MAUSAM, **70**, 2 (April 2019), 265-276

551.509.33 : 551.553.21 (540)

Seasonal prediction of Indian summer monsoon in India: The past, the present and the future

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सार – भारत में भारतीय ग्रीष्मकालीन मॉनसून के मौसम पूर्वानुमान का एक लंबा इतिहास रहा है और भारत ने विश्वसनीय मौसम पूर्वानुमान करने में महत्वपूर्ण रूप से प्रगति की है। यह लेख भारत मौसम विज्ञान विभाग द्वारा अनुभवजन्य तरीकों के आधार पर 1886 में मौसम पूर्वानुमान के प्रथम प्रयास से लेकर वर्तमान के अत्याधुनिक तरीकों के आधार पर दिए जाने वाले मौसमी पूर्वानुमान के क्षेत्र में हुई प्रगति की समीक्षा प्रस्तुत करता है, जिसे मॉनसून मिशन के अंतर्गत मॉडल डायनेमिक मॉडलिंग फ्रेमवर्क के तहत विकसित किया गया है। मौसमी पूर्वानुमान की सफलताओं और असफलताओं को कई लेखों में प्रलेखित किया गया है, इसमें इसकी विफलता पर विशेष रूप से जोर दिया गया है। वर्ष 1900 के शुरूआती दशक में अनुभवजन्य मॉडल ने कुछ दशकों तक बहुत अच्छा प्रदर्शन किया, उसके बाद ये विफल होने लगे। जिस प्रकार से पूर्वानुमानकर्ताओं के संबंधों में महत्वपूर्ण परिवर्तन हुए, अनुभवजन्य मॉडल को भी कई मौकों पर अद्यतन/ नया बनाया गया। मॉनसून मिशन से पहले (2010 से पहले) भारतीय मॉनसून का मौसमी पूर्वानुमान देने के लिए गतिशील मॉडल का उयोग करने का प्रयास किया गया था, विशेषरूप से टियर-।। मॉडलिंग फ्रेमवर्क में, जो कि सीमित सफलता के साथ सटैंडअलोन वायुमंडलीय सामान्य परिसंचरण मॉडलों (AGCMs) पर आधारित था। 2008-09 में मौसमी पूर्वानुमान तैयार करने के लिए भारत में युग्मित मॉडलिंग ढाँचे की तत्काल आवश्यकता महसूस की गई, मुख्य रूप से भारतीय मॉनसून की गत्यात्मक प्रकृति के मॉडल के लिए और इसलिए लगभग 38 कि.मी. के उच्च वायुमंडलीय क्षैतिज विभेदन में एक युग्मित डायनेमिक मॉडलिंग ढाँचा लागू किया गया जिससे कि प्रचालनात्मक/प्रायोगिक स्तर पर मौसमी पूर्वानुमान दिया जा सके जो अब तक के लिए अद्वितीय है। इस डायनेमिकल मॉडल ढाँचे को भविष्य में एयरोसोल/ग्रीन हाउस गैसों, महासागरीय बायो-जियो केमिस्ट्री और क्लोज्ड मॉडल हाइड्रोलॉजी को पृथ्वी विज्ञान प्रणाली के ढाँचे में शामिल करने के लिए अपग्रेड किया जाएगा।

ABSTRACT. Seasonal prediction of summer monsoon in India has had a long history and India has made significant strides in making reliable seasonal predictions. This article provides a detailed review of the progress made in the field of seasonal prediction by India starting from the first attempt of seasonal prediction by India Meteorology Department (IMD) in 1886 based on empirical methods to the present day state-of-the-art coupled dynamical modelling framework developed under "Monsoon Mission". The success and failures of seasonal prediction were amply documented in several articles particularly with more emphasis on its failures. Starting in the early 1900s, the empirical models performed very well for a few decades after which they started failing. As the relationship with predictors underwent significant changes, empirical models were also updated/revamped on several occasions. Prior to Monsoon Mission (before 2010) attempts were made to use dynamical models for seasonal prediction of Indian monsoon, particularly in the tier-II modelling framework, which was based upon the standalone Atmospheric General Circulation Models (AGCMs), albeit with limited success. The immediate need for coupled modelling framework in India was felt in 2008-09 for making seasonal forecasts, primarily to model the dynamical nature of Indian Monsoon and hence, a coupled dynamical modelling framework at a very high atmospheric horizontal resolution of ~38 km was implemented to make operational/experimental seasonal forecasts, so far unparalleled. The dynamical modelling framework will be upgraded in the future to contain an earth system framework with aerosols/greenhouse gases, ocean bio-geo chemistry and closed model hydrology.

Long-Range Weather Forecasting "The second most difficult problem in the world" (Human behavior presumably being the first) – John von Neumann.

Key words – Seasonal prediction, Monsoon, Monsoon mission.

1. Introduction

Long Range Prediction also known as "Seasonal prediction" is an attempt to estimate the change in the likelihood of a climatic event happening in the coming months. It is well known that the prediction of day-to-day weather event in the tropics is limited to 2-3 days (Lorenz, 1963). Thus the big question is how is it possible to make any useful predictions months ahead? The famous quote by Prof. John Von Neumann made in early 1964 is valid

even today. Seasonal prediction is not an attempt to predict the weather events of a particular location at a particular time, as is the case in weather prediction. Seasonal prediction deals with forecasting the average climate of a large region for the coming seasons, which may have a time span of 2-3 months. In the tropical regions, the low-frequency variability of climate is dependent on slowly varying boundary forcing which evolve slowly compared to the weather systems itself (Charney and Shukla, 1981). The predictability arising from these slowly varying boundary conditions is often referred to as the predictability of second kind. These boundary conditions include sea surface temperatures (SST), land temperature, soil moisture etc. This laid the foundation of seasonal prediction of tropical climate. Seasonal prediction approaches are generally of two types (statistical & dynamical). The seasonal prediction techniques of first type are based on statistical/empirical techniques. Statistical methods first identify predictors using past observations based on highly significant correlation coefficients (CC). One of the major problems with this technique is that it cannot include secular variations between the predictors and predictand, which can lead to inaccuracy in the predicted field (Rajeevan, 2003). Linear regression analyses based on large number of regression models are also used in the statistical analysis. By the early 1990s, with the availability of computational power, researchers started using standalone atmospheric general circulation models (AGCMS) for seasonal forecast (Sperber and Palmer, 1996). Basic limitation of this approach is that the boundary conditions need to be prescribed and hence was not able to predict the climate as such. Further advancement of computational power and better understanding of dynamic evolution of the major components of the Earth system, including their interactions, has led to the use of ocean-atmosphere coupled models for seasonal prediction. At present, majority of the seasonal prediction centers in the world are using dynamical system for operational seasonal prediction.

1.1. *Importance of Indian summer monsoon and its seasonal prediction*

Indian summer monsoon is one of the prominent tropical phenomenon and the rainfall associated with it provides more than 70% of freshwater to satisfy the needs of a densely populated country like India. The mean rainfall within a span of four months (June to September) is around 86 cm with an inter-annual variation of about 10% of the mean. This inter-annual variability determines the socio-economic behavior of the country and therefore the long range (seasonal) prediction of Indian summer monsoon rainfall (ISMR) is very crucial and useful. The inter-annual variability of ISMR is generally controlled by the slow varying boundary forcings such as SST anomalies in the east Pacific (Rasmusson and Carpenter, 1983) and Indian Ocean (Ashok *et al*., 2001; Rajeevan *et al*., 2001) land surface temperature (Rajeevan *et al*., 1998) and snow cover over Eurasia and Himalayas (Bamzai and Shukla, 1999). Amongst these boundary forcings, the ISMR relationship with Pacific SST in the form of El Nino Southern oscillation (ENSO) has been established long ago (Walker, 1924; Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). The slowly evolving nature of these boundary forcings makes seasonal prediction of ISMR possible (Charney & Shukla, 1981). Studies by Ajayamohan and Goswami (2000) and Webster *et al*. (1998) suggest that the entire variability of ISMR cannot be explained by the boundary forcing alone, but the internal dynamics also can play a significant role. These internal dynamics limit the ISMR predictability.

For the long range forecasting (LRF) of the ISMR, two main approaches are used. The first is a statistical method involving comprehensive diagnostic and empirical studies, which uses the historical relationship between ISMR and global ocean-atmosphere parameters (Walker, 1908, 1914 & 1923; Thapliyal, 1982; Gowariker *et al*., 1989 & 1991; Singh and Pai, 1996; Rajeevan *et al*., 2000 & 2004; Delsole and Shukla, 2002; Pai and Rajeevan, 2005). The second approach is based on the dynamical method, which uses General Circulation Models (GCM) of the either atmosphere or oceans to simulate the summer monsoon circulation and associated rainfall.

2. History of ISMR seasonal prediction

2.1. *Empirical models*

How well we can incorporate all the long period fluctuations in the statistical model will determine the degree of success of the forecasts – Jaganathan (1973).

This review basically restricts to the operational works carried out at IMD to make operational seasonal climate forecasts. Other groups within the country and outside have carried out several empirical studies (Thapliyal, 1982; Gowariker *et al*., 1989, 1991; Singh and Pai, 1996; Rajeevan *et al*., 2000, 2004, 2007; Delsole and Shukla, 2002; Pai and Rajeevan, 2006.), however this article do not cover those efforts.

2.1.1. *Efforts in late 19th century and early 20th century*

Seasonal prediction of ISMR started in the late 18th century when the country faced severe famine in 1877 and 1878 Then the Director General of India Meteorological Department (IMD), H. F. Blanford, started preparing

TABLE 1

History of LRF of ISMR

Year	Author	Predictors	Method	Reference
1886	H. F. Blanford	Snowfall in the Himalayas and the southern Sulaiman Range during the preceding January to May and Mean Pressure over Bombay	Checking the relation and issue the forecast (More Snowfall → weak Monsoon)	Savur (1939)
1887	Sir John Elliot	All of the above and Conditions all over India	Checking the relation and issue the forecast by plotting all the parameters and find parallelism with Indian rainfall	Savur (1939)
1896	Sir John Elliot	All of the above and south-east trades at Mauritius, Zanzibar and Seychelles	Do	Savur (1939)
1897	Sir John Elliot	All of the above and data from South Australia and the Cape Colony	Do	Savur (1939)
1900	Sir John Elliot	All of the above and Nile Flood	Do	Savur (1939)
1904-1910	Sir Gilbert T. Walker	Snowafall accumulation north of India, Mauritius PPressure, South American (Arzentina and Chile) pressure and Zanzibar rainfall	First use of correlations still used	Walker (1908, 1914, 1918, 1923, 1924, 1928)
1914-1924 Similar models are used until 1930	Sir Gilbert T. Walker	Peninsula → South American pressure, Zanzibar rain and Java Rain Northwest India → In addition to the above rainfall over SriLanka rain was also considered together with snowfall north of India	1914 → Divided India into four homogenous regions for issuing of forecasts: Burma, north-east India, south Madras and the rest called India-Main. Peninsula and North India were separated to issue forecasts	Do
1956		In addition to the above upper air observations over India (Agra and Calcutta for NW-India; Calcutta and Bangalore) were considered in the regression formulas of seasonal forecasting		Thapliyal (1982)
1981-1990		New LRF models such as Power Regression, Multiple Regression and Dynamic Stochastic Transfer models	LRF of AISMR as well as the monsoon rainfall over peninsular and north-western India	Thapliyal (1987)
1991	Gowariker and others	1. 50 hPa wind pattern (winter) 2. Eurasian snow-cover (December) 3. 500 hPa ridge (April) 4. Central India temperature (May) 5. 10 hPa zonal wind pattern (January) 6. East coast of India temperature (March) 7. Northern Hemisphere surface pressure anomaly (January-April) 8. Argentina pressure (April) 9. Northern Hemisphere temperature (January and February) 10. Southern Oscillation Index (spring) 11. El Nino (previous year) 12. North India temperature (March) 13. Indian Ocean equatorial pressure (January-May) 14. El Nino (same year) 15. Himalayan snow-cover (January-March) 16. Darwin pressure (spring)		Gowariker *et al*. (1991)

monsoon forecasts by relating the abnormally high pressures that extended to western Siberia, northern China and southern Australia during 1877 to ISMR. Blanford (1884) gave the forecast for the period 1882 to 1885 based on the hypothesis that "varying extent and thickness of the Himalayan snow exercises a great and prolonged influence on the climate conditions and weather of the plains of northwest India" (Hastenrath, 1987). Henceforth making seasonal forecast of ISMR then became a routine affair until 1905, though they were kept confidential

during world war II and later (Hastenrath, 1987). Success of the forecast in the coming years based on this hypothesis was encouraged by Sir John Elliot, who succeeded Blanford in 1895. He utilised more weather conditions like, (*i*) October-May snow over Himalaya, (*ii*) local Indian weather conditions in April-May (*iii*) and local conditions over Indian Ocean and Australia (Thapliyal, 1987) and issued long range monsoon forecast. Later, Sir Gilbert Walker, the then director of IMD extended the search for monsoon predictors to world wide variation of weather elements such as pressure, rainfall, temperature etc. These studies led Walker to identify three large-scale pressure seesaw patterns two in the Northern Hemisphere (the North Atlantic Oscillation, NAO and the North Pacific Oscillation, NPO) and one in the Southern Hemisphere (the Southern Oscillation, SO) (Walker, 1918 and 1923). While the NAO and the NPO are essentially regional in nature, the SO has since been recognised as a phenomenon with global-scale influences. The SO was later linked to the oceanic phenomenon called El Nino in the east equatorial Pacific which is characterised by warming of the sea surface along the Peru coast. This led to the theory of Walker Circulation (Bjerknes, 1969). Thus he was successfully able to introduce this pressure oscillation pattern also as a predictor for monsoon LRF (Walker, 1924). Thus Walker removed the subjectivity in the LRF by introducing the concept of correlated predictors between the fields. Walker (1924) also attempted to provide LRF for smaller geographic regions like north-east India, peninsular India and north-west India (Thapliyal, 1987) using separate multiple regression models. This practice of using different regression analysis for the sub-regions continued up to 1987 with some modifications. Verifications of these empirical forecasts from 1924-1987 revealed a success rate of 64% (based on categories) for northwest India and peninsular India regions (Rajeevan, 2001), however Gadgil *et al*. (2005) have shown that skill of operational models did not change even after desperate changes in the operational models. A brief of IMD LRF prediction system from 1886 to recent period is provided in Table 1.

2.1.2. *Efforts in late 20th century and early 21st century*

As the largest driver of tropical climate, ENSO is considered as the major driver of climate prediction and the subsequent studies focused on understanding the physical mechanism and the successful prediction of ENSO. Later on, studies identified the importance of other phenomenon like NAO (Lamb and Peppler, 1987), Pacific-North American (PNA) pattern (Frankignoul and Sennechael, 2007) in the extra tropics and the Indian Ocean Dipole (IOD, Saji *et al*., 1999) in the tropical regions. These modes listed above are not independent of equatorial Pacific influence (Yu and Zwiers, 2007; Schott *et al*., 2008; Jansen *et al*., 2009). ENSO, therefore, remains the principal global signal seasonal forecasting models seek to capture.

Subsequent to Walker's work and the global research on seasonal prediction, studies identified more predictors for LRF of ISMR by analysing the relationship between ISMR and different regional/global parameters of surface/upper air through correlation analysis. This lead to the identification and use of 16 parameters from preceding winter and spring seasons representing regional conditions, ENSO indicators, cross-equatorial flow and global hemispheric conditions as shown in Table 1. These efforts resulted in development of new types of LRF models such as dynamical stochastic transfer, parametric and power regression. Thus IMD started issuing LRF based on 16 parameters by using parametric and power regression models (Gowariker *et al*., 1989, 1991). The power regression model is a quantitative model, which uses non-linear interactions of different climate indices and monsoon. Meanwhile it is observed that the predictor-ISMR relationship (correlation) varies in time and in the year 2000, it was realized that out of the sixteen parameters, four of them have lost their correlation with ISMR and hence they were replaced by other predictors (Rajeevan, 2001). IMD provided regional forecasts also during this period. But the forecast error was more than model error for years like 1994, 1997 and 1999. Meanwhile, many predictors continued to lose its relationship with ISMR associated with the changes in the global circulation system. A statistical study by Rajeevan *et al*. (2001) using five predictors related to ENSO have shown that predictor-ISMR relationship was stronger in years having higher interannual variability of ISMR and in those years, ISMR is more predictable compared to the years with weak coupling between the predictors and ISMR. But the empirical models used during the period showed poor skill for these extreme years and has better skill for normal years. The failure of statistical models to in predicting the extreme monsoon years was noted by Gadgil *et al*. (2005). The study revealed that IMD's operational forecast skill has not improved over the seven decades despite continued changes in the operational models.

Following the failure of statistical forecast in 2002, a critical evaluation of the 16-parameter power regression and parametric models was made and two new models (8 and 10 parameter models) were introduced for the operational forecasts in 2003. Further, a two stage forecasting strategy also was adopted with the provision for a forecast update by end of June/first week of July (Rajeevan *et al*., 2004). According to this new strategy, forecasts for the seasonal ISMR for the country as a whole

TABLE 2

Skill of different statistical models developed by IMD during their developing, testing and operational period. The value indicates the skill and time period in bracket denotes the time for which the skill value is obtained

Model	Skill of the Model during tuning period (Period)	During Testing Period (Period)	During Operational Period (Period)
Power regression model (16 parameters) Developed In 1987 (Rajeevan *et al*., 1987; Gowariker *et al*., 1992)	0.96 (1958-1985)	0.94 (1986-1988)	0.24 (1982-2004)
8 parameter model in 2004 (Rajeevan *et al*., 2004)	0.89 (1958-1995)	0.72 (1996-2002)	0.42 (2002-2016)
10 parameter regression model (Rajeevan *et al*., 2004)	0.90 (1958-1995)	0.75 (1996-2002)	
EMR-1	0.86 (1988-2004)	N. A.	0.44 (2006-2016)
EMR-2	0.88 (19882004)		
PPR-1	0.82 (1988-2004)		
PPR2	0.76 (1988-2004)		

are issued in two stages. The first stage forecast is issued in mid-April and an update or second stage forecast is issued by the end of June. The operational forecasts for the southwest monsoon rainfall based on these new models were proved to be correct for 2003 monsoon. However, in 2004, the forecast for a normal monsoon again failed due to a weak monsoon. Following the forecast failure in 2004, IMD critically analyzed two major issues, (a) a re-visit of the suitable and stable predictors, which have physical relationships with monsoon rainfall and (b) critical way of model development based upon identifying the optimum number of predictors and optimum model training period etc. IMD further explored new statistical methods with an objective to improve model performance. These new statistical techniques are described in Rajeevan *et al*. (2007).

2.1.3. *Limitations of the empirical models for seasonal forecasting*

Using empirical models for seasonal forecasting has been going on for quite some time (Blanfolrd, 1884; Rajeevan *et al*., 2007) and it continues even today due to various advantages it has.

(*i*) Developing an empirical model with the past data based on the past information can be done with limited resources compared to more advanced state-of-the-art dynamical models.

(*ii*) The models' prediction skill happened to be better than dynamical models in earlier decades and as a result provided better forecasts with empirical models.

It is to be noted here that all empirical models consider the past teleconnections to develop the models and they also appear to perform well at least during the testing period, however once the models were operationalized and predictions were made based on these models, the prediction skill drops significantly (Table 2). Major limitations of the empirical models is that

1. The relation between predictors and predictand is assumed to be stationary and it is not the case in reality (Rajeevan *et al*., 2001, 2004). Hence the models do not perform well when employed for operational forecasts (Table 2).

2. Statistical models tend to produce a normal monsoon forecast most of the time and hence are successful in predicting normal monsoons only and not the extremes (Gadgil *et al*., 2005).

Fig. 1 shows the 11 year running correlation between observed ISMR anomalies and model predicted anomalies together with moving 11 year standardized ISMR anomalies using a statistical model developed with 100 years of data (1901-2000, Rajeevan *et al*., 2001). The model is using five predictors representing ENSO forcing (Darwin pressure tendency and Nino3 SST tendency from boreal winter to spring), land surface conditions over Eurasia (Northern hemisphere temperature during January and February months, Argentina pressure during boreal spring) and intensity of heat low in northwest India (northwest India minimum temperature in May). As is evident from this figure the model performance is very good during the periods when 11-year moving averages are on positive side and weaker during the periods when the moving averages were on negative side, which highlights that the normal monsoon years are well captured by the empirical models and failed to capture extreme years.

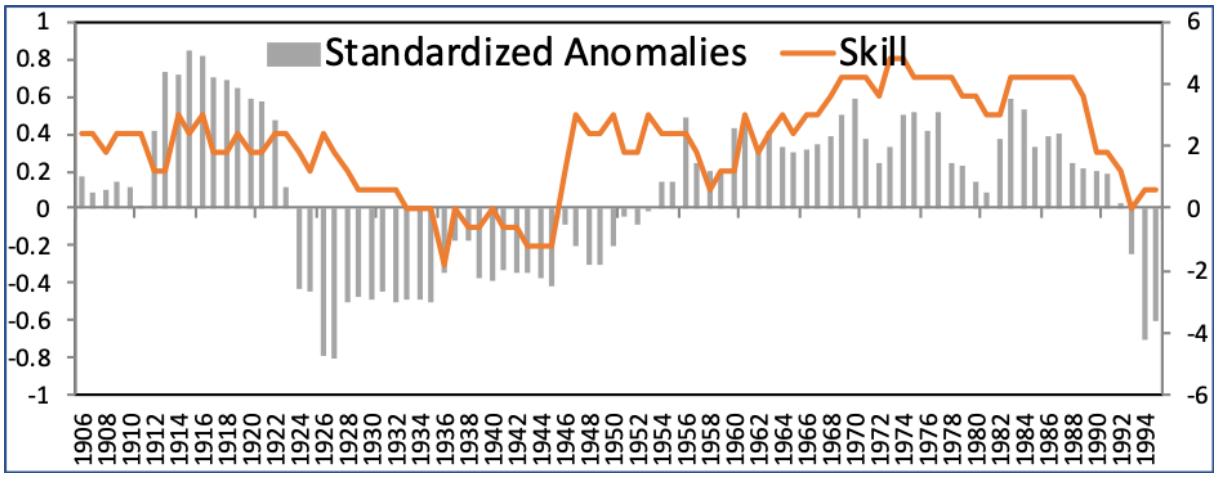

Fig. 1. Running correlations (11 Year) of ISMR standardized anomaly with operational model predictions (line) form 1906-1994 and moving-averages (11 year) ISMR standardized anomaly (Data extracted from Rajeevan *et al*. (2001). The data set are generated from statistical model developed (Rajeevan *et al*., 2001) from five predictors representing ENSO forcing (Darwin pressure tendency and Nino3 SST tendency from boreal winter to spring), land surface conditions over Eurasia (Northern hemisphere temperature during January and February months, Argentina pressure during boreal spring) and intensity of heat low in northwest India (northwest India minimum temperature in May)

2.2. *Dynamical Modelling Framework for forecasting Indian summer monsoon rainfall*

"It is known that significant ocean temperature anomalies persisting for decades or longer introduce anomalous atmospheric circulations. Thus in long range forecasting, the other boundary conditions will have to be taken into account and the atmosphere-ocean-continent complex will have to be treated as a whole" - Jagannathan (1976).

The above quote amply highlights the refined approach of the scientists at that time. Scientists involved in operational seasonal forecast quickly realized that coupled ocean-atmosphere models are must to address the seasonal prediction problem. This idea of coupled modeling led India to issue its first experimental seasonal forecast based on coupled model in 2009 due to the efforts made at IITM. This section highlights the various efforts by Indian Scientists towards producing dynamical forecasts of ISMR.

2.2.1. *Standalone atmospheric general circulation models*

Around mid-1980s, modelling groups started efforts to simulate the monsoon circulation using dynamical models. Under the monsoon numerical experimental group program (MONEG) different modelling groups around the world tried to simulate 1987 and 1988 monsoon features (Palmer *et al*., 1992). Even though the models differ from each other, the clear message that came out from this effort was that, the ISMR is mainly forced by Pacific SST anomalies. A similar and more organised Atmospheric inter-comparison project (AMIP, Sperber and Palmer, 1996) provided an opportunity to study the monsoon simulation for a longer period (1979-1988) using observed SST as the boundary condition, but the interannual monsoon variability differed from model to model. These dynamical models have not shown the required skill to accurately simulate the salient features of the mean monsoon and its inter-annual variability (Gadgil and Sajini, 1998; Krishnamurti *et al*., 2000; Kang *et al*., 2002; Gadgil *et al*., 2005; Krishna Kumar *et al*., 2005; Wang *et al*., 2005). Analysis of the failure of these GCMs in capturing the monsoon features indicated that even though observed SST is prescribed, the rainfall distribution and the extreme rainfall events could not be simulated. Thus the monsoon forecast skill further reduced in these models (Gadgil and Sajini, 1998). Therefore, it was established that an ocean-atmosphere coupled climate model is essential for seasonal prediction of ISMR (Wang *et al*., 2005).

2.2.2. *Seasonal prediction of Indian summer monsoon (SPIM) project*

As part of the seasonal monsoon prediction research, some experimental forecasts with atmospheric models have also been generated at India by major research institutes such as Centre for mathematical modelling and simulations (CMMACS) Bangalore; the Indian Institute of Tropical Meteorology (IITM), Pune; Space Applications Centre, Ahmedabad [in collaboration with the National Centre for Medium Range Weather Forecasting (NCMRWF), Delhi] and IMD [in collaboration with the

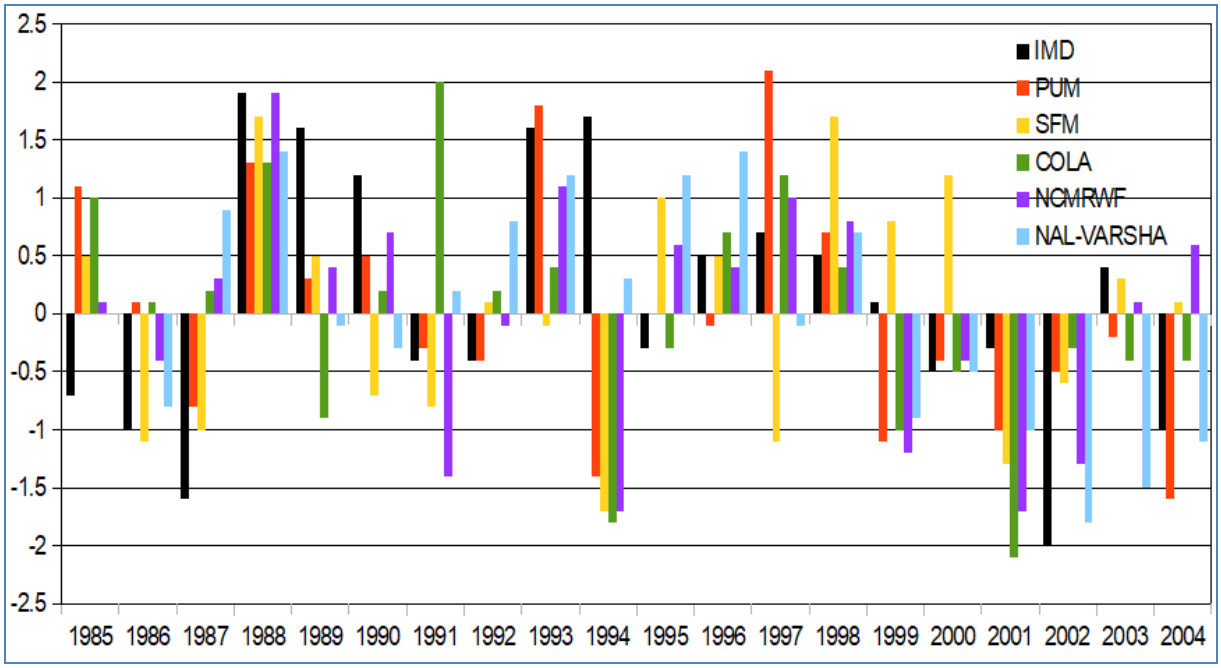

Fig. 2. Time-series of ISMR for the period 1985-2004 from five models used in the SPIM project along with IMD observations. The data is extracted from Gadgil and Srinivasan (2011)

Indian Institute of Science (IISC), Bangalore] by early 2000s. The performance and reliability of such atmospheric models was assessed by running them for several years with identical initial and boundary conditions from data available for each monsoon season. The error levels of each atmospheric model can be objectively assessed by analysis of these retrospective forecasts. Such an exercise would lead to a more focused research effort in developing better models for monsoon prediction. This idea led to the formation of a project called "Seasonal Prediction of Indian summer monsoon" (SPIM, Gadgil and Srinivasan, 2011). The project used five AGCMs and simulations for the period 1985-2004 were made with same initial conditions to assess the prediction of Indian summer monsoon rainfall. Two sets of simulations were conducted in which in the first set, the AGCMs were forced by the observed sea surface temperature (SST) for May-September. In the second set, runs were made for 1987, 1988, 1994, 1997 and 2002 forced by SST which was obtained by assuming that the April anomalies persist during May-September. The first set runs indicated that none of the models were able to simulate the correct sign of the Indian summer monsoon rainfall anomaly for all the years (Fig. 2). However, amongst the five models, one simulated the correct sign in the largest number of years and the second model showed maximum skill in the simulation of the extremes (*i.e.*, droughts or excess rainfall years), which is an advantage over AMIP simulations. Both these models correlated with observed ISMR with a correlation coefficient of 0.4 (Fig. 2) only. These runs also identified some common biases which could arise either from an excessive sensitivity of the models to El Niño Southern Oscillation (ENSO) or inability of the models to simulate the link of the Indian monsoon rainfall to Equatorial Indian Ocean Oscillation (EQUINOO), or both. Second set of runs showed that with a weaker ENSO forcing, some models could simulate the link with EQUINOO, suggesting that the errors in the monsoon simulations with observed SST by these models could be attributed to unrealistically high sensitivity to ENSO. Thus, this project laid the foundation of identifying the process/factors needed to be simulated for the better prediction of ISMR.

But generating predictions of the rainfall during the summer monsoon using such models, it is necessary to predict SST for the forthcoming season. Thus, predictions have to be eventually generated with models of the coupled atmosphere-ocean system using initial conditions for the ocean as well as the atmosphere. Meanwhile analysis of ISMR simulation of earlier generation coupled models developed by world centres as part of different projects like development of a European Multi-model Ensemble system for seasonal to inter-annual prediction (DEMETER, Palmer *et al*., 2004) for a longer period of more than 50 years showed poor skill (CC = 0.28) and the correlation is positive only over central India. Analysis by Preethi *et al*. (2010) has shown that the model failed to capture many of the extreme events during the period. Later analysis of European union project for developing

an ensemble prediction system for climate studies based on multiple models (ENSEMBLE) by Rajeevan *et al*. (2012) indicated that ISMR skill increased to 0.43 compared to 0.28 of DEMETER. By this time there were significant improvements in the theoretical understanding of the monsoon and the process that can control the monsoon variability. Still, prediction of ISMR was a tough challenge even for the available coupled models. These model intercomparison analyses (Preethi *et al*., 2010; Rajeevan *et al*., 2012) indicated that there are large biases in the mean monsoon rainfall simulated by the coupled models compared to the observations, with the models simulating excess rainfall over the equatorial Indian Ocean and less rainfall over the Indian monsoon zone. Most models have a systematic cold bias in the simulation of SST over the equatorial Indian Ocean and Pacific Ocean. Thus the coupled models have to be improved before they can generate accurate and reliable predictions of monsoon rainfall. Also, the coarse resolution of coupled models was thought to be a reason for the inaccurate simulations.

In the recent period, there has been considerable progress in the simulation and seasonal prediction of tropical Pacific SST and rainfall (Achutha Rao and Sperber, 2002; Doblas-Reyes *et al*., 2005; Randall *et al*., 2007) as a result of improvements in model dynamics and physics including resolution (Guilyardi *et al*., 2004; Roberts *et al*., 2009), better observations (Alves *et al*., 2004) and Four Dimensional Data Assimilation (4D-VAR)/Hybrid Kalman filter, etc. As the ISMR prediction in general circulation models is largely dependent on ENSO-ISMR relationship (Gadgil and Sajani, 1998; George *et al*., 2017) than other external boundary forcings, better simulation of ENSO was supposed to enhance ISMR skill. Meanwhile, 2004 onwards, IMD started experimental dynamical forecasting system using seasonal forecast model (SFM) having a resolution of T63L28 of the Experimental Climate Prediction Center (ECPC), USA. The forecast skill difference between the statistical model and the dynamical experimental forecast was not encouraging. The lack of visible progress in the simulation of the Indian monsoon by coupled GCMs in the backdrop of significant improvement of other global climate modes by the models urged for targeted model developments to improve the generic biases in simulating the Indian monsoon system.

Against this backdrop, the Ministry of Earth Sciences (MoES), Government of India launched the ambitious "Monsoon Mission (MM)" in 2010, a mission mode program, not only to implement a state-of-the-art dynamical prediction system for seasonal, extended and short range prediction of ISMR using a high resolution global atmospheric model but also to carry out Reseach and Development (R & D) required to improve the skill of Indian monsoon prediction in a time bound manner.

2.2.3. *"Monsoon Mission"- A targeted activity to improve ISMR prediction*

One of the major reasons behind the limited modelling activities in India was due to lack of trained manpower to work on model development and lack of High Performance Computing (HPC) infrastructure to run these models. Several academic and R&D institutes in India are carrying out research in the field of ISMR prediction and its contributors on different models (both empirical and dynamical), including diagnostics of why the models fail to predict a particular year's monsoon performance (Rajeevan, 2001; Gadgil *et al*., 2005; Wang *et al*., 2015). However, the knowledge gained at these institutes is not translated into improvement of operational weather and climate forecasts, as there is no concerted effort to link the knowledge gained at academic and R&D organizations to improve operational models as all these organizations are working at their will on different models which they can obtain easily. Hence, Ministry of Earth Sciences (MoES) had launched "Monsoon Mission" with an aim to focus on improving the prediction skill of dynamical models in forecast mode with clear deliverable improved forecasts.

Thus, the major aim of the Mission was

- To build a working partnership between the Academic and R & D Organizations, both national and international and MoES to improve the monsoon forecast skill over the country.

- To setup a state of the art dynamical modelling framework for improving prediction skill of (a) Seasonal and Extended range predictions and (b) Short and Medium range (up to two weeks) prediction.

Four MoES institutes (full name) are involved in the program with the Mission Directorate at IITM, Pune. The ocean-atmosphere coupled dynamical model "Climate Forecast System, Version-2" (CFSv2, adopted from NCEP, USA) was chosen as the base model. Several model developmental activities were taken up by ESSO-IITM for improving the skill of monsoon rainfall at different time and spatial scales in CFSv2 model. ESSO-NCMRWF worked on improving short to medium range forecasts using Unified Model (UM) of UK Met. Office (UKMO) for short to Medium range weather forecast (prediction up to 10 days in advance). Atmospheric data assimilation for the models was provided by NCMRWF and ocean component by INCOIS using GODAS.

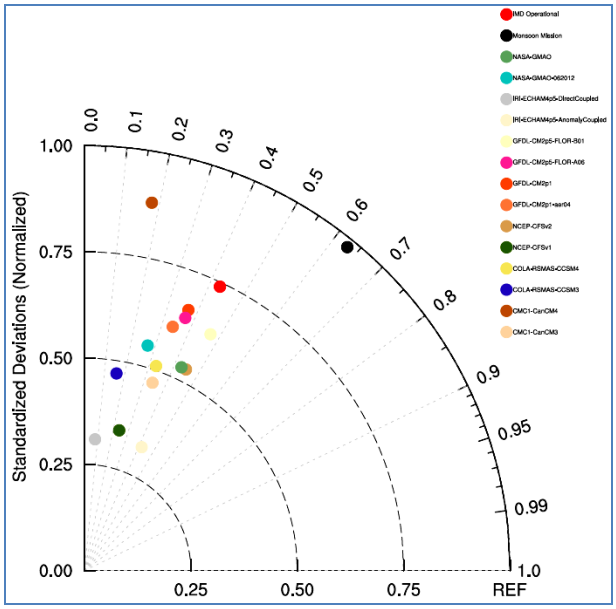

Fig. 3. Taylor diagram showing the skill of Monsoon Mission CFSv2 and other current generation seasonal prediction models and IMD operational statistical system forecast for the period 1981-2010

Under the Monsoon Mission program, the CFSv2, originally obtained from NCEP, was run at very high spectral resolution of T382 (~38 km) for the atmospheric model. Thus, first time in the world a seasonal prediction system was run at this high resolution globally. Analysis of the hindcasts generated indicated that Feb IC (3 month lead) hindcasts of CFSv2 has better skill for boreal summer monsoon rainfall (Chattopadhay *et al*., 2015; Ramu *et al*., 2016; Pillai *et al*., 2017) and is higher for CFSv2 - T382 (Monsoon mission model) compared to original T126 (100 km resolution) version. The skill of the model increased from 0.48 (T126) to 0.55 (T382) for the period 1981-2008 with the improvement of horizontal resolution of the atmospheric model, most importantly the inter-annual standard deviation improved from 0.4 mmday^{-1} (T126) to 0.5 mm day^{-1} (T382). At the same time model improvements were also being done, such as improvements in convective parameterization [utilization of modified Revised Simplified Arakawa Schubert (SAS)], cloud microphysics schemes, parameterization of Land Surface processes (including snow and sea-ice), Stochastic multicloud parameterization and also application of super parameterization schemes, improvement in ocean model, etc. (Goswami *et al*., 2015; Goswami *et al*., 2017a, 2017b, 2017c; Ganai *et al*., 2015, 2016; Abhik *et al*., 2017; Hazra *et al*., 2017; Saha *et al*., 2017; Pokhrel *et al*., 2018). These model developments have been useful to reduce the model biases and thereby showing improvements in prediction skill (Ramu *et al*., 2016; Pillai *et al*., 2017; Pradhan *et al*., 2017; Srivastava *et al*., 2017; Hazra *et al*., 2017). These improvements resulted in ISMR skill of 0.63 (0.67 pls check whether it is ISMR or skill over rectangular box) (Pokhrel *et al*., 2018), which is higher than the present generation seasonal prediction models (Pillai *et al*., 2018).

Using this monsoon mission model, IMD predicted, for the first time, the deficit monsoon of 2014 (14% lower than long term mean) successfully at a lead time of 3 months (February IC) with a large degree of spatial agreement with observations. Forecasts from other leading climate centers suggested a near normal monsoon during that year (Pai *et al*., 2017). The year 2015 was a consecutive deficit monsoon year after 2014 (12% lower than long term average). Such consecutive deficits in India are extremely rare and have occurred only thrice in the history of instrumented rainfall records (1871-2013). These consecutive droughts were captured successfully by the MM model. The skill of the IMD operational forecasts for 1988-2017 periods is 0.36 (Pai *et al*., 2017and Fig. 3 here), while the MM model skill for the same period is 0.54. This amounts to a 50% increase in the skill as compared to ESSO-IMD's operational forecasts. This is a major achievement of the MM. This forecast skill assumes significance as the prediction skill of ISMR in the dynamical coupled models at the time of launching of MM was only 0.28 (in DEMETER models, Preeti *et al*., 2010) and 0.46 (in ENSEMBLE models, Rajeevan *et al*., 2012) for 1960-2005 period which further decreases to 0.09 post 1980 (Wang *et al*., 2015). The high resolution model is currently operational at IMD since 2017. The latest seasonal forecasts can be obtained from http://www.imdpune.gov.in/Clim_Pred_LRF_New/Models.html.

Thus, the LRF of ISMR has gone through different stages from statistical prediction to dynamical forecasting system with highest resolution and better skill compared to the any other model at different forecast centers in the world (Fig. 3). Prediction skill (correlation between observed and re-forecasted ISMR for the period of 1988-2010) of state of the art models from different leading centers and IMD operational model are plotted in Fig. 3 as a Taylor plot. As is evident from Fig. 3, the monsoon mission CFS model shows highest skill compared to any other model in the world. Further the normalized interannual standard deviations with observed standard deviation for this model is closer to 1, suggesting that the interannual variations are also closer to observations.

3. Future directions

As coupled dynamical models have become a norm to issue seasonal forecasts worldwide, the present day coupled models do suffer with severe biases in the basic

state of monsoon as mentioned above. Various improved parametrization schemes (convection, radiation, boundary layer, ocean mixing, wave-wind-current interactions etc.) will be used in next generation seasonal prediction models. Further, future generation models will consider models with a better representation of the earth system for making seasonal forecasts. Improved initial conditions will also play a crucial role which will become available using state-of-the-art coupled data assimilation techniques for atmosphere, cryosphere, ocean and land.

4. Summary

India has had made significant strides in making seasonal prediction of monsoon. First seasonal predictions in the world were made by India in 1886 with empirical models. Even today, empirical models are used by India Meteorological Department for making operational seasonal forecasts (Rajeevan *et al*., 2007, monsoon report 2017). These models were successful and exhibited good (poor) skills particularly during the periods when 11 year moving average standardized rainfall anomalies are positive (negative). They normally failed to forecast extreme monsoons such as 2002, 2004 etc., (Gadgil *et al*., 2005). Hence, empirical model forecast skill is much less (Table 2) during operational period. Thereafter several attempts were made by India and outside to improve simulations of monsoon and its major features in dynamical models (Gadgil and Sajini, 1998; Kang *et al*., 2002; Gadgil *et al*., 2005; Krishna Kumar *et al*., 2005; Wang *et al*., 2005; Gadgil and Srinivasan, 2011). Attempts to predict Indian Summer Monsoon using these stand-alone models resulted in limited success (Fig. 2) due to the coupled nature of the monsoon system. Monsoon Mission has given the country a state-of-the-art dynamical prediction system with the highest horizontal resolution an unparalleled skill. The high resolution monsoon mission model has a skill of 0.55 (Ramu *et al*., 2016) for 3 month lead forecast and is able to capture all the extreme monsoon years in the recent period, where the empirical models failed in the past (Gadgil *et al*., 2005). As part of the developmental work carried out during monsoon mission, the ISMR skill is further improved to 0.63, which is the highest skill for any of the seasonal prediction system in the world for ISMR (Fig. 3).

The present generation seasonal prediction lacks various other components of earth system and therefore the future seasonal prediction models will incorporate various components of earth systems (such as interactive Hydrology, Ocean bio-geochemistry, interactive biosphere, aerosols and Green House gases through atmospheric chemistry). At the same time various data assimilation techniques (Coupled data assimilation involving Ocean, Land, cryosphere and Atmosphere with LETKF and 4D VAR) will be used to provide improved initial conditions for both atmosphere and Ocean.

Acknowledgments

Scientists of IMD who worked tirelessly, since 1870s to improve the seasonal forecasting of Indian Summer Monsoon for several decades, knowing very well that it is the second toughest prediction problem, certainly deserve appreciation for their efforts. They have kept the mantle burning for quite some time and present day researchers with lot of infrastructure available at their disposal for carrying out state-of-the-art research work to improve prediction skill need to keep that mantle shining. IITM is fully funded by Ministry of Earth Sciences.

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

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