MAUSAM, **63**, 3 (July 2012), 433-448

551.509.333 : 551.553.21

Dynamical-Empirical forecast for the Indian monsoon rainfall using the NCEP Coupled Modelling System – Application for real time monsoon forecast

D. R. PATTANAIK, AJIT TYAGI and ARUN KUMAR*

India Meteorological Department (IMD), New Delhi, India

**Climate Prediction Centre, National Centre for Environmental Prediction (NCEP), USA*

(*Received 12 October 2010, Modified 26 April 2011*)

e mail : pattanaik_dr@yahoo.co.in

सार – जून से सितंबर (जे.जे.ए.एस.) के दौरान समूचे भारत में ग्रीष्म कालीन मानसून वर्षा (ए. आई. एस. एम. आर.) का पूर्वानुमान करने के लिए जलवायु पूर्वानुमान प्रणाली (सी. एफ. एस.) नामक राष्ट्रीय प्र्यावरण पूर्वानुमान केन्द्र के प्रचालनात्मक युग्मित मॉडुलन प्रणाली के कार्य निष्पादन का मूल्यांकन किया गया है। यह मूल्यांकन वर्ष 1981 से 2005 तक की अवधि में मार्च, अप्रैल एवं मई के दौरान के 25 वर्षों के संचयित परवर्ती आँकड़ों के आधार पर 15 सदस्यीय समूह द्वारा तैयार किया गया है।

मार्च (लैग–3), अप्रैल (लैग–2) और मई (लैग–1), की आरम्भिक स्थितियों से जून से सितंबर के दौरान सी. एफ. एस. की जलवायविकी से सामान्यतया प्रेक्षित जलवायविकी की भाँति ही वर्षा के सदृश पैटर्न का पता चलता है जिसमें दोनों क्षेत्रों (भारत के पश्चिमी तटीय क्षेत्र में और बंगाल की खाडी के क्षेत्र में) के वर्षा के अधिकतम आँकड़ों को यथोचित रूप से शामिल किया गया है। इसमें भारतीय भूखंड और इसके समीपवर्ती महासागरीय क्षेत्र के भारतीय मानसून क्षेत्र (50 डिग्री पूर्व से 110 डिग्री पूर्व और 10 डिग्री दक्षिण से 35 डिग्री उत्तर की सीमा तक) के पूर्वानुमान तथा प्रेक्षित जलवायविकी के बीच महत्वपूर्ण सहसंबंध गुणांक देखा गया है। हालाँकि भारतीय मानसून क्षेत्र के लिए जलवायु पूर्वानुमान प्रणाली से दिया गया वर्षा पूर्वानुमान अधिक है, केवल जमीन पर हुई वर्षा का पूर्वानुमान प्रेक्षित की गई वर्षा से कम आंकलित हुई है। यद्यपि भारतीय भूखंड में होने वाली वर्षा के पूर्वानुमान का कौशल अपेक्षाकृत कमजोर है तथापि यह 0.44 के सहसंबंध सूचकांक के साथ अप्रैल के समूह के बाद 95 प्रतिशत तक लगभग सही पाया गया है।

अखिल भारतीय ग्रीष्मकालीन मानसून वर्षा (ए. आई. एस. एम. आर.) का सही समय पर पूर्वानुमान करने के लिए जलवायु पूर्वानुमान प्रणाली (सी. एफ. एस.) का उपयोग करते हुए इन क्षेत्रों में जून से सितंबर तक हुई वर्षा के पूर्वानुमान दिए गए जिसमें महत्वपूर्ण संहसंबंध सूचकांक भी थे और एक मिश्रित गत्यात्मक अनुभूतिमूलक मॉडल विकसित किया गया जिसकी स्टीकता पहले के सी. एफ. एस. पूर्वानुमानों की तुलना में काफी अधिक (इसका सी. सी. 99 प्रतिशत से ऊपर) पाई गई है। वर्ष 2009 और 2010 के मानसून के लिए वास्तविक समय के पूर्वानुमान के लिए गत्यात्मक अनुभूतिमूलक मिश्रित पूर्वानुमान का प्रयोग किया गया है जो प्रेक्षित किए गए ए. आई. एस. एम. आर. के काफी करीब पाया गया है। इस प्रकार जब मिश्रित मॉडल का उपयोग वास्तविक पूर्वानुमान के लिए किया गया कुछ संकेत एवं परिमाण में संशोधन करने पडे जैसा कि वर्ष 2009 के मानसून में किया गया है। अतः इसका उपयोग ए.आई.एस.एम.आर. के वास्तविक समय का पूर्वानुमान देने के लिए एक अच्छे साधन (टूल) के रूप में किया जा सकता है।

ABSTRACT. The performance of the National Centre for Environmental Prediction's (NCEP) operational coupled modeling system known as the Climate Forecast System (CFS) is evaluated for the prediction of all India summer monsoon rainfall (AISMR) during June to September (JJAS). The evaluation is based on the hindcast initialized during March, April and May with 15 ensemble members each for 25 years period from 1981 to 2005.

The CFS's hindcast climatology during JJAS of March (lag-3), April (lag-2) and May (lag-1) initial conditions show mostly an identical pattern of rainfall similar to that of observed climatology with both the rainfall maxima (over the west-coast of India and over the head Bay of Bengal region) well captured, with a signification correlation coefficient between the forecast and observed climatology over the Indian monsoon region (bounded by 50°E-110°E and 10°S-35°N) covering Indian land mass and adjoining oceanic region. Although the CFS forecast rainfall is overestimated over the Indian monsoon region, the land only rainfall amount is underestimated compared to observation. The skill of the prediction of monsoon rainfall over the Indian land mass is found to be relatively weak, although it is significant at 95% with a correlation coefficient (CC) of 0.44 with April ensembles.

By using CFS predicted JJAS rainfall over the regions of significant CCs, a hybrid dynamical-empirical model is developed for the real time prediction of AISMR, whose skill is found to be much higher (CC significant above 99% level) than the raw CFS forecasts. The dynamical-empirical hybrid forecast applied on real time for 2009 and 2010 monsoons are found to be much closer to the observed AISMR. Thus, when the hybrid model is used there is a correction not only to the sign of the actual forecast as in the case of 2009 monsoon but also to its magnitude and hence can be used as a better tool for the real time prediction of AISMR.

Key words – Indian monsoon rainfall, Climate Forecast System, Coupled Model, GCM, Dynamical-empirical, Forecast Skill.

1. Introduction

The southwest monsoon rainfall during June to September (JJAS) contributes more than 80% of the annual total rainfall over India. The two extremes of interannual variability (IAV) of monsoon rainfall led to the flood and drought conditions over the country. Predictability of monsoon drought depends on that of the monsoon IAV, which in turn depends on relative contributions of 'externally' forced to 'internally' generated components of IAV of the monsoon. Many droughts could be due to the internal variability of the Indian summer monsoon system, possibly through the monsoon intraseasonal oscillations (ISOs)/active & break cycles of monsoon (Goswami 1998; Kripalani *et al.* 2004). Thus, the forecasting of southwest monsoon rainfall on seasonal scale is vital for the policy planning and national economy for the agro-economic country like India.

More than a century ago the beginning of the long-range forecasting of Indian summer monsoon rainfall was initiated by Blanford (1884). In last few decades, many statistical (Shukla and Mooley, 1987; Gowariker *et al.*, 1991; Sahai *et al.*, 2003A, Sahai *et al.* 2003B, Rajeevan *et al.*, 2003; Pattanaik *et al.*, 2005) and dynamical methods (Palmer *et al.*, 1992; Chen and Yen, 1994; Sperber and Palmer, 1996; Soman and Slingo, 1997; Shukla *et al.*, 2000) have been developed for predicting the summer monsoon rainfall. After the failure in prediction of two drought years (2002 and 2004), IMD developed two-stage new forecast model (Rajeevan *et al.*, 2006) for the monsoon forecast, which is being used now for the operational long range forecast of monsoon rainfall over India. This model is based on the ensemble multiple linear regression (EMR) and projection pursuit regression (PPR) techniques. Charney and Shukla (1981) introduced the basis of the dynamical seasonal forecasting in tropics. According to them the lower-boundary forcing (sea surface temperature (SST), sea-ice cover, land-surface temperature and albedo, vegetation cover and type, soil moisture and snow cover etc.), which evolve on a slower time-scale than that of the weather systems themselves, can give rise to significant predictability of statistical characteristics of large-scale atmospheric events. Several observational and modelling studies (Charney and Shukla, 1981; Palmer and Anderson, 1994) provide evidence that bottom boundary forcing like the SST in the tropics contribute significantly to the internal variability of the tropical as well as monsoon circulations. Atmospheric General Circulation Models (AGCM) and Coupled GCMs (CGCMs) are the main tools for dynamical seasonal scale prediction.

Though, there have been significant improvement in dynamical modeling system through the improvement of the model physics and dynamics in last few years, but present day AGCM could not able to simulate mean and interannual variability of Indian summer monsoon very successfully (Kang *et al.*, 2002, Wang *et al.*, 2004). It is also found that the skill of the AGCM is poorer in simulating Indian monsoon, which can be due to lack of proper representation of realistic SST. Some of the recent studies have highlighted that the coupled models with one-tier approach can enhance the predictability of the summer monsoon precipitation (Wang *et al.*, 2008; Pattanaik & Kumar 2010; Krishnan *et al.*, 2010). As shown by Krishnan *et al.*, (2010), a fully coupled model will be able to better capture the observed monsoon interannual variability. Thus, the future climate prediction system should focus with coupled atmosphere-ocean models.

Now the growing demand for the country like India is to have a better forecast of all India summer monsoon rainfall (AISMR) in real time. In view of that, can we use the current generation coupled model for the same? How the skill of the coupled model for the forecast of AISMR can be further improved by using the hybrid concept (dynamical-empirical model), developed based on the other forecast variables having higher skill. The objective of the present study is to investigate this aspect by using the Climate Forecasting System (CFS), which is the coupled modeling system of the NCEP running operationally for the seasonal forecast. The skill of the Indian summer monsoon rainfall forecast during JJAS obtained from the coupled GCM (CFS) run at NCEP has been carried out by taking 15 members ensemble forecast for 25 years (1981-2005) with initial conditions of March (lag-3), April (lag-2) and May (lag-1). The lay-out of the paper is as follows: In sections 2, the components of the CFS, organization of the hindcasts and the observations used for the verification have been described. The skill of CFS for simulating mean and interannual variability of Indian monsoon rainfall has been discussed in section 3. In section 4, the CFS based empirical forecast for the real time prediction of AISMR is discussed. Section 5 discusses the verification of hybrid model (based on the CFS forecast variables as predictors) for the forecast of seasonal monsoon rainfall during 2009 and 2010. Finally, summary and conclusions are given in Section 6.

2. Details of CFS hindcast and observed data used along with the methodology

2.1. *CFS hindcast data used*

The atmospheric component of the CFS (version 1) is the NCEP atmospheric GFS model, as of February 2003 (Moorthi *et al.* 2001). It adopts a spectral triangular truncation of 62 waves (T62) in the horizontal (equivalent to nearly a 200 km Gaussian grid) and a finite differencing in the vertical with 64 sigma layers. This version of the GFS has been modified from the version of the NCEP model used for the NCEP/NCAR Reanalysis (Kalnay *et al.* 1996; Kistler *et al*. 2001), with upgrades in the parameterization of solar radiation transfer (Hou *et al.*, 1996 and Hou *et al*. 2002), boundary layer vertical diffusion (Hong and Pan 1996), cumulus convection (Hong and Pan 1998), gravity wave drag (Kim and Arakawa 1995). The oceanic component is the GFDL Modular Ocean Model V.3 (MOM3) (Pacanowski and Griffies 1998), which is a finite difference version of the ocean primitive equations under the assumptions of Boussinesq and hydrostatic approximations. It uses spherical coordinates in the horizontal with a staggered Arakawa B grid and the *z*-coordinate in the vertical. The ocean surface boundary is computed as an explicit free surface. The domain is quasi-global extending from 74°S to 64°N. The zonal resolution is 1°. The meridional resolution is 1/3° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 1° poleward of 30°S and 30°N. There are 40 layers in the vertical with 27 layers in the upper 400 m, and the bottom depth is around 4.5 km. Vertical mixing follows the non-local K-profile parameterization of Large *et al.* (1994). The horizontal mixing of momentum uses the nonlinear scheme of Smagorinsky (1963). The ocean-atmosphere coupling is nearly global (64°N - 74°S), instead of only in the tropical Pacific Ocean, and flux correction is no longer applied. Thus, the CFS is a fully 'tier-1' forecast system. For more details about the CFS, kindly see the article by Saha *et al*., (2006).

The CFS includes a comprehensive set of retrospective runs that are used to calibrate and evaluate the skill of its forecasts. An extensive set of retrospective forecasts ('hindcasts') was generated to cover a 25 years period (1981-2005), in order to obtain a history of the model. This history can be used operationally to calibrate and assess the skill of the real-time forecasts. Each run is a continuous nine month integration with 15 initial conditions that span each month. Each month was divided into 3 segments centered on the pentad ocean initial conditions of 11th of the month, 21st of the month and the first day of next month. The atmospheric initial states of 9th, 10th, 11th, 12th and 13th are used the same pentad ocean initial conditions of 11th. Similarly, for the other 10 atmospheric initial conditions the remaining two ocean initial conditions of 21st of the month and the first day of next month is used. In the present analysis the hindcast analysis obtained with 15 initial conditions of the months March, April and May are used for the skill analysis of CFS forecast for the simulation of Indian monsoon rainfall during June to September. These initial conditions were carefully selected to span the evolution of both the atmosphere and ocean in a continuous fashion. The atmospheric initial conditions were from the NCEP/DOE Atmospheric Model Inter-comparison Project (AMIP) II Reanalysis (R2) data (Kanamitsu *et al*. 2002), and the ocean initial conditions were from the NCEP Global Ocean Data Assimilation (GODAS), which was made operational at NCEP in September 2003.

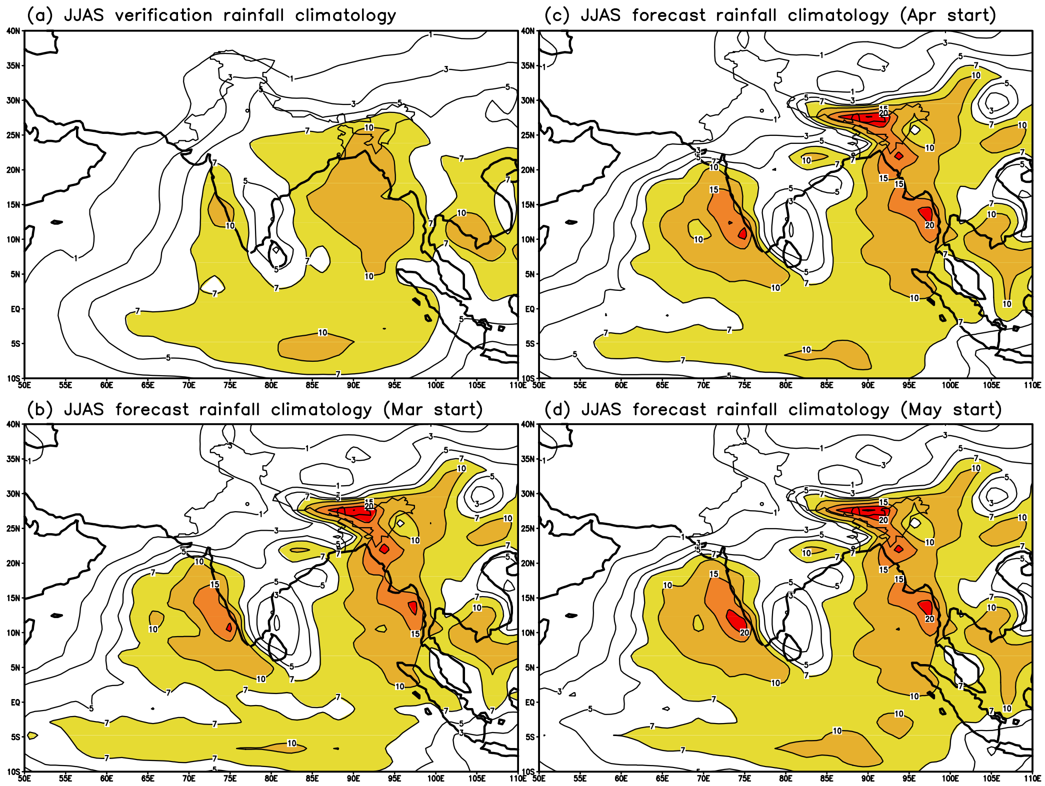
2.2. *Observed data used for the verification*

India Meteorological Department (IMD) has a good observational network in which rainfall observations mainly spaced over land. On the other hand, numerical models simulate rainfall over land as well as over water body (over the whole domain of interest). Thus, the verification of rainfall forecast is also compared not over the Indian land region but over the Indian monsoon region (bounded by 50° E - 110° E and 10° S - 35° N including the oceanic part). The Indian monsoon region is considered as the study area, which is the same as chosen by Krishnamurti *et al.* (2004) for verification of DEMETER results. The all India observed rainfall series prepared by IMD over the land stations of India is used for the verification of monsoon rainfall forecast from CFS over the Indian landmass. However, for the broader region defined above (the Indian monsoon region and on the global scale) including the Ocean region the merged rainfall from Xie and Arkin (1997), which has used surface observations, satellite data, buoys data and outputs from numerical models (GCM) have been used. For the verification of other variables such as, the wind and Sea Surface Temperature (SST), the reanalysis wind and SST available in NCEP reanalysis (Kalnay *et al*., 1996).

3. Skill of the CFS for simulating Indian monsoon rainfall

3.1. *Simulation of mean and interannual variability of monsoon rainfall*

The model climatology is represented here by retrospective forecasts (or "model simulations"), made with a 15-member ensemble, over the 25-year period from



Figs. 1(a-d). Spatial climatological rainfall (mm/day) for 25 years period from 1981 to 2005 valid for JJAS. (a) Verification analysis (Xie-Arkin; 1997), (b) corresponding CFS forecasts with March ensembles, (c) with April ensemble and (d) with May ensemble. Rainfall with more than 7 mm/day are shaded

1981 to 2005. Therefore, for each new forecast, there is a reference set of 375 (15 × 25) simulations. Fig. 1(a) shows the observed climatology of monsoon rainfall during JJAS for the period 1981 to 2005, which shows two rainfall maxima; one over the west coast region and the other over the head Bay of Bengal. Along with these two maxima the observed climatology has a zone of less rainfall over the northwestern parts of the country and the rain shadow region of Tamil Nadu situated on the south-eastern coastal state of India [Fig. 1(a)]. The corresponding rainfall climatology for the CFS forecasts from different initial conditions as shown in Figs. 1(b-d) indicates identical spatial pattern with both the rainfall maxima well captured although the west coast maximum is stretched and extends westward into the Arabian Sea. It is seen that the mean patterns show significant CC (at 99.9% level) over the Indian monsoon region (50° E - 110° E, 10° S -35° N) with CC for March, April and May initial conditions are found to be 0.72, 0.85 and 0.74 respectively. The CFS, however, simulates excessive rainfall over the northeastern parts of the country stretching westward along Nepal, Gangetic and Brahmaputra valley stretching from the Bay of Bengal region for all the three initial conditions [Figs. 1(b-d)], which is also indicated by positive bias over the region as also discussed by Pattanaik and Kumar, (2010).

The mean and coefficient of variability (CV) of the observed (verification analysis) and CFS rainfall with March, April & May initial conditions over the Indian monsoon region is given in Table 1. It is seen from Table 1 that the JJAS mean rainfall is slightly more in case of CFS forecasts (6.30 mm/day for March ensemble, 6.47 mm/day for April ensemble and 6.61 mm/day for May ensembles) against the verification analysis (5.48 mm/day). Thus, there is slight overestimation of CFS forecast rainfall compared to observation during JJAS over the Indian monsoon region. However, as also seen from Table 1 over the Indian land only region the rainfall amount is underestimated in case of CFS forecast. It is seen from Table 1 that the CV in case of CFS forecast (4.6% to 5.2%) is about 2% less than that of the CV of

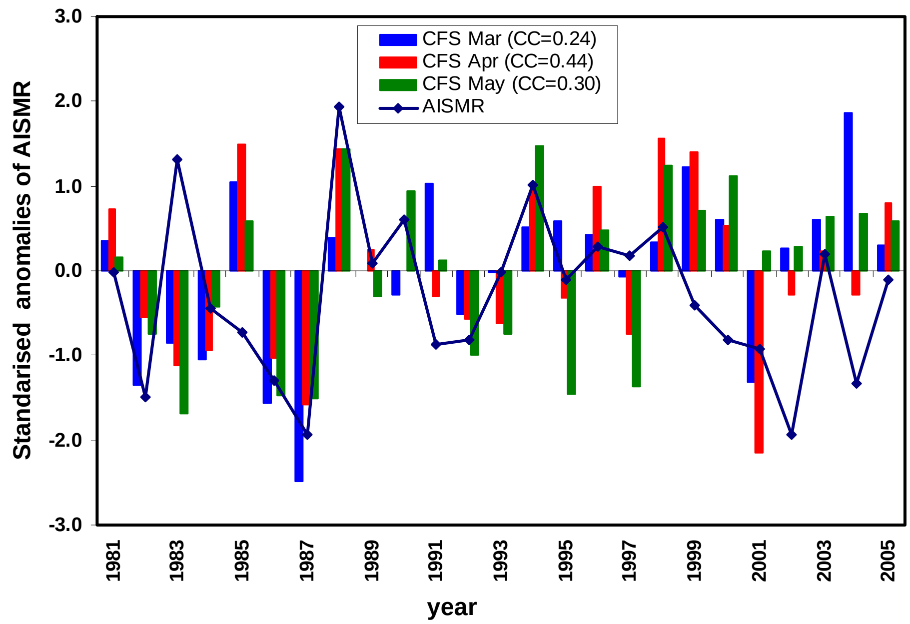


Fig. 2. Year-to-year variation of standardised JJAS total rainfall anomalies from CFS forecast with March to May initial conditions averaged over the Indian land region only during the 25 years period from 1981 to 2005

TABLE 1

The Correlation Coefficients (CCs) between verification rainfall climatology and model hindcast climatology during the 25 years period from 1981 to 2005 for June to September (JJAS) with initial conditions of March, April and May. The CCs are significant above 99.9% level for IMR, whereas it is only significant at 95% with April initial conditions in case of land only rainfall

Indian monsoon region (50° E - 110° E, 10° S - 35° N)	Verification analysis rainfall	CFS's hindcast		
		MAR ICs	APR ICs	MAY ICs
Mean (mm/day)	5.48	6.30	6.47	6.61
CV (%)	6.7 %	5.2 %	4.8 %	4.6 %
CC	-	$0.61^{99.9}$	0.56^{99}	$0.66^{99.9}$
Rainfall over Indian land only region (AISMR)	**IMD rainfall**	**CFS's hindcast**		
		MAR ICs	APR ICs	MAY ICs
Mean (mm/day)	7.21	5.21	5.33	5.38
CV (%)	≈ 10.0%	5.13 %	5.68 %	5.20 %
CC	-	0.24	0.44^{95}	0.30

verification analysis (6.7%) over the Indian monsoon region. With respect to land only region it is seen from Table 1 that the CV in case of CFS forecast (about 6 %) is less than that of CV of observed AISMR (about 10%). In order to study the interannual variability of model simulation 15-member ensemble mean departure of JJAS total rainfall from CFS forecast with initial conditions of March (lag-3), April (lag-2) and May (lag-1) over the land only region of India along with the observed AISMR departure obtained from IMD over the land region of India is shown in Fig. 2. In Fig. 2 the CFS forecast anomaly is calculated by subtracting the corresponding CFS model

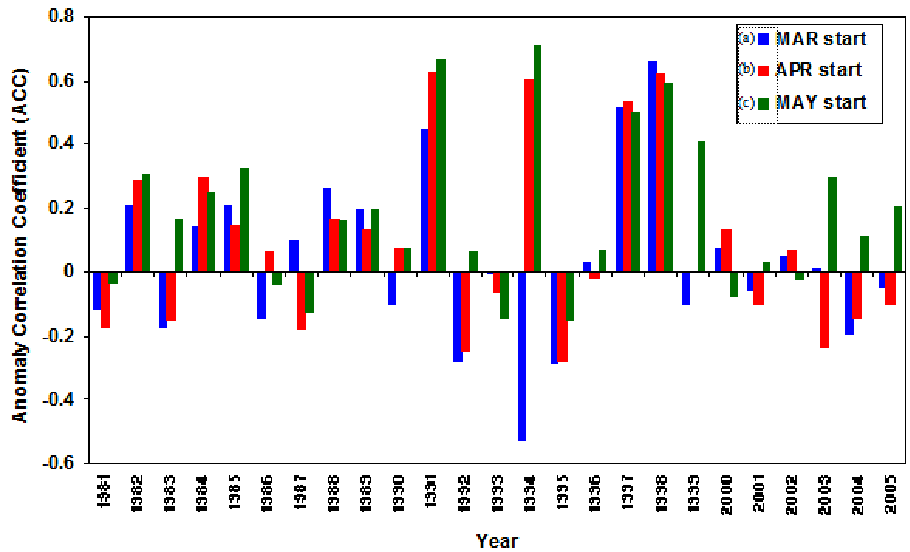
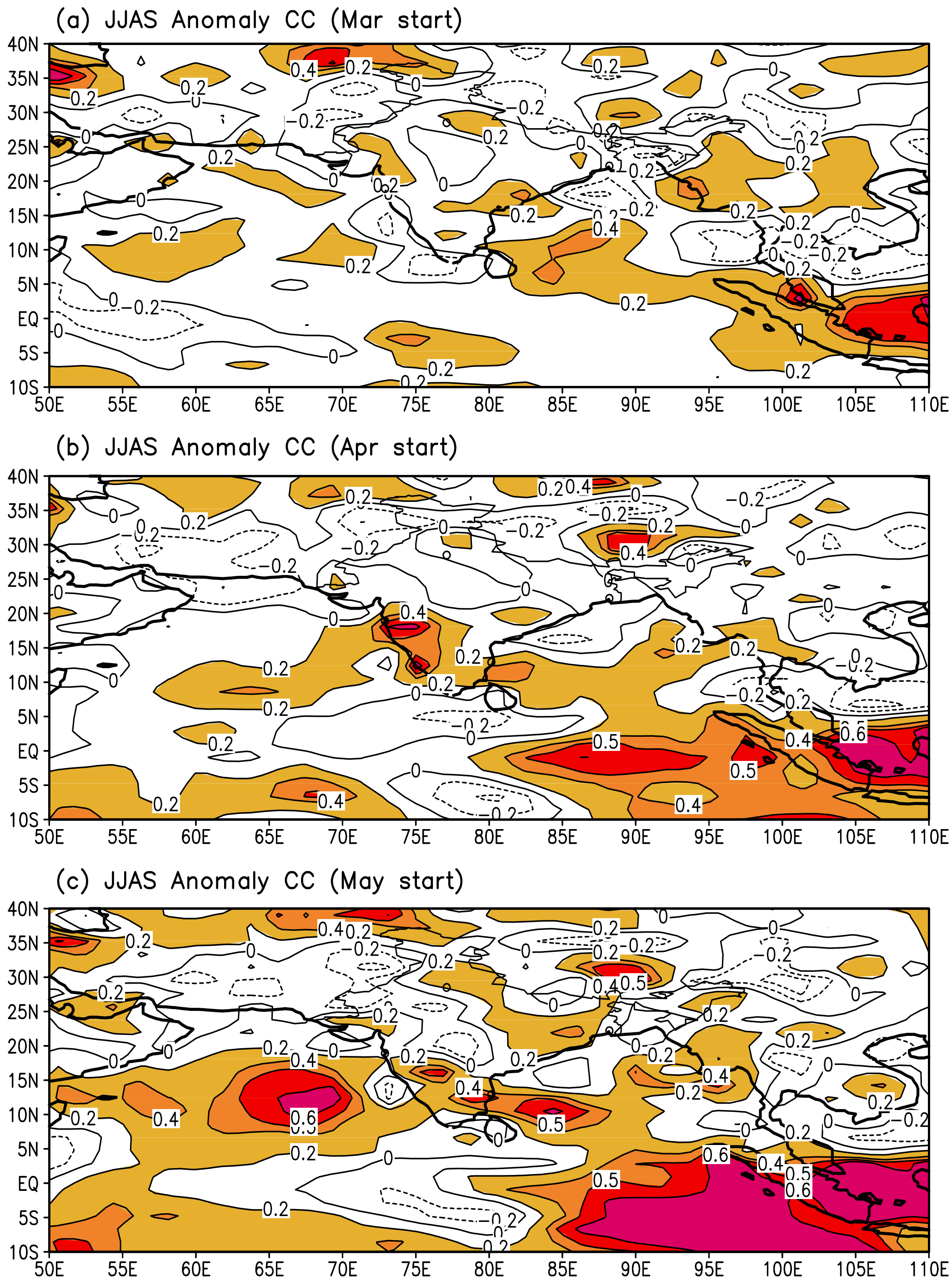


Fig. 3. Anomaly Correlation Coefficient (ACC) over the Indian monsoon region (50° E - 110° E, 10° S - 35° N) between verification rainfall anomalies and the CFS forecast rainfall anomalies during JJAS (a) for March ensembles (b) April ensembles and (c) May ensembles

climatology during the hindcast period from 1981 to 2005 with 15 ensemble members each on ever year. The correlation between verification and forecast rainfall anomalies over the Indian monsoon region (Table 1) is found to be statistically significant above 99% level for lag-3 (March), lag-2 (April) and lag-1 (May) seasonal forecast, whereas, the CC between observed and forecast rainfall over the land only region of India given indicates highest CC during April (0.44) followed by May and March initial conditions. The year-to-year variation of AISMR during 1981 to 2005 (Fig. 2) indicates many extreme years *viz*., 1982, 1986, 1987 & 2002, 2004 are considered to be deficient years and the years *viz*., 1983, 1988 & 1994 are considered to be the excess years. It may be mentioned here that although many earlier studies (Sperber *et al*., 2001; Ji and Vernekar, 2000) have noted poor performance of forecasts in prediction of Asian monsoon a season in advance, the skill of the forecast shown here is hopeful since the seasonal forecast is well simulated in the model with highly significant CCs.

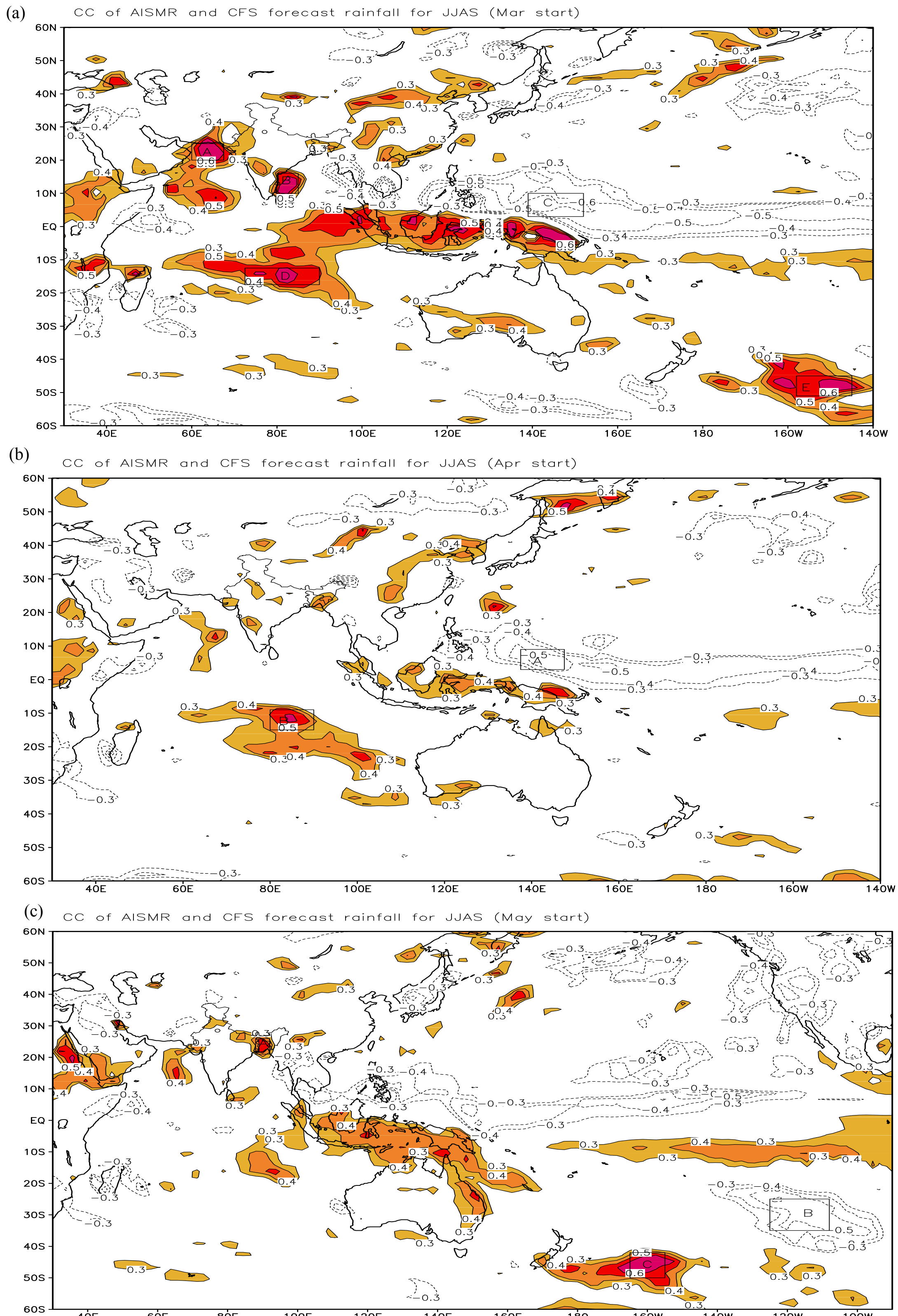
3.2. *Precipitation forecast skill from CFS*

In order to study the skill (anomaly correlation) of seasonal climate forecasts for individual season, the anomaly CC (ACC) over the Indian monsoon region (50° E - 110° E and 10° S - 35° N) between the forecast rainfall during JJAS with March, April and May initial conditions and the verification rainfall analysis (Xie and Arkin 1997) during 1981 to 2005 is shown in Fig. 3. It is seen from Fig. 3 that during many years like 1991, 1994, 1997 and 1998 the skill is very high (almost of the order of 0.6), whereas, during the year 1982, 1984, 1985, 1987 and 1989 the ACC is around 0.3 though there is slight differences with March, April and May initial conditions. The two major drought years 1987 and 2002 where the AISMR departure was –19% the skill in CFS is found to be very small with the ACC values is either slight positive or negative. It is also noticed from Fig. 3 that during the recent three years (2003, 2004 & 2005) the skill of lead-1 forecast (May initial conditions) are found to be better than that of March and April initial conditions. The higher values of ACCs can provide some useful guidance on whether to expect above or below normal monsoon rainfall a season in advance. However, the ACCs values given in Fig. 3 can not provide the forecast skill map over the entire Indian monsoon region and the spatial skill map will be more helpful. The map of ACC between the forecast rainfall anomaly during JJAS from CFS with March, April and May initial conditions (lag-3, lag-2 and lag-1 respectively) and the corresponding anomaly of rainfall from the verification analysis are shown in Figs. 4(a-c). The ACC is higher (more than 0.4) over the southern India, parts of central India and eastern parts of the country and it is smaller over the isolated pockets of northeastern and western parts of the country particularly



Figs. 4(a-c). Anomaly Correlation Coefficient (ACC) between JJAS rainfall from verification analysis (Xie-Arkin) and CFS forecast during the period from 1981 to 2005 with (a) March, (b) April and (c) May initial conditions. The positive values are shaded

with lag-1 and lag-2 [Fig. 4(b&c)]. The spatial maps for ACC shows almost identical spatial patterns with March, April and May initial conditions with slight difference in magnitudes indicating that rainfall forecasts with shorter



Figs. 5(a-c). Correlation maps between the All India Summer Monsoon Rainfall (AISMR) over India and the corresponding CFS forecast rainfall valid for JJAS at each grid point based on (a) March, (b) April and (c) May initial conditions during the training period from 1981-2000

TABLE 2

The selected regions mentioned in column 'a' identified for the development of regression equation for predicted rainfall from CFS from Figs. 5(a-c). The CC between predicted mean AISMR (equations 4, 5, 6) and observed AISMR based on regression equations of particular month are given in column 'd' with superscript as the significance level

Initial conditions Months of Forecast	Regions considered From Fig. 5 'a'	Corresponding Boxes identified in Fig.5 'b'	CC between AISMR and CFS forecast rainfall in training period (1981- 2000) 'c'	CC between CFS predicted mean AISMR & actual AISMR (1981-2005) 'd'
March (A)	20° N - 25° N, 60.0° E - 67.5° E	$Y1_{Mar} = a1x + c1$	0.69^{a}	$0.77^{99.9}$
March (B)	10° N - 16° N, 80° E - 85° E	$Y2_{Mar} = a2x + c2$	0.71^{a}	
March (C)	03° N - 10° N, 139° E - 152° E	$Y3_{Mar} = a3x + c3$	-0.63^{b}	
March (D)	12.5° S - 17.5° S, 72.5° E - 90° E	$Y4_{Mar} = a4x + c4$	0.67^{b}	
March (E)	45° S - 51° S, 162° W - 145° W	$Y5_{Mar} = a5x + c5$	0.66^{b}	
April (A)	03° N - 09° N, 137.5° E - 147.5° E	$Y1_{Apr} = a6x + c6$	-0.54^{c}	$0.65^{99.9}$
April (B)	09° S - 15° S, 80° E - 90° E	$Y2_{Apr} = a7x + c7$	0.57^{b}	
May (A)	21° N - 26° N, 88° E - 92° E	$Y1_{May} = a8x + c8$	0.60^{b}	$0.68^{99.9}$
May (B)	23° S - 30° S, 108° W - 125° W	$Y2_{May} = a9x + c9$	-0.57^{b}	
May (C)	42° S - 50° S, 155° W - 165° W	$Y3_{May} = a10x + c10$	0.72^{a}	

lag do not necessarily will improve the forecast particularly for the JJAS rainfall forecast over India.

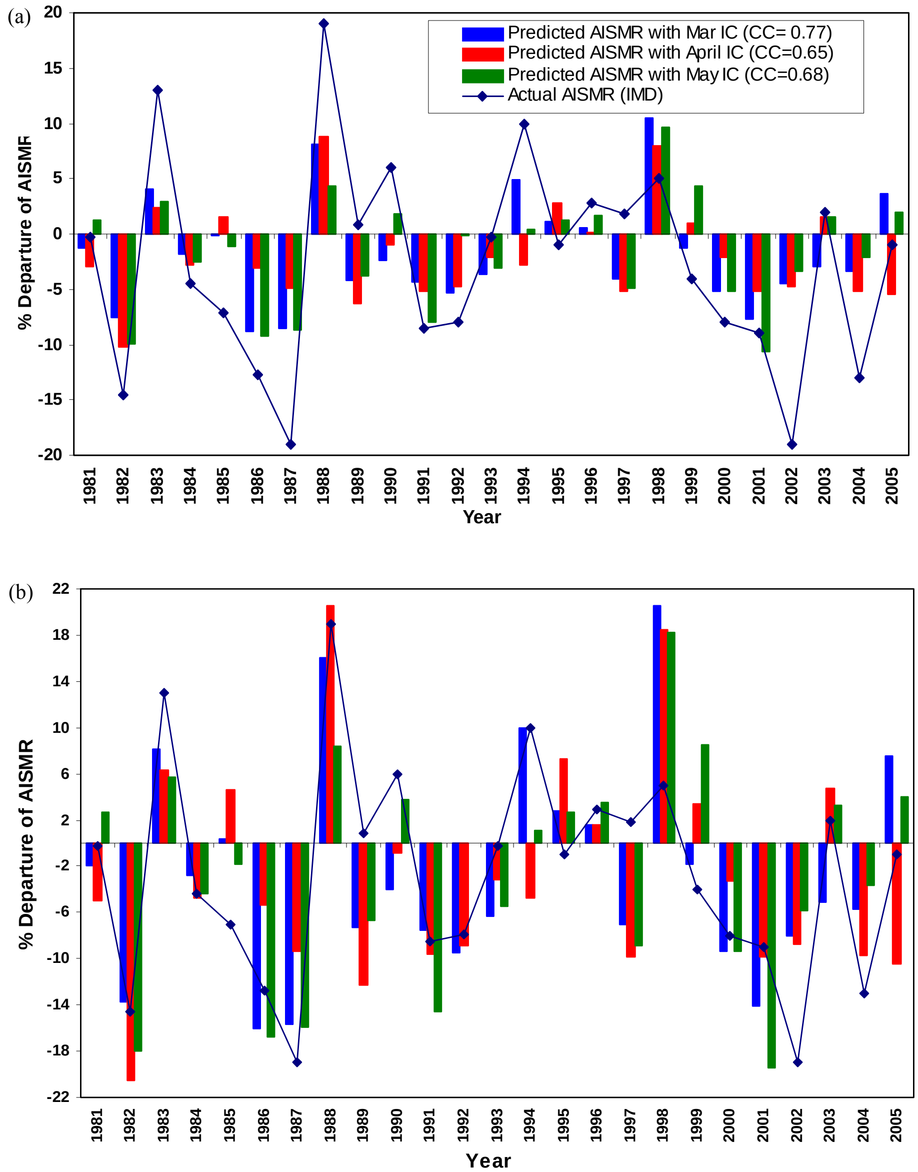
3.3. *Forecast skill of other dynamical variables in CFS*

As the Asian monsoon encompasses complex, multi-scale variability from days to decades, with spatial scales from a few kilometers to thousands of kilometers, its prediction of interannual variability is a complex problem. In spite of such difficulties, the skill of CFS forecast for AISMR is encouraging, although not highly significant. But it still remains a challenging task to use the same for real time forecasting of AISMR. Thus, it is desirable to examine the skill of other dynamical variables of CFS, which have got direct relationship with the Indian monsoon.

As shown by Pattanaik and Kumar (2010), the interannual variability of the large scale monsoon index (as defined by Webster and Yang, 1992; known as WY index) is well simulated in the CFS simulation with the CC between observed and forecast WY index is found to be highly significant at 99.9% level. Similarly the anomaly CC between the observed ENSO index (Nino3 SST/Nino 3.4 SST) during JJAS with the corresponding forecasts SST anomalies in the CFS for the period from 1981-2005 with March, April and May initial conditions also shows highly significant CC (above 99.9% level), although the skill is gradually decreasing from March initial conditions to May initial conditions. But unlike the better skill of ENSO prediction in CFS, the skill of prediction of Indian Ocean SST in terms of the Indian Ocean Dipole (IOD) is poor. The poor skill of IOD prediction in CFS is basically due to the poor skill of SST anomalies over the East Indian Ocean, whereas, the skill over the western Indian Ocean SST is relatively better (Pattanaik and Kumar, 2010).

4. CFS based empirical forecast for the real time prediction of AISMR

As seen in the previous section and also discussed by Pattanaik and Kumar (2010) the skill of prediction for atmospheric circulation fields such as the WY index and the ENSO indices are relatively good compared to that of skill of monsoon rainfall over the Indian land region. As the large scale feature are better predicted, it is worthwhile to explore use of these large scale variables as possible predictors for the downscaling of real time CFS forecast for the predictions of AISMR. However, as shown by Pattanaik and Kumar (2010) the use of forecast SST by CFS over Nino3/Nino3.4 regions and use of forecast WY index from CFS as predictors did not improve the raw skill of CFS with respect to AISMR forecast. Thus, there is a need to see other variables.



Figs. 6(a&b). (a) The mean forecast AISMR along with observed AISMR based on CFS forecast rainfall as predictors given in Table 2 with March, April and May initial conditions and equations 1-3 and (b) The final bias corrected forecast calculated using the formula 4-6

Again the south Asian monsoon over India is a part of large-scale monsoon system covering, monsoon of Southeast Asia, monsoon of west north Pacific and monsoon of south Asia and when we consider the skill of AISMR prediction it is the rainfall only over the land region of India. Though the prediction of AISMR with CFS is having reasonable skill, however, there is a need to explain how the AISMR is correlated with forecast rainfall from CFS over the different parts of the globe? Thus, the correlation map is prepared for the training period from 1981-2000 between observed AISMR and the corresponding forecast rainfall from CFS valid for JJAS with March (lag-3), April (lag-2) and May (lag-1) ensembles and are shown in Figs. 5(a-c) respectively. It is seen from Figs. 5(a-c) that there are many pockets of high CCs between AISMR and CFS forecast rainfall exists outside the Indian land region. Based on these regions of significant CCs some pockets with higher CCs are selected for March to May initial conditions from Figs. 5(a-c) and are tabulated in Table 2 as identified in column ‘a’. The corresponding CCs over these boxes during the training period along with the statistical significance level are given in column ‘c’ of Table 2. Using the time series of the predicted JJAS rainfall during the training period over these boxes, the corresponding 10 regression equations (5 for March, 2 for April and 3 for May indicated in column ‘b’ of Table 2) are developed for the corrected forecast of AISMR. The corrected forecast AISMR using forecast rain as predictors with March, April and May ensembles over the regions given in Table 2) are given as :

$$AISMR^{cr}_{Mar} = (Y1_{Mar} + Y2_{Mar} + Y3_{Mar} + Y4_{Mar} + Y5_{Mar})/5 \quad (1)$$

$$AISMR^{cr}_{Apr} = (Y1_{Apr} + Y2_{Apr})/2 \quad (2)$$

$$AISMR^{cr}_{May} = (Y1_{May} + Y2_{May} + Y3_{May})/3 \quad (3)$$

The superscript in AISMR ‘cr’ stands for corrected forecast using forecast rain as variable. The predicted AISMR is obtained based on each regression equation and the CC for whole period (1981-2005) is obtained between actual AISMR and predicted mean AISMR (column ‘d’ of Table 2). Thus, it is found that the predicted AISMR and actual AISMR shows highly significant CCs (99% or more significance level) as given in column ‘d’ of Table 2. The mean forecast AISMR is calculated for the month of March, April and May using 5, 2 and 3 regression equations respectively based on equations 1, 2 and 3 and are shown in Fig. 6(a) along with the actual AISMR. It is seen that the predicted mean AISMR and actual AISMR shows highly significant CCs (99% or more significance level) during March, April and May initial conditions although the month of April the CCs between predicted AISMR and actual AISMR is relatively less compared to that of March and May initial conditions. It is also observed that during most of the years the predicted and actual AISMR are in phase even in the test period of 2001 to 2005.

As seen from Table 1 the CFS forecast has got very low coefficient of variability (CV) compared to that of observed CV of AISMR. In order to prepare the final forecast the variance inflated/deflated bias corrected forecast is prepared**,** by correcting the equations 1, 2 and 3 in a manner as discussed by Sahai and Satyan (2000), where the final model forecast =(Standardized model value) × SD (OBS)+ Mean (OBS) and are represented as .

$$Y^{cr}_{Mar}\,(Final) = Standarised\,(AISMR^{cr}_{Mar}) \times SD(AISMR) + mean(AISMR) \quad (4)$$

$$Y^{cr}_{Apr}\,(Final) = Standarised\,(AISMR^{cr}_{Apr}) \times SD(AISMR) + mean(AISMR) \quad (5)$$

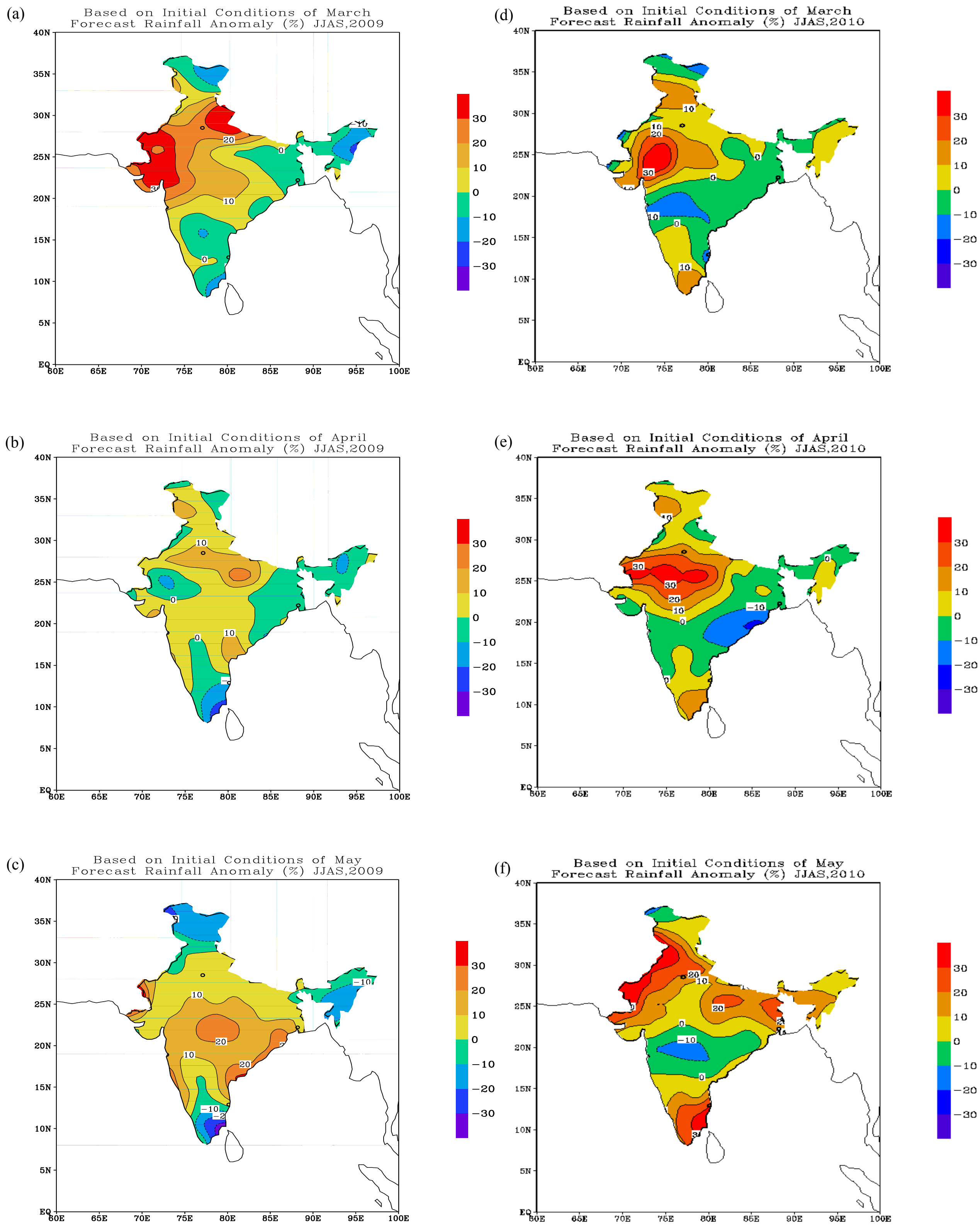
$$Y^{cr}_{May}\,(Final) = Standarised\,(AISMR^{cr}_{May}) \times SD(AISMR) + mean(AISMR) \quad (6)$$

In order to prepare the final forecast the variance [Fig. 6(b)] inflated/deflated bias corrected forecast using the predicted rainfall as variables is prepared by using the equations 4, 5 and 6 for March, April and May ensembles. In this case too the magnitudes of the anomalies are improved. This analysis suggests that it may be possible to use the prediction of large-scale variables by the CFS to construct improved empirical-dynamical hybrid forecasts of AISMR on real time basis.

5. Verification of dynamical-empirical hybrid forecast for 2009 & 2010 monsoon

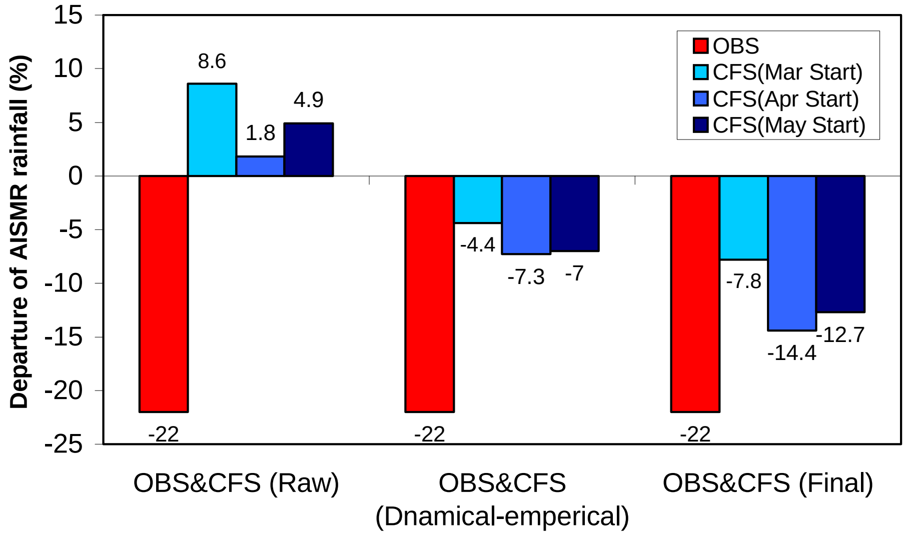
The year 2009 was the third highest deficient AISMR year during the period 1901-2009 with a percentage departure of –22% (Srivastava, 2010; Tyagi and Pattanaik 2010) from its long period average (LPA). The highest ever monsoon rainfall deficiency during this period was observed in 1918 (-25%) followed by 1972 (-24%). The real time forecast from CFS is used for March, April and May initial conditions for the forecast of JJAS. It may be mentioned here that the year 2009 was a moderate El Nino year, which was in the development stage from pre-monsoon season and during the monsoon season the anomalies of SST over Nino3.4 region became more than 0.5° C. On the other hand the southwest monsoon 2010 was a moderate La Nina year with the SST over El Nino regions was in decaying mode from November/December 2009 and by the time the monsoon season of 2010 arrived the SST anomalies over the Pacific was in moderate La Nina phase. The observed AISMR departure over India in association with the positive anomalies of rainfall from July to September was found to be +2.2% during 2010 (Tyagi *et al*., 2011). Thus, the two monsoon seasons were in contrasting SST patterns over the Pacific with 2009 under the developing El Nino condition and 2010 under developing La Nina conditions. Thus, the question arises, how the real time forecasting of monsoon rainfall during 2009 and 2010 in the CFS responded to the contrasting SST patterns over the Pacific? And secondly how the dynamical-empirical model is of any help in predicting the AISMR more accurately compared to the raw CFS forecast.

The forecast rainfall anomaly for JJAS based on March, April and May ensembles of CFS obtained on real time basis for the year 2009 is shown in Figs. 7(a-c). Similarly, the real time CFS forecast rainfall anomaly for 2010 monsoon season is shown in Figs. 7(d-f). About 50 ensemble members each are used for the CFS forecast rainfall anomaly during 2009 [shown in Figs. 7(a-c)], although there is slight variation in exact number of

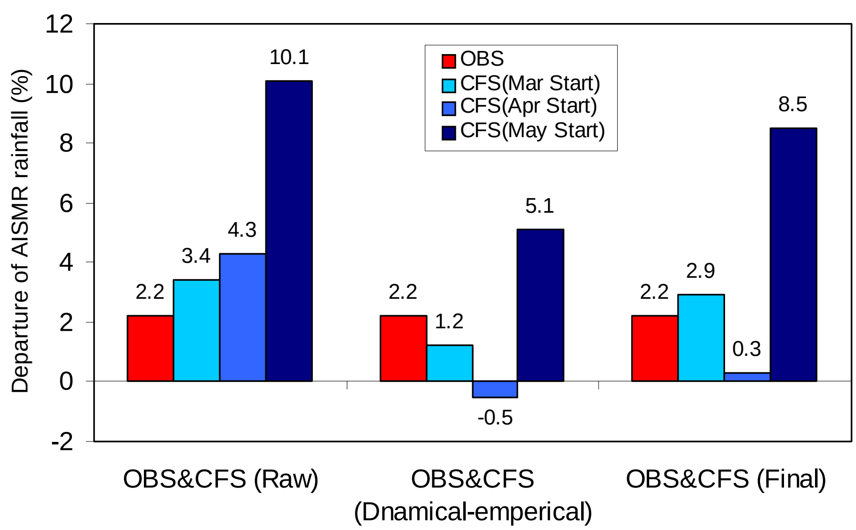


Figs. 7(a-f). (a) to (c) are the forecast rainfall anomaly in percentage for JJAS during 2009 using March, April and May ensemble members. (d) to (f) are corresponding anomaly for JJAS 2010

(a) 2009



(b) 2010



Figs. 8(a&b). (a) The observed AISMR departure in percentage for 2009 and corresponding operational CFS (raw) forecast rainfall, dynamical-empirical CFS forecast rainfall (Eqns. 1-3) and the variance inflated/deflated dynamical-empirical CFS final forecast (Eqns. 4-6) with March to May ensembles. (b) Same as 'a' but for the monsoon 2010

ensembles for March, April and May ensembles. However, for 2010 a 60 ensemble members were used with March, April and May initial conditions [Figs. 7(d-f)]. The quantification of forecast rainfall from CFS is calculated by considering the land only points over India. The observed AISMR departure along with the raw forecast JJAS rainfall from CFS over the land region of India obtained from Figs. 7(a-c) is given in Fig. 8(a). It may be seen here that for 2009 the raw forecast rainfall departure from CFS was found to be 8.6%, 1.8% and 4.9% of LPA with March, April and May ensembles respectively. Thus, the CFS (raw) forecast for 2009 indicated a positive rainfall departure for the 2009 monsoon rainfall over India. As highlighted by some recent articles most of the coupled models had in fact predicted above normal rainfall for the 2009 monsoon season (Pai and Sreejith 2010 and Nanjundiah 2009). Thus, the model could not anticipate rainfall associated with impending El Nino conditions. Similarly the percentage departure of JJAS rainfall from CFS forecast with March, April and May ensembles of CFS for 2010 monsoon obtained from Figs. 7(d-f) was found to be

3.4%, 4.3% and 10.1% of LPA respectively, thus indicating a positive rainfall departure during 2010 monsoon with all three ensembles.

Now applying the dynamical-empirical hybrid forecast (equation 1, 2, 3) for 2009 and 2010 monsoon the forecast rainfall from CFS is also seen in Figs. 8(a&b). The hybrid forecast for 2009 is found to be –4.4%, –7.3% and –7.0% of LPA, which is just the opposites of raw CFS forecast for 2009 over the land only region of India but more closer to the observed departure. Thus, the hybrid forecast of 2009 could capture the negative departure reasonably well (although the magnitude was less), which was not anticipated in the raw CFS forecast. Similarly, the hybrid forecast for 2010 as shown in Fig. 8(b) indicates slight positive departure of rainfall. Using the equations 4, 5, 6 the variance inflated/deflated corrected final forecast for 2009 and 2010 monsoon rainfall over India during June to September is found to be much closer to the observed rainfall departure (Fig. 8), although the variance corrected forecast rainfall with May initial condition was found to be over estimated for 2010 monsoon. Thus, in case of 2010 monsoon the hybrid model forecast did not change the sign of raw CFS forecast although it slightly modify the magnitude, whereas for 2009 the hybrid forecast completely changed the sign from its raw CFS forecast and was more closer to observed departure of –22%. Thus, when the hybrid model is used the forecast was found to be much better and are closer to the observations with April ensembles in 2009 (departure of –14.4%) and with March ensembles in 2010 (departure of +2.9%).

6. Summary and conclusions

From the above results, following broad conclusions can be drawn:

The CFS's hindcast climatology during JJAS of March, April and May ensembles show mostly the identical patterns of rainfall like that of the observed climatology with both rainfall maxima, over the west-coast of India and the head Bay of Bengal region simulated well although the west coast maximum is stretched westward over the Arabian Sea. The pattern co-correlation between verification and forecast climatology over the global tropics and Indian monsoon region shows significant CCs. The observed and CFS forecast climatology of rainfall indicated a negative bias over the Indian land region, thus indicating a underestimation of CFS forecast rainfall over Indian land region in CFS. It is also found that the forecast rainfall from CFS has got lower coefficient of variability (CV) of seasonal rainfall compared to that of observed CV. With respect to the interannual variability of CFS forecast rainfall over the extended Indian monsoon region (50° E - 110° E and 10° S - 35° N) the signs are matching with the signs of observed rainfall departure with CC significant at or above 99% level with March, April and May ensembles. However, the CC between observed and forecast rainfall over the land region of India is comparatively less with highest CC (0.44) for April ensembles followed by that of May and March ensembles during the year 1981-2005. It is seen that Anomaly CC (ACC) maps show almost identical patterns with March, April and May initial conditions with higher ACCs particularly over the southern and eastern parts of the country (more than 0.4) and it is comparatively less over the northeastern and western parts of the country particularly with May and April ensembles.

In order to construct the hybrid dynamical-empirical model for the real time forecast of AISMR the CFS forecast variables are used to improve the overall skill of AISMR prediction. Based on the regions of significant CCs between the observed AISMR and the corresponding forecast rainfall from CFS the hybrid dynamical-empirical model is developed for the real time prediction of AISMR. Now applying the dynamical-empirical hybrid forecast and incorporating the variance correction the final forecast for 2009 and 2010 monsoon was found to be much closer to the observed AISMR even with March ensembles (forecast lead of 3 months). Thus, when the hybrid model is used there is a correction not only to the sign of the departure from the actual forecast but also its magnitude and hence can be used as a better tool for the real time application.

Acknowledgements

The authors are very much thankful to the National Centre for Environmental Prediction (NCEP) for providing the hindcast data sets from the Climate Forecast System (CFS) and the observational data for the verification purpose for a period of 25 years from 1981 to 2005 and also for the real time forecast products. The first author is also thankful to Dr. Suranjana Saha, EMC, NCEP and Dr. Wanju Wang, NCEP for the valuable discussion about the NCEP CFS forecast system. Thanks are also due to the office of Additional Director General of Meteorology (Research), IMD Pune for providing the observed rainfall data used in our analysis.

References

Blanford, H. F., 1884, "On the connection of the Himalayan snowfall with dry winds and seasons of droughts in India", *Proc. R. Soc. London*, **37**, 3-22.

Charney, J. G. and Shukla, J., 1981, "Predictability of monsoons", In: Lighthill J, Pearce RP (eds) Monsoon dynamics. (University Press), 99-109.

Chen, T. C. and Yen, M. C., 1994, "Interannual variation of the Indian monsoon simulated by the NCAR Community Climate Model: Effect of the tropical Pacific SST", *J. Climate*, **7**, 1403-1415.

Goswami, B. N., 1998, "Interannual variation of Indian summer monsoon in a GCM : external conditions versus internal feedbacks", *J. Climate*, **11**, 501-522.

Gowariker, V., Thapliyal, V., Kulshrestha, S. M., Mandal, G. S., Roy, N. Sen and Sikka, D. R., 1991, "A power regression model for long-range forecast of southwest monsoon rainfall over India", *Mausam*, **42**, 125-130.

Hong, S. Y. and Pan, H. L., 1996, "Non-local boundary layer vertical diffusion in a medium-range forecast model", *Mon. Wea. Rev*., **124**, 2322-2339.

Hong, S. Y. and Pan, H. L., 1998, "Convective Trigger Function for a Mass-Flux Cumulus Parameterization Scheme", *Mon. Wea. Rev*., **126**, 2599-2620.

Hou, Y., Moorthi, S. and Campana, K., 2002, "Parameterization of solar radiation transfer in the NCEP models", NCEP Office Note, 441. http://www.emc.ncep.noaa.gov/officenotes/FullTOC.html #2000.

Hou, Y. T., Campana, K. A. and Yang, S. K., 1996, "Shortwave radiation calculations in the NCEP's global model", International Radiation Symposium, IRS-96, August 19-24, Fairbanks, AL.

Ji, Y. and Vernekar, A. D., 2000, "Simulations of the Asian summer monsoons of 1987 and 1988 with a regional model nested in a global GCM", *J. Climate*, **10**, 8, 1965-1979.

Kalnay, E. and Coauthors, 1996, "The NCEP/NCAR 40-year Reanalysis Project", *Bull. Amer. Meteor. Soc*., **77**, 1057-1072.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S. K., Slingo, J. J., Fiorino, M. and Potter, G. L., 2002, "NCEP–DOE AMIP-II Reanalysis (R-2)", *Bull. Amer. Meteor. Soc*., **83**, 1631-1643.

Kang, I. S., Jin, K., Wang, K. B., Lau, K. M., Shukla, J., Krishnamurthy, V., Schubert, S. D., Waliser, D. E., Stern, W. F., Kitoh, A., Meehl, G. A., Kanamitsu, M., Galin, V. Y., Satyan, V., Park, C. K. and Liu, Y., 2002, "Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs", *Climate Dynamics*, **19**, 5-6, 383-395.

Kim, Y. J. and Arakawa, A., 1995, "Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model", *J. Atmos. Sci*., **52**, 1875-1902.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R. and Fiorino, M., 2001, "The NCEP-NCAR 50–Year Reanalysis: Monthly Means CD–ROM and Documentation", *Bull. Amer. Meteor. Soc*., **82**, 247-268.

Kripalani, R. H., Kulkarni, A., Sabade, S. S., Revadekar, J. V., Patwardhan, S. K. and Kulkarni, J. R., 2004, "Intraseasonal oscillations during monsoon 2002 and 2003", *Current Science*, **87**, 325-331.

Krishnamurti, T. N., Mitra, A. K., Yun, W. T., Vijaya Kumar, T. S. V. and Dewar, W. K., 2004, "Seasonal climate forecasting of the Asian monsoon using multiple coupled models", FSU Report No. 04-05. June 2004.

Krishnan, R., Sundaram, Suchithra, Swapna, P., Kumar, Vinay, Ayantika, D. C. and Mujumdar, M., 2010, "The crucial role of ocean-atmosphere coupling on the Indian monsoon anomalous response during dipole events", *Climate Dynamics*, DOI 10.1007/s00382-010-0830-2.

Large, W. G., McWilliams, J. C. and Doney, S. C., 1994, "Oceanic vertical mixing: A review and a model with non-local boundary layer parameterization", *Rev. Geophys*., **32**, 363-403.

Moorthi, S., Pan, H. L. and Caplan, P., 2001, "Changes to the 2001 NCEP operational MRF/AVN global analysis/forecast system", *NWS Technical Procedures Bulletin*, **484**, pp14. [Available at http://www.nws.noaa.gov/om/tpb/484.htm].

Nanjundiah, Ravi S., 2009, "A Quick-look assessment of forecasts for the Indian summer monsoon rainfall in 2009", A report of IISc., Bangalore, 1-32.

Pacanowski, R. C. and Griffies, S. M., 1998, "MOM 3.0 Manual", NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, USA 08542.

Pai, D. S. and Sreejith, O. P., 2010, "Global and regional and regional circulation anomalies", In "Monsoon 2009 - A Report" Ed. Ajit Tyagi, H. R. Hatwar and D. S. Pai, India Meteorological Department Met Monograph No: Synoptic Meteorology No: 09/2010, 56-76.

Palmer, T. N. and Anderson, D. L. T., 1994, " The prospects for seasonal forecasting – A review paper", *Quart. J. Roy. Meteor. Soc*., **126**, 2013-2033.

Palmer, T. N., Brankowic, C., Viterbo, P. and Miller, M. J., 1992, "Modelling interannual variations of summer monsoons", *J. Climate*, **5**, 399-417.

Pattanaik, D. R. and Kumar, Arun, 2010, "Prediction of summer monsoon rainfall over India using the NCEP climate forecast system", *Climate Dynamics*, **34**, 557-572.

Pattanaik, D. R., Kalsi, S. R. and Hatwar, H. R., 2005, "Evolution of convection anomalies over the Indo-Pacific region in relation to Indian monsoon rainfall", *Mausam*, **56**, 811-824.

Rajeevan, M., Pai, D. S., Dikshit, S. K. and Kelkar, R. R., 2003, "IMD's new operational models for long-range forecast of southwest monsoon rainfall over India and their verification for 2003", *Curr. Science*, **86**, 422-430.

Rajeevan, M., Pai, D. S., Anil Kumar, R. and Lal, B., 2006, "New statistical models for long-range forecasting of southwest monsoon rainfall over India", *Climate Dynamics*, DOI 10.1007/ s00382-006-0197-6.

Saha, S., Nadiga, S., Thiaw, C., Wang, J., Wang, W., Zhang, Q., Van den Dool, H. M., Pan, H. L., Moorthi, S., Behringer, D., Stokes, D., Pena, M., Lord, S., White, G., Ebisuzki, W., Peng, P. and Xie, P., 2006, "The NCEP climate forecast system", *J. Climate*, **19**, 3483-3517.

Sahai, A. K., Grimm, A. M., Satyan, V. and Pant, G. B., 2003B, "Long-lead prediction of Indian summer monsoon rainfall from global SST evolutions", *Climate Dynamics*, **20**, 855-863.

Sahai, A. K., Pattanaik, D. R., Satyan, V., Grimm, A. M. and Alice, M., 2003A, "Teleconnections in recent time and prediction of Indian summer monsoon rainfall", *Meteor. Atmos. Physics*, **83**, 217-227.

Sahai, A. K. and Satyan, V., 2000, "Reduction of AGCM systematic error by artificial neural network", A new approach for dynamical seasonal prediction of Indian summer monsoon rainfall. IITM Research Report No-088.

Shukla, J. and Mooley, D. A., 1987, "Emperical prediction of the summer monsoon rainfall over India", *Mon. Wea. Rev*., **115**, 695-703.

Shukla, J., Anderson, J., Baumhefner, D., Brankovic, C., Chang, Y., Kalnay, L., Marx, L., Palmer, T. N., Paolino, D. A., Ploshay, J., Schubert, S., Straus, D. M., Suarez, M. and Tribbia, J., 2000, "Dynamical Seasonal Prediction", *Bull. Amer. Meteor. Soc*., **81**, 2593-2606.

Smagorinsky, J., 1963, "General circulation experiments with the primitive equations: I. The basic experiment", *Mon. Wea. Rev*., **91**, 99-164.

Soman, M. K. and Slingo, J., 1997, "Sensitivity of Asian summer monsoon to aspects of sea surface temperature anomalies in the tropical Pacific Ocean", *Quart. J. Roy. Meteor. Soc*., **123**, 309-336.

Sperber, K. R. and Palmer, T., 1996, "Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project", *J. Climate*, **9**, 2727-2750.

Sperber, K. R., Brankovic, C., Deque, M., Frederiksen, C. S., Graham, R., Kitoh, A., Kobayashi, C., Palmer, T., Puri, K., Tennant, W. and Volodin, 2001, "Dynamical seasonal predictability of the Asian summer monsoon", *Mon. Wea. Rev*., **129**, 9, 2226-2248.

Srivastava, A. K., 2010, "Rainfall Statistics", In "Monsoon 2009-A Report" Ed. Ajit Tyagi, H. R. Hatwar and D. S. Pai. India Meteorological Department Met Monograph No: Synoptic Meteorology No: 09 /2010, 41-55.

Tyagi, Ajit and Pattanaik, D. R., 2010, "Real time monitoring and forecasting of Intra-seasonal monsoon rainfall activity over India during 2009", India Meteorological Department Met Monograph No: Synoptic Meteorology No: 10 /2010, 1-42.

Tyagi, Ajit, Mazumdar, A. B. and Pai, D. S., 2011, "Monsoon 2010-A Report", India Meteorological Department Met Monograph No: Synoptic Meteorology No: 10 /2011, 1-210.

Wang, B., Kang, I. S. and Lee, J. Y., 2004, "Ensemble Simulations of Asian-Australian Monsoon Variability by 11 AGCMs", *J. Climate*, **17**, 803-818.

Wang, B., Lee, J. Y., Kang, I. S., Shukla, J., Park, C. K., Kumar, A., Schemn, Cocke, J. S., Kug, J. S., Luo, J. J., Zhou, T., Wang, B., Fu, X., Yun, W. T., Alves, O., Jin, E. K., Kinter, J., Kirtman, B., Krishnamurti, T. N., Lau, N. C., Lau, W., Liu, P., Pegion, P., Rosati, T., Schubert, S., Stern, W., Suarez, M. and Yamagata, T., 2008, Advance and prospects of seasonal prediction : assessment of the APCC/CliPAS 14-model ensemble retrospective seasonal prediction (1980-2004).

Webster, P. J. and Yang, S., 1992, "Monsoon and ENSO: Selectively interactive systems", *Q.J.R. Meteorol. Soc*., **118**, 877-926.

Xie and Arkin, 1997, "Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs", *Bulletin of the American Meteorological Society*, **78**, 2539-2558.