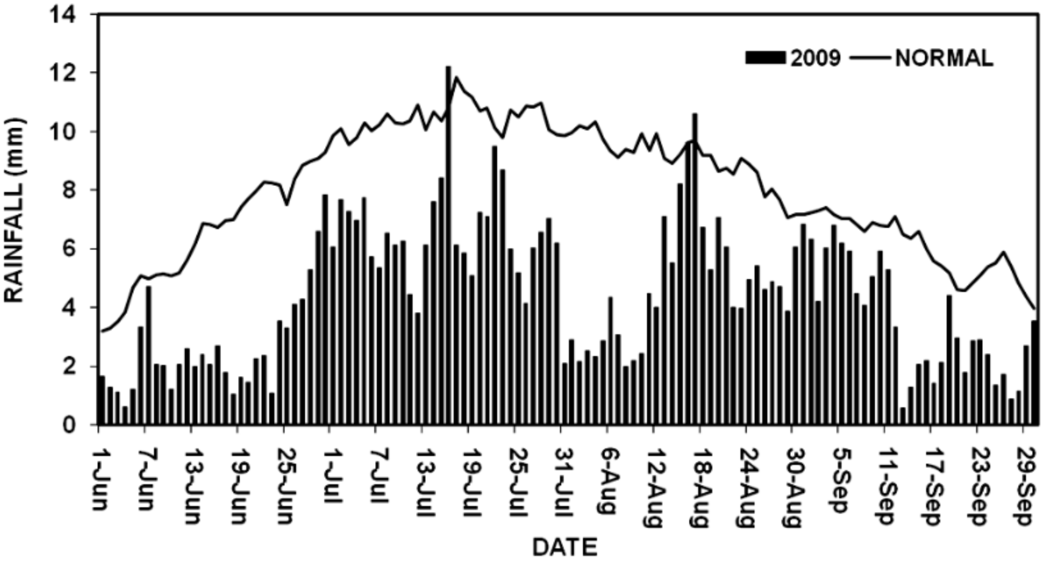


Fig. 2. Observed day-to-day fluctuations of ISMR for the monsoon season of 2009

coefficient of variability (CV). CV is defined as (SD/Mean) X100.

From 2009 onward the LRF of monsoon is produced by CDAC and is communicated to IMD based on all-members ensemble average (deterministic forecast). Our forecast also happened to be unsatisfactory for the season of 2009 as it had predicted seasonal ISMR to be 96% of the normal (-4%) whereas in the observed data it was 78 % of normal (-22%) showing vast difference between forecast and observations.

Section 2 in the paper gives the background of the model as well as the data used and methodology followed in this study. Section 3 tests our methodology for the year 2009 which has been a severe drought. Section 4 analyzes simulated pentad rainfall of 20-year period hindcast simulations based on all-members ensemble average to determine seasonal rainfall departures from the model climatology. Also ensemble averaging is restricted to only those individual members, which are similar to each other, based on seasonal collections of B and A events, and also based on simulations with respect of percentage anomaly ISMR for the season. Section 5 examines the El Niño-Monsoon relationship in the simulations based on our new methodology during the five warm El Niño years (1986, 1987, 2002, 2004 and 2009) and the two cold La Nina years (1988 and 1998) as well as for the near-neutral El Niño conditions for the season of 1990 and abrupt transition from warm phase El Niño to cold phase La Nina in 1994 which occurred between July and August 1994. Section 6 devoted to further discussions of the results of our present study. Summary and conclusions are given in section 7.

2. Data and methodology

The NCEP T170/L42 AGCM was used for making the seasonal monsoon simulations for the 20-year period from 1985-2004. The model used five initial conditions in first week of May every year and was forced by observed global SST conditions (Reynolds and Smith, 1994) for the months from May to September. The monthly forecast SST of National Center for Environmental Prediction (NCEP) coupled forecast system (CFS) was used as the lower boundary condition for the forecast-mode experiments for 6-year (2005-2010). The initial conditions for the model integration were provided by NCEP-National Centre for Atmospheric Research (NCAR) reanalysis-2 data (Kalnay *et al*., 1996) available at 2.5 × 2.5 degree resolution. The simulations for the month of May are not used in the study as we are concerned with the four ISM months of June to September only. The model is the same which was used in the studies of Ratnam *et al*. (2007 & 2009) with regard to its physics packages. Other details of the model are given in the NCEP Office Note 442 (2003). The model output was saved once in 24 hours of the model integration. 5-day average rainfall for the entire grid points, falling over the landmass of India, was calculated for each monsoon season for 20 years hind cast simulations and 6 years of forecast-mode runs. Similarly, pentad rainfalls for the observed rainfall of India were calculated from the data by Rajeevan *et al*. (2005). The two pentad rainfall series were

TABLE 1

IMD observed pentad-wise percentage rainfall departure from long-term climatology for the season of 2009 from pentad 1 (1-5 June) to pentad 24 (24-28 September)

Pentad	Percentage Departure of 2009 observed IMD ISMR from long term observed climatology and Category	Long-term observed pentad coefficient of variability (CV) in percentage
P1 (1-5 June)	-57.4 (B)	44.6
P2 (6-10 June)	-44.1	52.4
P3 (11-15 June)	-67.7 (B)	34.9
P4 (16-20 June)	-75.2 (B)	28.3
P5 (21-25 June)	-72.1 (B)	32.3
P6 (26-30 June)	-37.9 (B)	33.2
P7 (1-5 July)	-11.6	26.9
P8 (6-10 July)	-32.2	32.5
P9 (11-15 July)	-43.5 (B)	25.1
P10 (16-20 July)	-28.5	28.6
P11 (21-25 July)	-27.9 (B)	21.2
P12 (26-30 July)	-40.4 (B)	28.3
P13 (31 July- 4 August)	-64.4 (B)	24.3
P14 (5-9 August)	-66.9 (B)	25.2
P15 (10-14 August)	-55.9 (B)	22.7
P16 (15-19 August)	0.1	20.3
P17 (20-24 August)	-35.2 (B)	20.3
P18 (25-29 August)	-40.3 (B)	25.5
P19 (30 August-3 September)	-22.2	35.1
P20 (4-8 September)	-14	37.2
P21 (9-13 September)	-25.2	27.3
P22 (14-18 September)	-72.5 (B)	25.2
P23 (19-23 September)	-40.7 (B)	38.3
P24 (24-28 September)	-68.1 (B)	46.7

plotted for each year and inferences were drawn based on number of pentad-wise fluctuations in the model versus observations, cumulative over the season as a whole. Since the observed rainfall of India fluctuates on 10-20 day and 30-60 day modes, the filtered series of the observed and simulated rainfall were also analysed by using the model values of average of maximum and minimum amplitudes for each season in the series.

3. Features of the drought monsoon season of 2009

Monsoon season of 2009 was one of the worst drought seasons as the seasonal ISMR was in deficit by 22%. Sikka *et al.* (2010) have described the evolution of ISMR for the drought of 2009. According to them the rainfall deficiency mostly resulted in the following three spells.

(*i*) The unusual hiatus in the advance of the monsoon for nearly two weeks between 8 June and 20 June over the Karnataka coastal region along the southern part of the west coast of India near 12° N.

(*ii*) Unusual long 'break' in the monsoon which began towards the end of July and lasted up to mid-August.

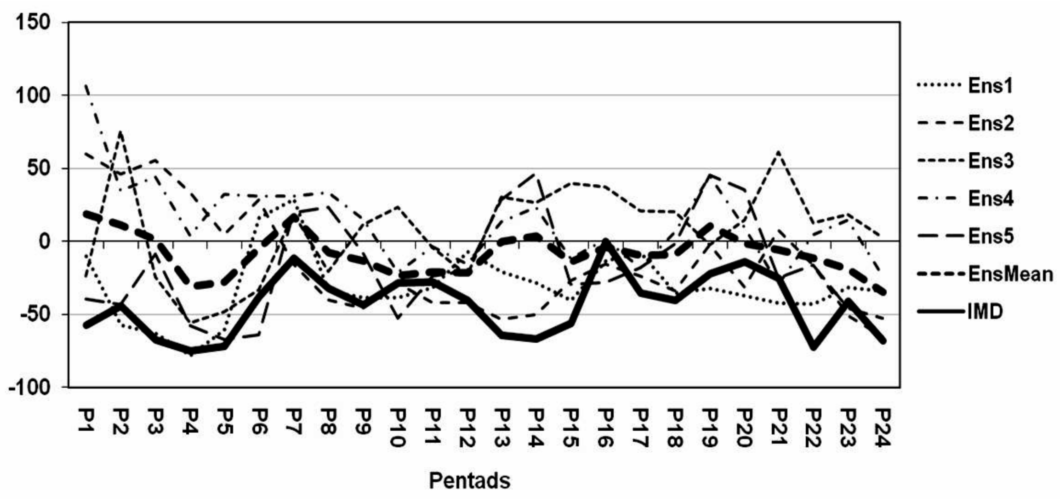


Fig. 3. Time series of percentage departure of model simulated rainfall and IMD observed rainfall from respective climatologies for the year 2009

(*iii*) Suppressed monsoon conditions during the second fortnight of September.

Due to these three long spells of suppressed ISV of the monsoon activity, the accumulated rainfall for the month of June was below the normal by 47 %, the highest for the month in the long-term record. It was 27 % below normal for August and 21 % below normal for September. As a result, the ISMR was below one standard deviation (S.D.) for three out of four months in the season (June, August and September). Fig. 2 shows the observed day to day fluctuation of ISMR for the season in which the major deficiency of rainfall in the above mentioned spells can be noticed. Table 1 shows the IMD observed pentad-wise percentage rainfall anomaly for the season of 2009 from pentad 1 (1-5 June) to pentad 24 (24-28 September). The table brings out the following features:

(*i*) Large negative departure in the pentad rainfall for IMD observed data for pentad 1 to pentad 6, in which except pentad 2 all the other five pentads had rainfall significantly below the long-term respective pentad mean rainfall.

(*ii*) Significantly below normal rainfall (by more than respective CV of the pentad) also occurred for the pentad 9, pentads 11 to 15, pentad 17, pentad 18 and pentads 22 to 24. Thus, out of 24 pentads of the season, there were 16 pentads in which the observed rainfall percentage departures were below the respective pentads CV. This was a very unusually long number of below rainfall pentad events during which the rainfall remained significantly below the pentad climatological normal. Not a single pentad witnessed rainfall significantly above the respective observed climatological CV. Therefore the season as a whole performed much below (-2 SD) the normal ISMR.

The abnormal circulation features (Sikka *et al.*, 2010) of the season were:

(*i*) Evolving warm El-Niño episode in the equatorial central Pacific Ocean from April/May and amplifying El Niño warming during June to September which continued till the end of the 2009.

(*ii*) Long monsoon break in August.

(*iii*) Quasi-persistent mid-tropospheric anticyclone from 700 hPa to 300 hPa levels throughout the season.

(*iv*) Quasi-persistent trough in mid-latitudes westerlies along 60°-70° E over Iranian-Afghanistan region.

(*v*) Invasion of dust aerosols over the Indo-Gangetic plain and central India during June and August months and the curtailment of moisture within the lower troposphere only (Krishnamurti *et al.*, 2010).

We now analyse the evolution of the drought based on pentad mean rainfall for the model as well as the observations. Fig. 3 shows the percentage departure of pentad mean rainfall for the IMD observations, model individual ensemble members and the all-members ensemble average. The two curves, IMD observations and all-members ensemble averages in the season are widely

TABLE 2

The numbers of pentads out of 24 pentads in which the model simulated rainfall for 2009 ISMR were below CV (B) and above CV (A) of the IMD observed long-term climatology of the respective pentad. Seasonal percentage departure of rainfall values are given in bracket

Ens1	Ens2	Ens3	Ens4	Ens5	Ensemble Average	IMD	Average B and A of 5 ensemble members
11 B	11 B	3 B	1 B	10 B	1 B	16 B	7.2 B
0 A	1 A	5 A	7 A	4 A	3 A	0 A	4.0 A
(-13.1)	(-10.3)	(7.3)	(10.0)	(-16.1)	(-4.0)	(-22.0)	

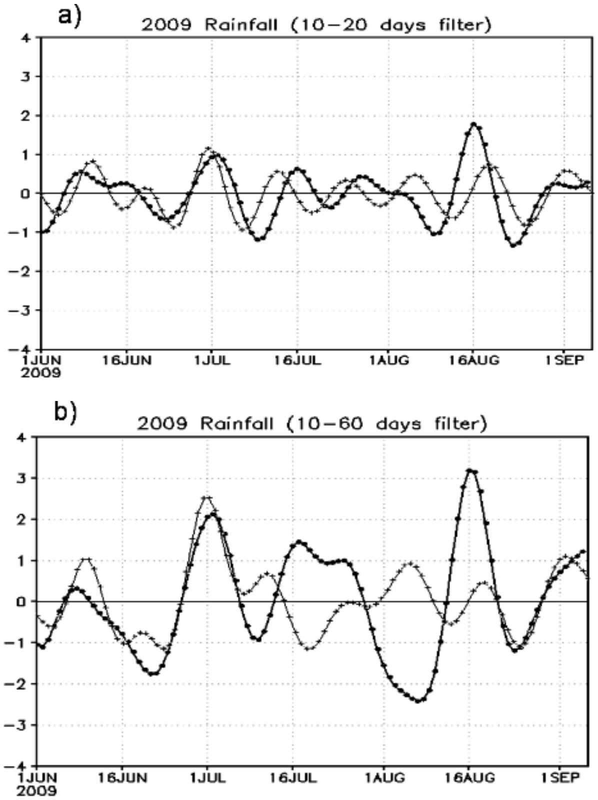
separated from pentad 1 (1-5 June) to pentad 5 (21-25 June) but the separation becomes small between pentad 10 (16-20 July) and pentad 12 (26-30 July). The two curves get separated again from pentad 13 (31 July-4 August) to pentad 15 (10-14 August) and again from pentad 22 (14-18 September) to pentad 24 (24-28 September). The other ensemble members show large deviation from the mean on pentad to pentad basis.

Analysis of the data for the model simulated pentad rainfall for the individual ensemble members and all-members ensemble average showed the following features.

(*i*) In the all-members ensemble average there was one pentad (P7) in which the percentage rainfall departure was below its CV and no pentad witnessed rainfall above its CV. Thus, the pentad-wise all-members ensemble average for the season as a whole did not show any resemblance with the observed pentad rainfall. The observed pentad rainfall had 16 pentads significantly below the normal (B category).

(*ii*) Again, for each pentad there was no consensus among the individual ensemble members as the number of pentads within the season departed both on the negative (B category) and the positive (A category) side in terms of respective pentad CVs. This indicated that by averaging of all ensemble members, the percentage departure for the individual ensemble members was smoothed out and as such little significant signal remained of the persistent pentad anomalies in the all-members ensemble average rainfall. Incidentally, for the pentad 7, three out of five ensemble members have large negative departures (less than 50%) from the respective climatology.

We compared the performance of the pentad-wise percentage departure of rainfall for individual ensemble members with the respective observed climatological CVs. Table 2 shows the ensemble-wise performance of the pentad rainfall in terms of the B and A events. By this way we isolated the numbers of B and A events for the season as a whole for each ensemble member, all-members ensemble average and IMD observed series for the season of 2009. Analysis of the table showed somewhat irregular behaviour with respect to number of B and A events for each ensemble member as well as for all-members ensemble average. Thus, the reproducibility of pentad rainfall among the ensemble members on pentad to pentad basis was not right. However, when B and A events are accumulated within the season, the similarity or reproducibility on season basis among selected individual members of the ensemble becomes clearer. The average of B and A for all-members ensembles is 7.2 B and 4.0 A events respectively. The all-members ensemble average smoothed out the individual ensemble members consistent behavior which was present in the individual members pentad rainfall series. Ensemble1, ensemble2 and ensemble5 are close to each other. They are also somewhat close to the observed total B and A events in the IMD series. Thus, we find that the all-members ensemble average for the season had lost any resemblance to the observed seasonal behaviour with respect to B and A events. However, B and A events for the season as a whole had good resemblance to each other for three ensemble members (ensemble1, ensemble2 and ensemble5). The seasonal rainfall forecasts for ensemble1, ensemble2 and ensemble5 and average of these three similar ensemble members were -13.1%, -10.3%, -16.1% and -13.2% respectively against the observed value of -22% of the normal. Hence, these three individual ensemble members as well as the average based on these three members did show the signature of a drought but when they were taken together for averaging with other two ensemble members (ensemble3 and ensemnle4), the ensemble mean smoothed out the signal and the predicted ISMR became only -4% of the normal (within the category of a normal season). The number of B events in ensemble5 resembled more closely to the observed number of B events. Thus, the evolution of the monsoon which was found in the ensemble1, ensemble2 and ensemble5 was close to the observed behaviour for the



Figs. 4(a&b). Filtered rainfall series for IMD observations and all-members ensemble averages for the monsoon season of 2009. (a) 10-20 days (b) 10-60 days. Solid line for IMD and dotted line for the model

season as a whole. It may be stated that the forecast SSTs in the equatorial Pacific Ocean basin by the CFS model were less warm (as the model has cold bias) than the observed SST and hence even though the AGCM produced drought monsoon with our methodology, the rainfall deficiency was less than the observed.

In the above comparison, it is only implied that the number of B and A events for the season as a whole should closely match amongst each other for averaging purpose. We do not, by any means, imply that the matching should agree on individual pentad to pentad basis as climate simulations under forced SST boundary conditions are required to match the observed behaviour on seasonal basis and not for individual events. This is because we are not using the model for medium-range weather forecast based on initial conditions, but having guidance from the model in simulating overall behavior of impending ISMR on the scale of the monsoon season and also for India as a whole. In case the total matching of B and A events for the simulated rainfall does not agree among the ensembles, the all-members ensemble average would not give clear signal about the impending LRF of the ISMR. A priory, it is very difficult to decide as to which ensemble member is to be chosen for the final forecast when ensemble members do not resemble among each other (low seasonal reproducibility of ISMR) in a reasonable manner. The above analysis showed that the model has the capability to foreshadow an extreme event, like the monsoon drought of 2009, provided we lay faith on individual ensemble members resembling each other and averaging is performed on those resembling (similar) members only. It is also possible to give a probability of occurrence of drought based on ratio of resembling members and total members in the ensemble. It is concluded that for the season of 2009 forecast resulting from similar ensemble members (1, 2 and 5) or ensemble average based on averaging over these three ensembles would have foreshadowed the impending drought for the 2009 season. Also the probability of drought occurrence was 60 per cent – indicating a considerable shift from climatological probability of drought being only 17%.

The observed monsoon rainfall is known to fluctuate on different temporal scales (synoptic scale 3-5 days; extended range 10-20 days; low frequency intra-seasonal scale 30-60 days). We have also examined ensemble average model rainfall and observed rainfall in two bands 10-20 days and 10-60 days. For this purposes the daily simulated and observed rainfall were subjected to Lanczos filter, which allowed us to retain maximum signal in the two selected frequency bands. Figs. 4 (a&b) show the comparison between the filtered ensemble average model rainfall series for 10-20 days and 10-60 days bands. It was observed that the amplitude of fluctuations on the average was about 50% higher in the IMD observed rainfall compared to the all-members ensemble average rainfall. In the observed rainfall series the rainfall fluctuations are higher as the pentad rainfall would depart widely from each other in most of the spells but the averaging over all-members ensemble would not give this signal unless 3 to 5 ensemble members were close to each other. Even though the model has fidelity to show wide fluctuations in pentad rainfall and even extended spells of higher or lower values of rainfall over 2 to 5 pentad periods in individual member simulations, but in the all-members ensemble averaging, the signal is smoothed out.

4. Analysis of pentad averages of rainfall for the extreme ISMR seasons in relation to the observed climatological pentad rainfall CVs

We now analyse the number of B and A events for the 24 pentads for the observed droughts (1986, 1987, 2002 and 2004) in ISMR series and observed excess/near-excess monsoon years (1988, 1990, 1994) and for 1998 which was on the positive side of the normal (+5.7%)

TABLE 3

The numbers of pentads out of 24 pentads for drought and excess/near-excess ISMR seasons in which the model simulated rainfall were below respective CV (B events) and above CVs (A events) of the IMD observed long-term climatology of the respective pentad. Seasonal percentage departure of rainfall values are given in bracket

	Ens1	Ens2	Ens3	Ens4	Ens5	Ensemble Average	IMD
				(a) For observed drought ISMR seasons			
1986	6B	2B	8B	3B	6B	1B	7B
	4A	7A	2A	3A	2A	1A	3A
	(-6.4)	(7.4)	(-7.3)	(1.5)	(-7.7)	(-2.5)	(-13.7)
1987	2B	10B	8B	14B	1B	4B	6B
	5A	2A	3A	3A	3A	0A	1A
	(16.8)	(-17.1)	(-17.0)	(-25.1)	(15.4)	(-5.4)	(-13.2)
2002	7B	6B	9B	1B	5B	6B	7B
	1A	1A	2A	5A	5A	1A	1A
	(-17.0)	(-13.5)	(-9.0)	(21.0)	(-1.5)	(-4.0)	(-17.4)
2004	1B	2B	4B	7B	5B	3B	5B
	3A	3A	2A	4A	0A	1A	3A
	(8.9)	(6.9)	(-9.1)	(-1.3)	(-6.9)	(-0.3)	(-13.2)
2009	11 B	11 B	3 B	1 B	10 B	I B	16 B
	0 A	1 A	5 A	7 A	4 A	3A	0 A
	(-13.1)	(-10.3)	(7.3)	(10.0)	(-16.1)	(-4.0)	(-22.0)
				(b) For observed excess/near-excess ISMR seasons			
1988	3B	0B	0B	0B	0B	0B	1B
	2A	12A	7A	14A	8A	8A	7A
	(-8.7)	(25.5)	(22.8)	(39.6)	(22.8)	(20.4)	(22.6)
1990	5B	8B	3B	8B	4B	4B	1B
	2A	2A	2A	5A	3A	1A	6A
	(-5.5)	(-13.7)	(-1.1)	(-1.0)	(-0.7)	(-4.4)	(9.0)
1994	8B	14B	11B	11B	10B	8B	1B
	1A	1A	2A	1A	0A	0A	4A
	(-23.6)	(-28.8)	(-22.5)	(-19.9)	(-26.6)	(-24.2)	(12.2)
1998	4B	0B	0B	3B	7B	1B	0B
	7A	10A	9A	9A	2A	8A	6A
	(13.1)	(29.0)	(21.3)	(16.7)	(-32.6)	(9.5)	(5.7)

but in simulated all-members ensemble average and individual ensemble members it was excess year (9.5%). This analysis is given in the Table 3. The table is divided into two parts. The first part is for the four drought years Part (a) and the second part is for four excess/near-excess years Part (b). We notice that in the IMD observed rainfall series, the number of B and A events during the extreme seasons occurred in sequences of four or more similar pentad events during a season. This is due to the well known ISV of ISMR. Such behaviour on intra-seasonal scale was also noticed to some extent in the all-members ensemble average series but to a much lesser extent than in the IMD observed series. However, in the simulated individual ensemble member ISMR for different years, particularly in extreme ISMR seasons, the number of B and A events occurred in several sequences similar to what was found in IMD observations, though no matching was observed for individual sequences. We do not expect one to one matching as in the climate simulation but expectation of matching is only for the accumulated seasonal behaviour only.

4.1. *Analysis of number of B and A events for model ensemble average with respect to the IMD series*

4.1.1. *For the observed drought monsoon years*

For the drought year in the IMD series there were 5 to 7 B events for the years 1986, 1987, 2002 and 2004 and 1 to 3 of A events for the same years. In the cases of all-members ensemble average the picture is different. Except for the drought year of 1987 and 2002, in which there was preponderance of B events (4 B and 6 B respectively) over A events (0A and 1A respectively), the case is not same for the other two drought years, where no clear preponderance B over A (1986 and 2004) was noticed. However, for individual ensemble member ISMR, the case is quite different as 3 to 4 members show preponderance of B over A events suggesting drought monsoon for all the years (1986, 1987, 2002 and 2004), similar to what was noticed in the drought monsoon season of 2009, discussed in Section 3.

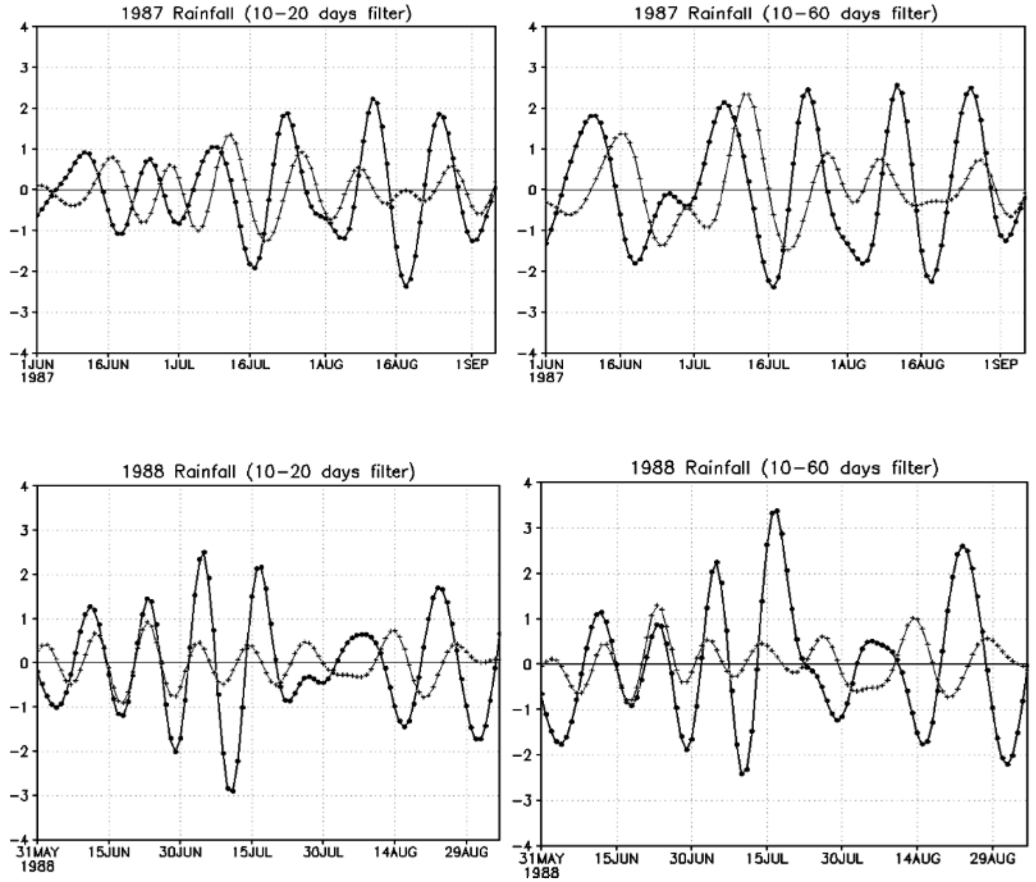


Fig. 5. Filtered rainfall series for the monsoon season of drought year 1987 (top panel) and excess year 1988 (bottom panel) for all-members ensemble average. Solid line for IMD and dotted line for the model

4.1.2. *For the observed excess/near-excess monsoon years*

For the excess monsoon years of 1988 and 1994 in the IMD series, there was a clear preponderance of A events over B events in the season. Similarly, in the all-members ensemble average also preponderance of B events over A events for the years 1988 is observed. However, for the year 1990 and 1994, which were near-excess or excess monsoon years in the observed series, no preponderance of A events over B events was noticed and instead preponderance of B over A events was observed in 1994. These are the two years (1990 and 1994) in which the model forecast departed widely from the observed seasonal ISMR as observed seasonal rain was 9.0% and 12.2% of the long-term normal in the respective cases but the model simulated rainfall was -4.4% and -24.2% of the normal. As such the difference between the observed and model simulation became 13.4% and 36.4% as the model under predicted seasonal rainfall by nearly 1.5 and 3.0 times the SD of the observed series in 1990 and 1994 seasons respectively. The observed ISMR was above normal but the model forecast was for below normal. These are the two years in which the signal is completely opposite in the all-members ensemble average with respect to IMD observations. Particularly for the season of 1994 the model predicted drought based on all-members ensemble average where the observed ISMR was excess and the difference between observed and simulated seasonal rainfall departed by two categories (excess vs. drought). For the near-normal (5.7%) ISMR in the observed series for 1998 season, we observe preponderance of A events in the all-members ensemble average.

4.1.3. *Analysis of the filtered rainfall series*

Just like for the year 2009, we have also examined two filtered series for all the 20 years (1985-2004), which have been used in this study for preparing the climatology

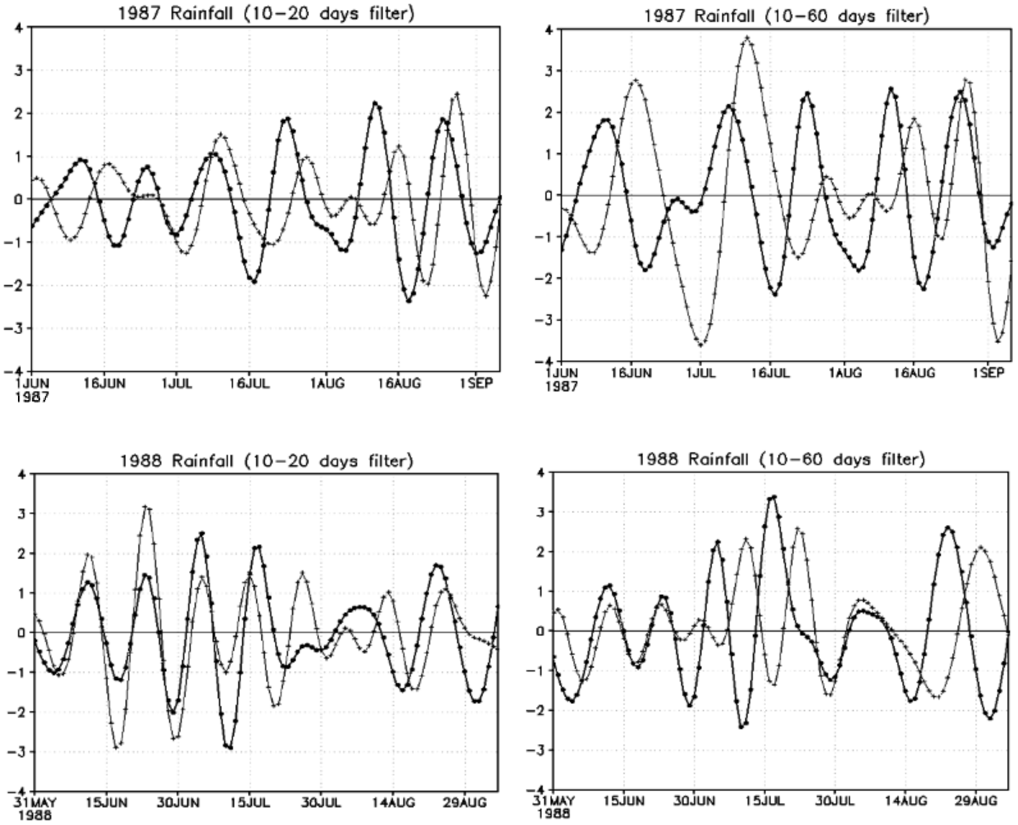


Fig. 6. Same as Figure 5 but for similar-member ensemble averages

of the model. The analysis of two filtered series of 20-year simulation showed that the amplitudes of rainfall fluctuations either on the positive or negative side in the observed series were much larger than in the all-members ensemble average series. However, in individual ensemble member series fluctuations in daily rainfall were similar to those in the observed series for the season as a whole (cumulatively) but not on day to day basis. This is expected as we are comparing the IAV and not validating the simulations for medium range forecasting. The two typical case for the drought year of 1987 and excess year of 1988 are provided in the Fig. 5 for all-members ensemble average basis. Just like in the case of 2009 (discussed in section 3), the amplitudes of the rainfall fluctuations in IMD observed filtered series are much higher than in the all-members ensemble average filtered series. Fig. 6 provides the same filtered series but for similarity based ensembles averages. Unlike in Fig. 5, the amplitude fluctuations on daily basis have enhanced.

4.2. *Analysis of number of B and A events for individual members of the ensemble with respect to the IMD series*

Table 4 shows the performance of seasonal forecast based on the individual ensemble members and average of similar ensemble members with respect to the observed seasonal rainfall for extreme monsoon seasons.

4.2.1. *For the observed drought monsoon years*

The number of B and A events in the individual ensemble members differ considerably in four different drought years under consideration. For the year 1987 and 2002 individual ensemble members are predominately giving higher number of B over A events (1987: ensemble 2, 3 and 4) and (2002; ensemble1, 2 and 3). For the year 1986 there were only two ensemble members (ensemble 3 and 5), which indicated preponderance of B over A events (8 B and 2 A events; and 6 B and 2 A events respectively).

TABLE 4

Simulated seasonal ISMR based on average of similar individual ensemble members (in terms of A and B events) and their average for the drought and excess/near-excess ISMR seasons with respect to the IMD ISMR and all-members ensemble average. Values are given in percentage departure from the respective climatologies

Year	Forecast based on similar ensemble members (Ensemble number are in bracket)	Forecast based on averages of similar ensemble members	IMD ISMR observations	all-members ensemble average
	(a) For observed drought ISMR seasons			
1986	-7.3 (Ens3), -7.7 (Ens5)	-7.5	-13.7	-2.5
1987	-17.1 (Ens2), -17.0 (Ens3), -25.1 (Ens4)	-20.0	-13.2	-5.4
2002	-17.0 (Ens1), -13.5 (Ens2), -9.0 (Ens3)	-13.2	-17.4	-4.0
2004	-9.1 (Ens3), -6.92 (Ens5)	-8.0	-13.2	-0.3
2009	-13.1 (Ens1), -10.3 (Ens2), -16.1 (Ens5)	-13.2	-22	-4
	(b) For observed excess/near-excess ISMR seasons			
1988	25.5 (Ens2), 22.8 (Ens3), 39.6 (Ens4), 22.8 (Ens5)	27.6	22.6	20.4
1990	-5.5 (Ens1), -13.7 (Ens2)	-9.6	9.0	-4.4
1994	-23.6 (Ens1), -28.8 (Ens2), -22.5 (Ens3), -19.9 (Ens4), -26.6 (Ens5)	-24.2	12.2	-24.2
1998	29.0 (Ens2), 21.3 (Ens3), 16.7 (Ens4)	22.3	5.7	9.5

For the drought year of 2004, only one member (ensemble 5) showed clear preponderance of B over A and ensemble 4 showed such a performance but to a lesser extent. As such individual similar ensemble average clearly could foreshadowed drought seasons for 1987 and 2002, but in the case of 1986 and 2004, the selection only foreshadowed near-drought (CV of model climatology is 8 per cent).

4.2.2. *For the observed excess/near-excess monsoon years*

For the excess/near-excess year in IMD observations (1988, 1990, 1994) and positive side of the normal for 1998 the behaviour is rather mixed. For the year 1988 and 1998 (La Nina years) four and three individual member average respectively give clear signal for an impending excess season. However, for the near-excess year of 1990 and the excess year of 1994 in the IMD series, similar ensemble averaging would indicate drought in both the years, as discussed previously in Section 4.1.2. This is somewhat puzzling but these two years were conspicuous by slightly warm SSTs over the central equatorial Pacific Ocean but not to the extent of reaching a warm El Niño condition. These two years also witnessed developing IOD (Saji *et al*., 1999; Webster *et al*., 1999) in the eastern equatorial Indian Ocean or EQUINOO-like developments (Gadgil *et al*., 2004 and 2007). As such the model individual ensemble members were responding to the warmer SST conditions in the equatorial Pacific Ocean and did not respond to the developing IOD or EQUINOO conditions in the equatorial Indian Ocean. This shows that AGCM we have used is quite sensitive to warm SST boundary conditions in the equatorial Pacific Ocean and would not respond to the local forcing of IOD/EQUINOO. We discuss this aspect further in Section 5.

The relationship between ENSO and ISMR has been studied since early 1980s (Sikka, 1980; Parthasarathy and Pant, 1981; Rasmusson and Carpenter, 1983) based on observations and some authors have tried to show that ENSO-Monsoon connections have weakened in the last 3-4 decades (Krishna Kumar *et al*., 1999; Kinter *et al*., 2002). However, the last three droughts in ISMR (2002, 2004 and 2009) show that the ENSO-Monsoon relationship is still strong. Similarly, since the discovery of IOD in 1999 several papers have been written about the diagnostic and prognostic aspects of IOD and its relationship with ISMR. For details reference may be made to Behera *et al*. (1999); Yamagata *et al*. (2004), Ashok *et al*. (2004) and Krishnan and Swapna (2009). Again, Behera *et al*. (1999) have examined in detail the unusual ocean-atmosphere coupling in the tropical Indian Ocean during 1994. Krishnan *et al*. (2010) have used

Indian Ocean observed SSTs for the 1994 IOD event as well as other events (1983, 1997, 2006 and 2007) in a modeling study and showed that the ongoing IOD events resulted in excess ISMR. Similarly Ashok *et al.* (2004) examined the individual and combined influences of ENSO and IOD on ISMR and found that both phenomena, individually and combined, would influence performance of ISMR. Our study also shows that in the years 1994 and 1998, developing IOD in the eastern pole of the IOD, resulted in enhanced ISMR even though the SSTs in the equatorial central Pacific Ocean remained warm. Thus, the real atmosphere appears to be sensitive to IOD/EQUINOO events in spite of lower amplitudes of SST variations in the equatorial Indian Ocean as compared to the equatorial Pacific Ocean. The AGCM on the other hand, has high sensitivity to El Niño region and could not respond to evolving IOD/EQUINOO events thereby producing drought forecast for 1994.

4.3. *Matching of the individual ensemble members with respect to the seasonal percentage departure from normal*

It is expected that the amplitudes of B and A events in each pentad may differ from each other. We have adopted another strategy to match the individual ensemble members. We have calculated the seasonal percentage departure of ISMR from normal as simulated by each individual ensemble member and as given by all-members ensemble average and compared these values with the IMD seasonal rainfall observed data. We notice that for the drought years 1986, 1987 and 2004 the matching are identical with the matching in respect of seasonal incidence of B and A events. For the year 2002 instead of three identical members with respect to B and A events one extra ensemble member has come in case of matching with percentage departure from the seasonal climatology. On the whole the matching between the two methods can be said to agree well with each other. For the excess years the matching between two methods is exactly identical in the case of 1994 and 1998 whereas for the year 1988 one extra member has come in the matching based on observed ISMRs seasonal percentage departure from normal. However, for the year 1990 the matching between the two methods cannot be said to be in satisfactory agreement primarily because there is a big scatter in the matching with respect to B and A events whereas in respect of percentage departure from normal the matching is quite reasonable. This leads us to the conclusion that it would be preferable to decide the matching on the basis of seasonal percentage departure of normal method.

We notice that for the observed drought years, the average departure predicted by the model based on similarity amongst ensemble members are considerably on the negative side of the normal and the difference between the observed and simulated rainfall is small. However, in the case of excess years the difference between the IMD observations and the method followed by us, based on similar matching, is good for La Niña years of 1988 and 1998, but for the year 1990 and 1994 the model simulated rainfall is totally opposite to what happened in the IMD observations. The model based forecast would suggest drought season but the in observations the two seasons turned out to be near-excess and excess ISMR. However, in a recent study by Pattanaik *et al.* (2010), it has been shown that the CFS model produced the improved correct signal of ISMR in both the years when the CFS model is validated on the grids over the landmass of India. This would suggest that CFS performed much more realistically compared to AGCM used by us even though observed SSTs were used in our study for 1990 and 1994. Thus the coupled processes are able to provide better guidance for ISMR than the process which occurs under the AGCM forced by SST boundary condition. However, it is worth mentioning that CFS model has a cold bias and thus it simulates enhancement of IOD as well as less warming over the El Niño region which would allow it to respond to the evolving IOD event as simultaneous the El Niño warming is being reduced. The CFS model had simulated enhanced amplitude of developing IOD event in 1994 than was seen in the observed SST and this enhanced cooling the eastern mode of the IOD favoured excess performance of the ISMR through enhanced regional SST forcing as CFS model has a cold bias over the equatorial Indian Ocean. By this even for the wrong reason (cold SST bias) the CFS model produced higher rainfall (near-excess ISMR) for 1990 and 1994. However, in the observed SSTs used by AGCM, the El Niño warm phase had higher magnitude and Indian Ocean cooling was also lower and so the AGCM produced drought or deficiency of ISMR for 1990 and 1994 season. Janakiraman *et al.* (2010) have also reported that CFS model produces more skillful ISMR forecast than the AGCM. Our AGCM was unable to set up observed teleconnection with IOD. For the drought years of ISMR series (1986, 1987, 2002 and 2004), warm El Niño phases was amplifying and therefore several individual members of the model responded to the warm El Niño boundary conditions and hence correctly foreshadowed drought monsoon. Non-agreement of the model simulations for 1990 and 1994 has been already discussed in sub section 4.2.

4.4. *Performance of the model in the forecast mode*

As mentioned earlier, the model has been run for six years from 2005 to 2010 in the forecast mode, using the NCEP CFS forecast SST from June to September, as available in the month of May. Fig. 1(b) shows the

TABLE 5

Performance of forecast mode experiments of all member ensemble average seasonal ISMR for the model in comparison to IMD observations. Forecast categories are given in bracket. (E-Excess; N-Normal; and D-drought)

ISMR season	Model simulated all member ensemble average forecast (percentage departure from normal)	IMD observed ISMR (percentage departure from normal)	Difference in forecast category between all-members ensemble average and IMD ISMR
2005	10.7 (E)	-2.7 (N)	1
2006	9.8 (Near-E)	-2.1 (N)	1
2007	9.5 (N)	5.5 (N)	0
2008	3.4 (N)	-2.3 (N)	0
2009	-4.3 (N)	-22 (D)	1

predicted and observed rainfall in the form of percentage departure from the respective climatology. Of these six years, 2009 happened to be very severe drought and we have already discussed in Section 3 the detail of our analysis. Similar individual ensemble members with similar pentad rainfall fluctuations indicated impending drought for 2009 season though all-members ensemble average indicated deficient rainfall but within the normal monsoon category. The other five years 2005, 2006, 2007, 2008 and 2010 were all near-normal monsoon seasons. Even though the difference between all-members ensemble average and observed ISMR was somewhat quite large but the model simulation and observed ISMR remained in the same category.

Table 5 shows the performance of the all-members ensemble average model simulations for the season as a whole in comparison to the IMD observations. Table shows that the model over predicted the ISMR by a considerable margin in the year 2005 (13.4%), 2006 (11.9%) and 2009 (19%), which are one category difference (excess over normal). However, for two years 2007 and 2008, the model prediction and IMD observations are close to each other within 4 to 6% of the normal. We have already discussed in section 3 that the model prediction could be improved by adopting similar member averaging methodology. This was because as in the cases of the drought of 1986, 1987, 2002, 2004 and 2009, four years happened to be an evolving warm El Niño event prior to the beginning of the monsoon season or peak phase of warm El Niño (1987). We now diagnose the model forecast different by one category (on the positive side of the normal) in the two year 2005 and 2006.

The SST anomalies over Niño3.4 region from May to September for the year 2005 were 0.4, 0.6, 0.4, 0.2 and -0.1 °C respectively and mostly slight warm conditions. For the year 2006 also the SST anomalies over this region from May to September were 0.2, 0.4, 0.3, 0.5 and 0.7 respectively that is slightly on the warm side. Thus in the season of 2006 El Niño-like SSTs emerged in August and persisted till January 2007. Since our model has used forecast SSTs from CFS, we find that the forecast SSTs over Niño 3.4 region from May to September were 0.4, 0.2, 0.0, -0.1 and -0.2 °C respectively for the year 2005 (neutral El Niño). Similarly the CFS SSTs from May to September were 0.2, -0.1, 0.0, 0.1 and 0.2 °C respectively for the year 2006 (Neutral El Niño).

The observed and forecast SSTs were in near-neutral El Niño conditions for 2005 and 2006 seasons. The model did not respond to near-neutral SSTs over central equatorial Pacific Ocean and instead produced higher ISMR values compared to the observed ISMR because of cold bias over EEIO. To sum up, we are able to validate the potential predictability of the model for drought years with respect to El Niño-Monsoon relation in our hindcast run, if we adopted the technique based on similar member ensemble averaging. Also, it has been validated for the drought forecast of 2009. However, for 2005 and 2006 seasons, the prediction of the CFS SST on Niño 3.4 region had not matched the observed conditions and hence the model predictions deviated by one category.

For the season of 2010, we used 10-member ensembles and the all-members ensemble average foreshadowed 15% departure of ISMR for the season making the season as one of excess ISMR. However based on our technique of similar member ensemble averaging on pentad rainfall basis, the forecast could be 17.4% of normal (under excess ISMR category) as 8 ensembles (ensembles 1, 2, 3, 5, 6, 7, 9, 10) were quite similar to each other based on incidence of B and A events on cumulative basis on the seasonal scale. The all-members ensemble makes the rainfall anomaly as 15.3% again in the excess ISMR category. The signal for the season of 2010 either on the basis of similar ensemble average basis or on all-members ensemble average basis was for excess ISMR category. However, the observed ISMR for 2010 ended as normal (102%) but on the positive side. Hence, the model performance differed by one category in this La Nina year. For the year 2010, the CFS SST forecasts anomalies over Niño3.4 region from May to September were -0.5, -1.4, -2.2, -1.1 and 0.3 °C respectively are making June, July and August as under La Nina conditions. The CFS forecasts anomaly for the EEIO were -0.1, -0.3, -0.6, -0.7 and -0.1 °C respectively. Hence, the enhanced cooling in the CFS model for the equatorial Pacific and equatorial Indian Ocean resulted in excess ISMR prediction. However, the observed SSTs from May to September for the Niño3.4 region were -0.1, -0.5, -1.0, -1.2 and -1.5 °C respectively and that for the EEIO region were 0.9, 0.8, 0.5, 0.6 and 0.4 °C respectively and hence the ISMR performed near-normal category. The excessive cooling in Niño 3.4 and EEIO regions in CFS forecast had led to the excess ISMR season in 2010 compared to observations.

5. El Niño - Monsoon relationship

The year 1986, 1987, 2002 and 2004 were the years of evolving warm El Niño events and as such the model simulations, based on our matching methodology either by B and A events or by anomaly of ISMR on seasonal basis, would have given correct forecast in the category of drought. However, all-members ensemble averaging for these four years, because of some dissimilarity in the ensemble members, reduced the magnitude of negative departure from normal and as such for all these years the all-members ensemble average had pointed to a normal monsoon category. For the case of 1987 which was a major drought year, the simulated rainfall based on both of the proposed methodologies, would have been -20% against the IMD observed -19%, a very good foreshadowing by the model. Similarly for the excess year of 1988, the signal from the simulation was excellent as all the five members simulated more than 11% positive departure from normal and the average was +20% against the IMD observed value of 22%. For the year 1990 the model simulation, based on similarity within the individual ensemble members indicated negative departure of -9.6% (under near-drought category) whereas in the observed IMD rainfall it was a near-excess ISMR season (9.0%). However, for the case of 1994, in which all-members ensemble average also showed highly negative departure from the normal (average showing -24.2 % departure from normal which under extreme drought category below 2 SD), the observed IMD rainfall was near +12.2% (excess year). Therefore, the simulations for 1990 and 1994 seasons fell quite apart from the reality making the model based forecast depart by two categories (drought in simulation vs. excess in observations). This was totally unacceptable guidance from the model. The model was strongly responding to persisting warm El Niño conditions in the equatorial Pacific Ocean. On the contrary the CFS produced more satisfactory forecast for these two years (1990 and 1994) because of the cold SST bias of the model, already discussed in Section 4.3.

The two years 1990 and 1994, in which the model gave simulations quite contrary to the observed IMD data, were the years of persistent warm SST conditions prevailing over Niño 3.4 region and evolving cold SSTs in EEIO (IOD mode). As such the model responded to these boundary conditions and produced drought simulations. Gadgil *et al.* (2004 & 2007) have shown that in these two years the EQUINOO signal in the equatorial Indian Ocean was in opposite phase to the persistent warming in the equatorial Pacific Ocean. Also, 1994 was the season of strongly evolving IOD mode. Because of this the real atmosphere responded more favorably to the favorable IOD/EQUINOO conditions for the regional monsoon. These authors have also shown that the matching between the drought and excess monsoon years is perfect provided both the El Niño signal prevailing over the Pacific Ocean and the emerging signal over the equatorial Indian Ocean are considered together.

As a result of intensive El Niño prediction activity under TOGA, the dynamical coupled models have shown fidelity to predict evolving warm El Niño as well as cold La Nina phase over the equatorial Pacific Ocean by 6 to 12 months in advance. Hence, emerging El Niño/La Nina events could be factored in dynamical forecast system of the ISMR to provide good guidance for drought/excess monsoon conditions. However, skillful IOD/EQUINOO signal predictions are needed for a better forecast of the seasonal evolution of the ISMR as there could be years like 1994 in which the model responded to the El Niño signal and ignored the emerging IOD/EQUINOO signal. Therefore effort should be made for monitoring the emerging IOD/EQUINOO from April to June as well as in predicting the signal three to six months prior to the event, similar to the case for the warm El Niño and cold La Nina event predictions over the equatorial Pacific Ocean. Pattanaik and Kumar (2010) have mentioned that the CFS forecasts are not good for the equatorial Indian Ocean, particularly in the eastern pole of the IOD mode. Also, the CFS SST forecasts suffer from a cold bias.

We provided in Table 6 the Niño 3.4 SST anomaly for the 9 years (5 drought years and 4 excess/near-excess years) which we have considered in this study. The table shows that out of four drought years (1986, 1987, 2002 and 2004) emerging El Niño signal was seen in three years 1986, 2002 and 2004 whereas the peak phase of

TABLE 6

Niño3.4 SST anomaly for April to September for the five drought ISMR seasons and four excess ISMR seasons

Year	April	May	June	July	August	September	Assessment of El Niño/La Nina conditions
(a) For observed drought ISMR seasons							
1986	-0.25	-0.26	0.19	0.29	0.45	0.09	Emerging El Niño
1987	1.1	0.99	1.53	1.73	1.88	1.75	Peak El Niño
2002	0.26	0.39	0.94	0.90	1.08	1.19	Emerging El Niño
2004	0.17	0.29	0.27	0.61	0.83	0.83	Emerging El Niño
2009	-0.18	0.27	0.62	0.86	0.82	0.83	Emerging El Niño
(b) For observed excess/near-excess ISMR seasons							
1988	-0.36	-1.28	-1.38	-1.51	-1.46	-1.21	Peak La Nina
1990	0.33	0.30	0.09	0.18	0.35	0.11	Neutral El Niño
1994	0.22	0.28	0.49	0.28	0.65	0.36	Neutral El Niño
1998	0.87	0.71	0.78	-1.14	-1.22	-1.04	Transition from El Niño to la Nina in July

ongoing warm El Niño of 1986 was observed in the 1987 season. The observed and simulated atmosphere responded as per the warm El Niño-monsoon relationship. For the excess years, we noticed that 1988 was a strong La Nina year and the model forecast and observed monsoon rainfall also agreed in respect of this excess monsoon season. The year 1998 is a peculiar year in which the El Niño condition of 1997 persisted till June and the La Nina conditions were quickly established abruptly in the month of July. The model simulation responded to the established La Nina conditions and produced guidance for the excess ISMR season. However, the observed ISMR was 5.7%, as the positive side of the normal ISMR. For the other two years 1990 and 1994 near-neutral El Niño conditions prevailed in the Niño 3.4 region though SST anomaly was slightly on the positive side of the normal. However, in 1994 ISMR the model behaviour was totally in opposition to the observed ISMR. It is very difficult to assess the causes for the observed near-excess (9.0%) monsoon year of 1990 as near-neutral La Nina conditions prevailed from April to September for this year. Perhaps the observed monsoon rainfall was responding to the favorable evolving IOD/EQUINOO signal in the EEIO though the conditions over the central equatorial Pacific SSTs was slightly warm and hence somewhat unfavorable monsoon performance. If there is success in IOD prediction just like in El Niño prediction, it would be reasonably possible to predict such extreme ISMR seasons which are not forced by equatorial Pacific Ocean boundary conditions. EQUINOO is the atmospheric part of the coupled IOD mode just like Southern Oscillation in the atmospheric part of El Niño-Southern Oscillation (ENSO) mode. Considerable understanding of the IOD and its simulation has been achieved in the last decade but its skillful prediction is yet to be accomplished and till it is done (just it has happened in the case of ENSO prediction), guidance provided from dynamical model forecast about ISMR would remain wanting, particularly in those years when El Niño and IOD/EQUINOO are evolving in opposition to each other.

6. Further discussions of the result

We have observed in the Sections 3 and 4 that even though the drought monsoon could not be predicted by the model based on all-members ensemble averaging, yet by using the special screening technique suggested by us, all the drought years could be forecast correctly in category term. For the excess observed ISMR seasons except for the year 1988 the other excess year 1994 could not be foreshadowed even by adopting the similar ensemble member technique. The year 1994 happened to be an ongoing warm El Niño event as such the model responded strongly to this boundary conditions and predicted drought whereas in the observations it was an excess monsoon season, due to the emerging favorable signal of IOD/EQUINOO mode over the eastern equatorial Indian Ocean. It is encouraging to note that the warm El Niño and cold La Nina boundary conditions, if properly prescribed to the model, could foreshadow the drought or excess monsoon year in a skillful manner provided we adopt ensemble average based on matching the individual members for seasonal similarity of pentad rainfall among individual ensemble members rather than using all-members ensemble average. We also notice that there is a bias in our model for not simulating excess/near-excess monsoon years of 1994 and 1998 which could be attributed to an excessive sensitivity of our model to warm El Niño condition and the inability of the model to respond to simultaneous evolution of IOD/EQUINOO mode in the Indian Ocean. Coupled models have yet to demonstrate consistent skill in predicting IOD/EQUINOO mode. However, as discussed in Section 4.3, we found that NCEP CFS could predict the near-excess and excess seasons of ISMR over the land grid points of India. This leads us to conclude that the ISMR prediction for the two years 1990 and 1994 could become very close to observation when coupled model was used instead of forecast based on our AGCM which forced with even observed SSTs. This is because the coupled model produced enhanced cooling over the EEIO. Thus CFS responded favourably to realistic simulation of ISMR as it produced cooler than observed SSTs in the EEIO. There is also a problem of internal variability of the model through initial conditions versus the boundary forced SST variability in ISMR. We have noticed that the reproducibility of pentad to pentad rainfall in model simulations is low but cumulatively in the season a similarity among some ensemble members is present. This similarity provides the scope in identifying ensemble members for averaging. However, effort should be made to determine the extent of internal variability and SST forced variability. For such determination we should need about 20 ensembles for several years which are not available and hence we are unable to determine the variability ratio of internal versus boundary forced variability.

6.1. *Suggested strategy for foreshadowing drought/excess monsoon years based on dynamical prediction systems*

We have attempted to show that our methodology for matching the individual ensemble members on the basis of either B or A events on the pentad scale cumulatively in a season or on the basis of percentage departure of ISMR from normal for a season appeared to work quite satisfactorily for foreshadowing extreme monsoon seasons. We present the following strategy for producing dynamical model based seasonal ISMR on deterministic or probability estimate basis:

(*i*) Make five to 10 ensemble forecasts with initial conditions within the first fortnight of May every year using high resolution AGCM T170L42 version with CFS forecast global SST as boundary conditions from May to September. Assess the similarity of individual ensemble members, based on the two methods (similarity in B and A events or similarity in percentage departure of seasonal ISMR from the normal). Provide the deterministic forecast based on this methodology and also expectation in terms of drought or excess category.

(*ii*) Find the probability of drought or excess ISMR season based on the ratio of similar ensemble members and the total number of ensemble members used in the forecast system. This would indicate the probability of drought or excess monsoon season.

If the dynamical forecasts based on above strategy are produced, the guidance from the dynamical models is likely to have higher skill than forecast based on all-members ensemble averaging. While further research to improve the AGCMs and the CGCMs must continue, in the mean while ensemble members for averaging purpose could be selected on similarity basis. There is also a need to isolate the influence of IOD/EQUINOO forcing through modeling experiments. For this purpose active monitoring of the surface and sub-surface thermal status of temperatures in the equatorial Indian Ocean is a primary need. Currently a system of buoys is being installed (RAMA Buoy), which would fulfill such a need exceedingly well and the data would ultimately lead to better predictability IOD/EQUINOO events. Understanding and prediction of interaction between IOD and El Niño hold the key for more skillful seasonal monsoon predictability and a beginning has been made in the work of Behera *et al*. (2006).

7. Summary and conclusions

The basic foundation of long-range seasonal ISMR lay on the premise that basin scale SST anomalies over the Indo-Pacific region are the primary drivers of the ISMR. SST anomalies over the Indo-Pacific region may drive the interannual hydro-climate variability but its detail may be modulated over the sub-continental region of India through land-atmosphere feedback. Therefore, we should, at best, only expect category-wise (drought or excess ISMR) success of a dynamical forecast system over India. Even the auto-correlation on pentad-wise rainfall could be modulated by details of the SST anomalies as well as initial conditions of the observed atmospheric state. Thus, global or equatorial ocean SST anomalies may set the background for an impending ISMR season, the details may be modulated by land-atmosphere feedback or initial observed state of the atmosphere.

Our study is to be taken in the context of Ratna *et al*. (2010) in which we have shown little skill in forecasting the extreme ISMR seasons based on the all-members ensemble averaging in our 20 years hindcast runs. Even the severe monsoon drought of 2002 could not be predicted by our model based on all-members ensemble averaging when the model was run in the hindcast mode. This has lead to our thinking as to how to derive the major signal for the long-range forecasting of the monsoon by using high-resolution AGCMs forced by SST boundary conditions. In this study we first analysed the inability of the model to foreshadow the drought of 2009. In order to understand the failure of the model in the season of 2009, we examined the evolution of the ISMR on all India pentad average rainfall basis spread over 24 pentads during the monsoon season (1 June to 28 September). The monsoon droughts in the past have resulted from more persistent below normal rainfall on pentad/weekly basis. On the scale of all-India rainfall averaging, we adopted the strategy to derive the pentad departure of simulated ISMR from long-term climatology of each pentad and identify those ensemble members which were very similar to each other with regard to seasonal number of below or above normal ISMR on pentad basis. When we adopted the ensemble averaging based on similar member ensembles with regard to overall seasonal performance of below/above normal rainfall, we found that the signal for impending drought of seasonal monsoon rainfall for 2009 was absolutely clear. We then adopted the same methodology for similar individual ensembles averaging the extreme ISMR seasons (drought/excess) in our 20-year (1985-2004) hindcast runs. It was found that selective ensemble averaging suggested by us on seasonal basis was able to foreshadow the droughts of 1986, 1987, 2002, 2004 and 2009. The excess monsoon season of 1988 was also given correctly by our all-members ensemble average basis as all the five members had simulated excess ISMR. We found that the ISMR was excess in the year 1994 but even our similar member ensemble average showed that the simulated rainfall would be for the drought ISMR. This happened because the model was responding to the persistent warm El Niño conditions in the equatorial Pacific while the observed monsoon perhaps responded to emerging signal of IOD/EQUINOO mode. Thus, it became clear as discussed by Gadgil *et al.* (2004 & 2007) that both the El Niño and IOD/EQUINOO mode have to be considered jointly in foreshadowing extreme seasons of the ISMR. We have also noted that the prediction of ISMR in near-excess and excess years of 1990 and 1994 proved immensely in the CFS model as shown in a study by Pattanaik *et al.* (2010). This is a major success over the results discussed by us by using the AGCM forced by even observed SSTs. It shows that only an enhanced cooling of EEIO region would result in countering the effect of ongoing warm conditions in the equatorial Pacific as the AGCM is highly sensitive to prevailing SSTs in the equatorial Pacific Ocean basin. Since TOGA years (1985-1995), prediction of the El Niño over the equatorial Pacific Ocean has been quite successfully achieved by the coupled ocean-atmosphere modeling community. As the forecast impending El Niño/La Nina are available 6 to 9 months in advance, the foreshadowing for the development of El Niño/La Nina conditions are available in India much before the forecast for ISMR are given. This could be an important input for category-wise prediction for ISMR. However, through using AGCMs with the forecast SSTs by coupled models, deterministic forecasts for ISMR as well as probability of an extreme monsoon season can be given by using even AGCMs by adopting our strategy of selective averaging of similar ensemble members. The discovery of the IOD/EQUINOO mode has resulted in the last 10 years only. The IOD/EQUINOO signal is rather weak in observations compared to the El Niño signal. Also, prediction of IOD would require further research through observations and modeling before a reasonable prediction of the onset of the IOD/EQUINOO could be made. The recent introduction of RAMA buoys in the near-equatorial Indian Ocean along with ARGOS data may help in recognizing the emerging IOD/EQUINOO signal by middle of May. If the coupled models could predict the amplification of this regional mode, then along with the prediction of El Niño mode, the real-time prediction of the IAV of the monsoon in terms of drought/excess ISMR would become possible. Also, we must consider the emerging latent heat anomalies on the intra-seasonal and inter-annual scales for assessing the role of anomalous latent heat on the evolution of the South Asian Summer Monsoon System over land as well as over sea. This would be possible if TRMM-like satellite is available and the technique suggested by Zuluaga *et al.* (2010) is adopted on the near-real time basis.

We have also proposed a strategy for operational long-range forecasting of the ISMR using dynamical AGCM with observed/forecast SSTs and producing the deterministic as well as probability forecast based on matching in the similarity of events on the intra-seasonal scale (pentad wise ISMR) as the ISV of monsoon is strongly linked to IAV of monsoon. Our further research in this direction would continue but this study has shown promise that indeed it is possible to recognise the impending monsoon droughts more skillfully if the proper ensemble average on similarity basis is used for producing either deterministic or probability forecast. Finally, the success of long-range seasonal dynamical forecast by SST forcing depends on the predictability of tropical SST anomalies both over the equatorial Pacific Ocean (ENSO signal) as well as over the EEIO (IOD/EQUINOO signal). As such coupled models should improve the prediction of SSTs on both the oceanic regions on the annual cycle basis. The stress now should be to achieve skillful prediction of SSTs over the EEIO region three to six months in advance just like it has been achieved over the Niño 3.4 region in the past decade.

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