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Evolution of monitoring and forecasting of southwest monsoon

M. RAJEEVAN and D. R. PATTANAIK*

Atria University, Bengaluru, India

**India Meteorological Department, MoES New Delhi*

email : rajeevan61@yahoo.co.in

सार – इस समीक्षा लेख में, पिछले 150 वर्षों में मॉनसून की निगरानी और पूर्वानुमान के विकस की चर्चा की गई। चूंकि इस अंक में आईएमडी के लघु-अवधि और प्रचालनात्मक पूर्वानुमानों पर कई अन्य अध्ययन हैं, इसलिए केवल मॉनसून निगरानी, विस्तारित अवधि पूर्वानुमान (10-30 दिन) और ऋतुनिष्ठ पूर्वानुमान (एक ऋतु तक) के विवरण पर ध्यान केंद्रित किया गया है। आईएमडी के पास अब दैनिक आधार पर जिला स्तर पर मॉनसून के प्रदर्शन की निगरानी करने की प्रणाली है। मॉनसून मिशन के तहत, आईएमडी एक विस्तारित अवधि पूर्वानुमान प्रणाली स्थापित करने में सक्षम है, जिसमें अब 2 सप्ताह तक कुशल अनुमान करने की क्षमता है। कुछ विशेष मामलों में, कौशल को तीन सप्ताह तक बढ़ाया जाता है। आईएमडी ऋतुनिष्ठ मॉनसून पूर्वानुमान में व्यवस्थित शोध शुरू करने वाला पहला देश है। सांख्यिकीय मॉडल आईएमडी की ऋतुनिष्ठ पूर्वानुमान प्रणाली की रीढ़ बने हैं। 2017 से, आईएमडी ऋतुनिष्ठ पूर्वानुमानों के लिए गतिकी मॉडल का भी उपयोग कर रहा है। मॉनसून निगरानी और पूर्वानुमान प्रणालियों को और बेहतर बनाने के अवसरों की भी पहचान की गई और उन पर चर्चा की गई।

ABSTRACT. In this review article, we discuss how monsoon monitoring and forecasting has evolved over the last 150 years. Since there are several other articles in this issue on short-range and operational forecasts of the IMD, we focus only on the details of monsoon monitoring, extended range forecasts (10-30 days) and seasonal forecasts (up to one season). IMD now has a system to monitor the monsoon performance at the district level on a daily basis. Under the monsoon mission, IMD has been able to set up an extended range forecasting system which now has a capability of skillful prediction up to 2 weeks. In some special cases, the skill is extended to three weeks. IMD is the first country to begin systematic research into seasonal monsoon forecasting. Statistical models formed the backbone of the IMD's seasonal forecasting system. Since 2017, the IMD has also been using dynamic models for seasonal forecasts. Opportunities to further improve monsoon monitoring and forecasting systems are also identified and discussed.

1. Introduction

The vagaries of the southwest monsoon over India have profound socio-economic implications for agriculture, drinking water supply and most importantly, the economy. The monsoon is the main deity of Indian agriculture and any major deviation in its performance is a matter of public interest. Although the annual variation in India's summer monsoon rainfall (ISMR) is only about 10% of the mean (87 cm), there is a strong correlation between the country's food production and gross domestic product (GDP) and ISMR (Gadgil and Gadgil 2006). The impact of a severe monsoon drought on India's GDP ranges from 2 to 5 percent. The southwest monsoon has been the subject of intense study for over four centuries. More than 300 years ago, Halley (1753) proposed that the main cause of the monsoon was the differential heating between the ocean and the land and considered it to be a giant land-sea breeze. Over the last 150 years, meteorologists in India have studied various aspects of the monsoon, including its dynamics and prediction. Since the 1950s, the Indian monsoon has been extensively studied by researchers around the world. They have studied many aspects of the Indian monsoon and published numerous research papers. They have also participated wholeheartedly in major research campaigns such as IIOE and MONEX-79.

The India Meteorological Department (IMD) was established in 1875 with Henry Blanford as its first head and the title "Meteorological Reporter to the Government of India". In 1875, there were not yet many observations to monitor or predict the various facets of the southwest monsoon. However, the IMD has continuously improved its monitoring systems for the development of the monsoon season and the dissemination of information on the development of the monsoon to the government and the general public. Since then, the IMD's observation network has grown manifold with over 500 surface observatories, more than 2000 automatic weather stations, 56 RS/RW stations and 25 Doppler weather radars. Other modern technologies such as weather satellites, fast communication systems and supercomputers are also used to collect and compile observational data and update the information base. The success of such intensive monitoring was even evident during the monsoon drought of 2002, when the government was informed of the impending drought as early as the third week of July (Sikka 2003).

In this review article, we discuss how monsoon monitoring and forecasting has evolved over the last 150 years. Since there are several other articles in this issue on short-range and operational forecasts of the IMD, we focus only on the details of the extended-range forecasts (10-30 days) and the seasonal forecasts (up to one season).

2. Monsoon monitoring

When the IMD was founded in 1875, there were not many precipitation and air pressure observations. After the great drought of 1877 and the resulting famine, the IMD set up a large network of rain gauging stations, which provided a valuable source of data for analysing the space-time structure of monsoon rainfall and its variability.

With unusual zeal, Blanford dedicated himself to the task of establishing a standardised rainfall monitoring system and verifying the records of the rain gauge network. With the introduction of the telegraph system, daily rainfall and other meteorological observations were collected and analysed. Over the years, IMD has maintained a very high standard of monitoring rainfall and other meteorological parameters in India with great care and accuracy (Sikka 2003). The system of meteorological observations has been improved with the introduction of upper air meteorological observatories in the 1920s to 1950s, weather radars since the 1950s and the Indian Meteorological Satellite System (INSAT) in the 1980s. Currently, IMD uses a range of technologies to obtain information on meteorological conditions from the surface up to an altitude of about 30 km on a regional and global basis and complements these with INSAT and other satellite products as well as Doppler weather radar products.

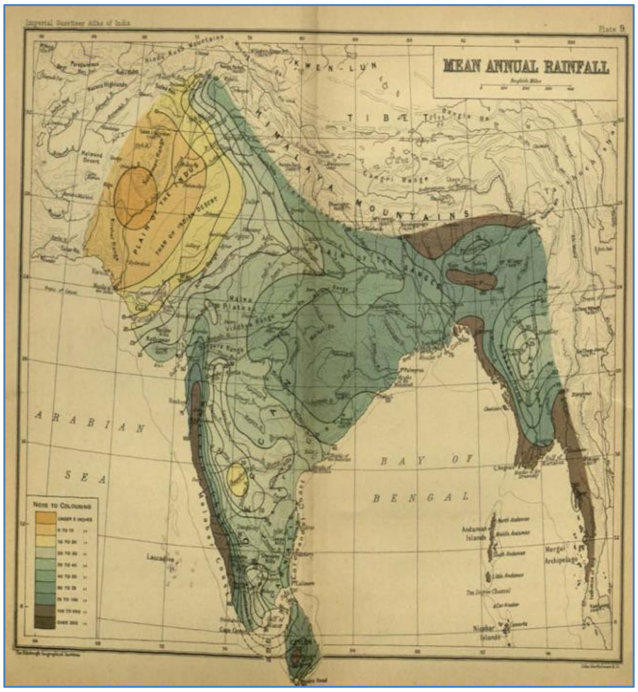


Fig.1. Mean annual rainfall (in inches) from the Climatological Atlas of India by John Eliot (1906). The maps from this atlas are available at https://ignca.gov.in/Asi_data/74946.pdf

Blanford (1886) was the first meteorologist to analyse rainfall data from 1500 rain gauging stations for a period of 20-30 years for British India, which includes present-day India, Pakistan, Bangladesh and Burma. Blanford (1887) published an article in Nature on "The Meteorology of India" in which he stated, "It appears that the average rainfall over the whole of India, with the exception of Burma and the Himalayas, is about 42 inches. The range of rainfall over this wide area is one of the most marvellous in the world, namely, from about 500 or 6oo inches in Cherra Punji to 1 to 5 inches in Sindh". Sir John Eliot also published meteorological memoirs about India in the late 19th century, based on observations from the IMD observatories. Some of the IMD memoirs are available at the following link: https://searchworks.stanford.edu/view/414525.

Later, Walker (1910) analysed about 2000 stations from 1841-1908 to study the rainfall of the southwest monsoon in British India. However, the number of rain gauges considered by Blanford and Walker was not the same. The number of rain gauges was about 5 from 1865-1890 and about 2000 from 1891 onwards (Parthasarathi and Mooley 1978). Based on the observed rainfall data, a climatological atlas of India was published by Sir John Eliot, then Rapporteur to the Government of India, through the firm of John Bartholomew and Co. in Edinburgh (Hann, 1907). The annual precipitation map from John Eliot's climatological atlas is shown in Fig. 1.

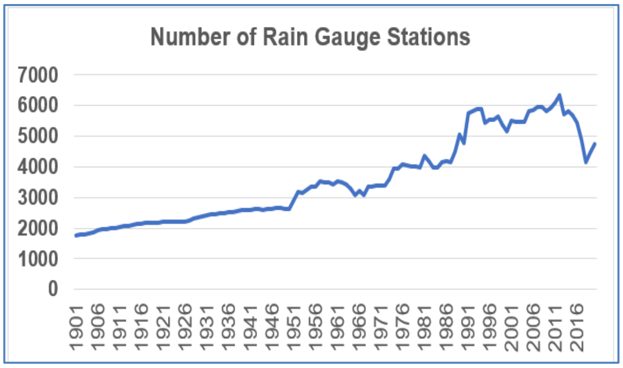


Fig. 2. Number of rain-gauge stations maintained by IMD for daily monsoon monitoring. (Source: IMD). This includes IMD stations and State rain-gauge stations

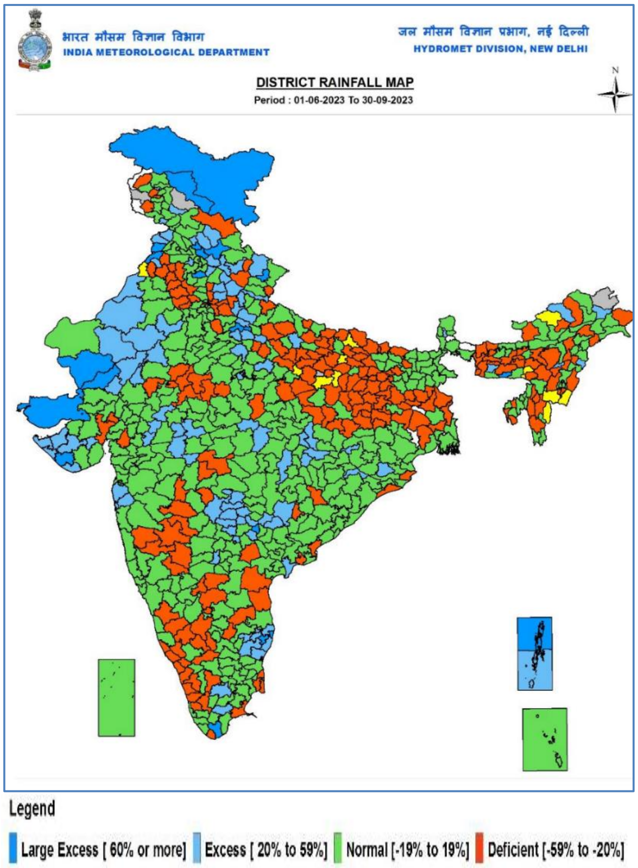


Fig.3.a District-wise monsoon seasonal rainfall distribution during the 2023 monsoon season (Source: IMD)

Before 1866, the instruments were mainly provided by the Board of Health or the Department of Mathematical Instruments, usually without instructions to the observer to ensure a uniform exposure or method of observation. After 1891, Symon's rain gauge was adopted as the standard for all sheets because of its precipitation resolution (Sikka 2003). As a result, Walker (1910) considered that rain gauge data prior to 1865 were less reliable. For more details on monsoon monitoring, see Walker (1910), Parthasarathy and Mooley (1978) and Sikka (2003). The number of rain gauges maintained by IMD has increased significantly from 1901 to 2022, as shown in Fig. 2. Since 1901, the number of rain gauges has systematically increased from about 2000 to about 6000 in 2005. In recent years, there has been a procedural delay in receiving and archiving the data after quality control.

Since 1992, the IMD has introduced a District Rainfall Monitoring System (DRMS), under which 2821 selected monitoring stations record rainfall and transmit it in real time to the respective IMD regional monitoring centres to better visualise rainfall at the district level. Currently, the IMD receives daily real-time rainfall observations from 5896 rainfall monitoring centres across the country. The DRMS is the backbone of the IMD's monitoring mechanism to assess the progress of the monsoon and its spatial and temporal distribution. Using the DRMS data, the IMD compiles daily, weekly, monthly and seasonal rainfall statistics, which are very important and informative for monitoring monsoon development. These statistics are extensively used by policy makers to monitor the monsoon and take appropriate policy measures. Many operational and research products are prepared on the basis of rainfall data collected by IMD on an operational basis. An example of monsoon monitoring based on daily rainfall observations can be found in Fig. 3, which shows (*i*) district-wise seasonal rainfall anomalies and (*ii*) active and intermittent monsoon periods during the 2023 monsoon season.

IMD has also developed many high-resolution data products, such as gridded precipitation datasets (Rajeevan *et al*., 2006, Rajeevan *et al*., 2008, Rajeevan and Bhate 2009, Pai *et al*., 2014) and temperature datasets (Srivastava *et al*., 2009). These data products are used by researchers and operational meteorologists for monitoring monsoons and research. Based on rainfall observations since 1875, IITM Pune has developed a time series of all India rainfall since 1875 and the time series is shown in Fig 3c.

3. Extended range forecasting

The Indian summer monsoon exhibits a wide range of variability on daily, sub-seasonal, interannual, decadal and centennial time scales. The sub-seasonal oscillations with time scales longer than the synoptic but shorter than the seasonal scale, known as intra-seasonal variability (ISV), have emerged as the primary building block of monsoon systems (Goswami *et al*. 2011). ISV manifests itself in active periods with good rainfall and weak periods or intermittency with low rainfall (Ramamurthy 1969, Gadgil and Joseph 2003, Rajeevan *et al*., 2010) within the monsoon season. The active and intermittent periods have a huge impact on agricultural production, health, energy

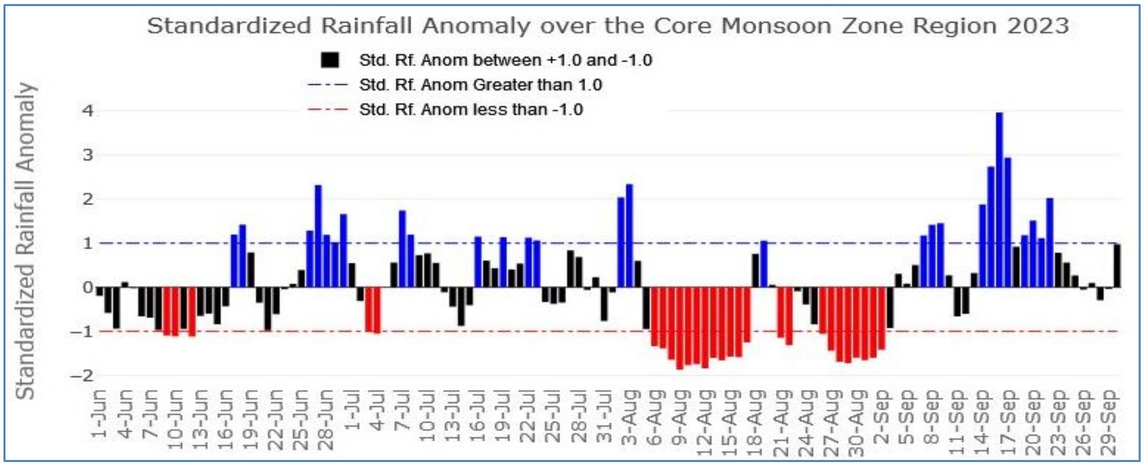


Fig.3.b Standardized rainfall anomaly over the Monsoon core region during 2023 southwest monsoon season. The red (blue) lines indicate break (active) monsoon days. The criteria are based on Rajeevan et al. (2010). (Source: IMD).

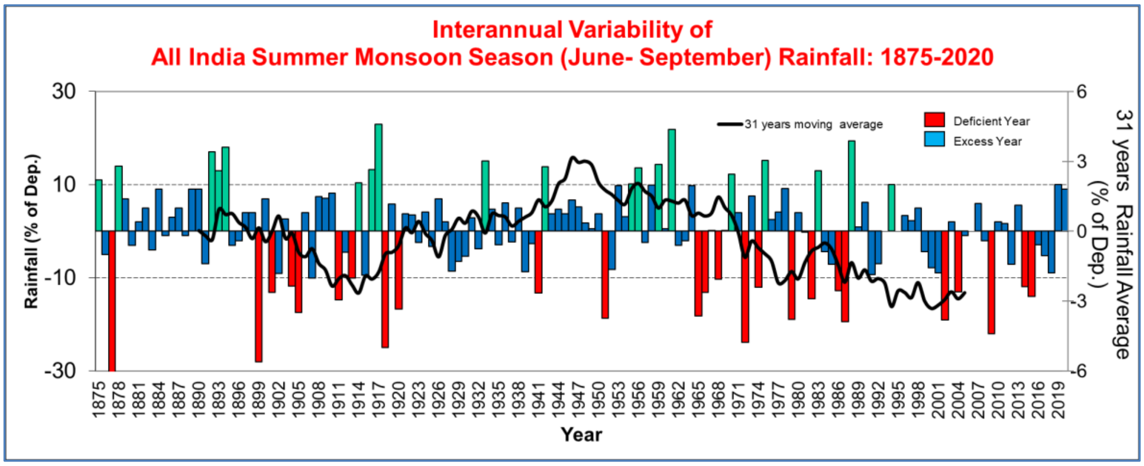


Fig. 3.C. Time series of All India monsoon rainfall (June to September) from 1875 to 2020. Source IITM Pune.

supply and water resource management. The amplitude of ISV is much larger than that of the interannual variability (IAV) of the seasonal mean and comparable to that of the seasonal cycle, allowing optimistic prediction over a longer period (Goswami *et al*., 2011). An interesting overview of the ISV of the Indian monsoon is provided by Goswami (2005), Waliser (2006) and Goswami *et al*., (2011) and many others.

The monsoon ISV is characterised by a seesaw pattern of the two convergence systems (one over the monsoon core region and the other over the equatorial Indian Ocean) oscillating out of phase with each other, a phenomenon that has been described in earlier studies (Yasunari 1979; Sikka and Gadgil 1980; Gadgil 2000; Krishnamurti and Subrahmanyam 1982). This oscillation is accompanied by a northward movement of circulation anomalies, convection and precipitation. Consequently, the Monsoon Intra-Seasonal Oscillation (MISO) is associated with a recognisable northward propagation of either positive or negative precipitation anomalies (or convection) (Sikka and Gadgil 1980).

The predominant variance in sub-seasonal monsoon rainfall variability is associated with a periodicity of 30 to 60 days and has a common mode of variability with the seasonal mean. It is hypothesised that this sub-seasonal variability strengthens the seasonal mean during the active phases, while weakening it during the intermittent phases. In addition, the large-scale structure of the active and pausing phases, the 30-60 day mode and the seasonal mean often show similarities (Goswami 2012). Intra-seasonal variations can influence synoptic activity and lead to a spatial and temporal clustering of depressions and depressions (Goswami *et al.*, 2003; Pattanaik 2003; Rajeevan *et al*., 2010), which in turn can influence regional precipitation patterns. Extended range forecasts beyond the average limit of predictability of individual synoptic weather systems can arise either because there are large-scale components of the general atmospheric circulation whose forecast time is longer than that of individual synoptic weather patterns, or because underlying boundary conditions that evolve on a slower time scale than the weather can confer considerable predictability to atmospheric evolution (Palmer and Anderson 1994). It is becoming increasingly clear that skilful predictions of the ISV of the monsoon can provide optimal information for regional agriculture and water resource management. Over the past two decades, research efforts to understand, simulate and predict ISV have increased significantly. Webster and Hoyos (2004) developed a new physically based 20-30 day variability prediction scheme for the Indian monsoon region that shows promise. Later, Webster *et al*. (2010) developed another prediction model for probabilistic forecasts of Ganges and Brahmaputra floods in Bangladesh with an accuracy of up to 10 to 15 days.

Accurate extended-range forecasts (ERF) covering a period of 2 to 4 weeks have the potential to offer significant benefits to the agricultural sector, especially in drought preparedness and management (Tyagi and Pattanaik, 2010; Pattanaik, 2014). In addition to their utility for forecasting India's monsoon rainfall, cyclogenesis and the northeast monsoon, ERFs for surface air temperature, which include forecasts for heat waves and cold spells, have a wide range of applications in various sectors, including agriculture, energy, health, insurance, power and finance. ERF can also play a crucial role in managing reservoirs to mitigate flood risks, as Pattanaik and Das (2015) have shown in a pilot study on the Mahanadi river basin in Odisha during the 2011 floods.

3.1. *Evolution of operational ERF of IMD*

A modest start in the production of ERF products was made at IMD in 2008, with the potential application for surgical use. Pattanaik *et al*. (2019) have documented the development of operational ERF in IMD in an excellent review paper. Originally, ERF in IMD was mainly based on empirical models (Xavier and Goswami 2007), Jones *et al*. 2004, Wheeler and Hendon 2004, Sahai and Chattopadhyay 2006). These empirical models (with the exception of Sahai and Chattopadhyay 2006) were mainly developed for the prediction of OLR anomalies, which are an indicator of convection rather than precipitation. Sahai and Chattopadhyay (2006) used the dynamic indices from the NCEP data in real-time mode for the prediction of precipitation anomalies.

Subsequently, the data and products from the dynamic models for the ERF activities of the IMD were introduced. The products of the ECMWF monthly forecast system, which is based on 32-day coupled ocean-atmosphere integrations established at ECMWF with 51 ensemble members Frederic (2004), were considered at IMD for the creation of the multi-model ensemble (MME). The data of the coupled Climate Forecast System Version 1 (CFSv1) model of the operational centre NCEP, USA (Saha *et al*., 2006) were also used to create the MME-based ERF. The second version of the NCEP CFS (CFSv2) was launched at NCEP in March 2011 (Saha *et al*., 2014). The CFSv2 runs at NCEP with 16 members per day at a resolution of 126 km (Saha *et al*., 2014; Pattanaik and Kumar, 2014) were very useful for IMD in preparing the operational ERF. The results of the Ensemble Prediction System (EPS) of the Japan Met Agency (JMA) were also used for the preparation of the MME-based ERF. Like the ECMWF model, the JMA model also produces forecasts for 32 days based on each Thursday. Thus, during the first period from 2008-2017, the dynamic models of the leading centres were used to produce the MME-based ERF in the IMD.

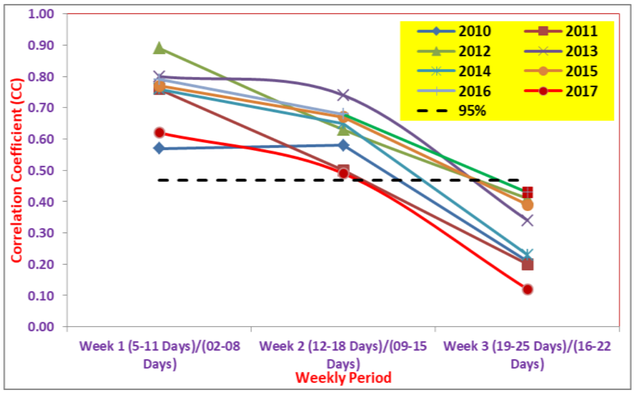


Fig. 4. The correlation coefficient between the observed and forecast rainfall averaged over India for the monsoon season from 2010-2017 based on the MME ERF up to 3 weeks

As shown in the review paper by Pattanaik *et al.* (2019), proper monitoring of intra-annual fluctuation of monsoon rainfall during the 2009 monsoon season by IMD was quite useful to assess the extent and severity of drought situation of the country (Tyagi and Pattanaik, 2010). As they showed, the dry spells of monsoon during almost the entire June, first half of August and second half of September 2009 were well predicted in the model forecasts and hence were very useful for real-time prediction of these dry spells of monsoon 2009. Similarly, the real-time prediction skill of ERF based on the MME of the dynamic models shows a very useful skill for at least 2 weeks during the period of 2010-2017 as shown in Fig. 4. The correlation coefficient between the observed and predicted rainfall on average over India for the monsoon season from 2010 to 2017 based on the MME prediction based on the available models is shown in Fig. 4 up to 3 weeks (up to 22-25 days). As can be seen in Fig. 4, the MME ERF shows a useful skill for at least up to 2 weeks (up to 15 -18 days). As discussed in the review paper by Pattanaik *et al*. (2019), the performance of ERFs for the southwest monsoon has clearly captured the intra - seasonal variability of the

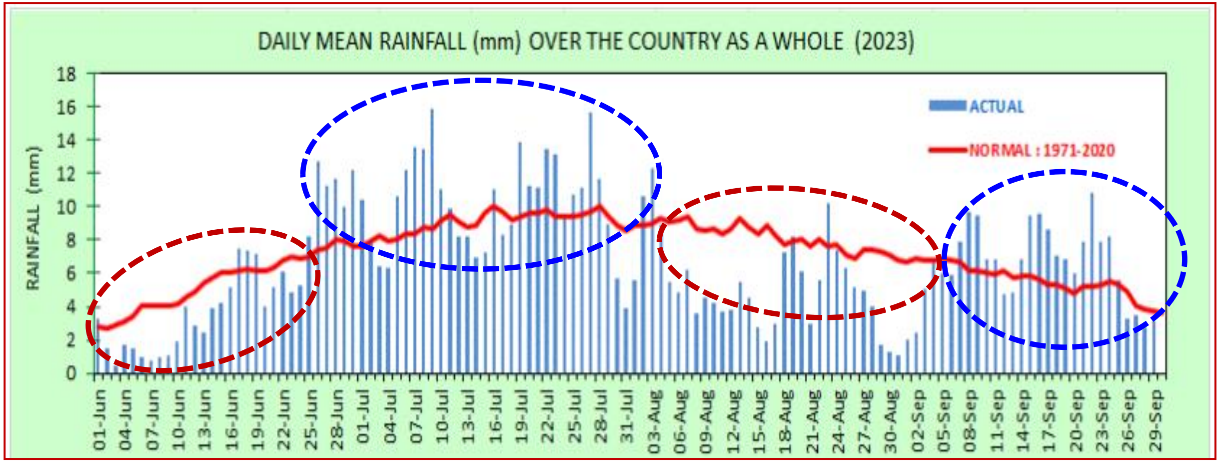


Fig. 5. Daily all India actual and normal rainfall observed during the 2023 monsoon season from 1st June to 30 September. Source IMD

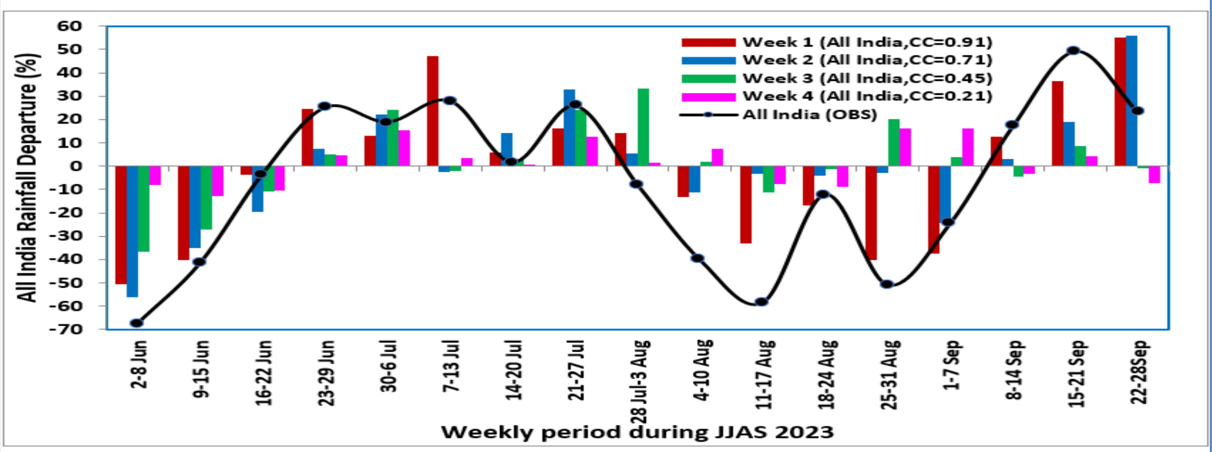


Fig 6. Actual and weekly forecasts of All India monsoon rainfall during the monsoon season, June to September 2023. (Source IMD)

monsoon, including the delay/early onset of the monsoon, the active/break periods of the monsoon and the retreat of the monsoon in real time in providing guidance for various applications.

3.2. *The coupled model implemented in IMD for operational ERF in 2017.*

The IMD's ERF system is currently in operation and produces weekly forecasts every Wednesday. These forecasts cover a 4-week period starting on Friday and extending to the following Thursday. The operational ERF modelling system consists of a collection of models with different resolutions, all derived from the coupled model CFSv2, which was adopted from NCEP. The model was originally developed at IITM (Sahai *et al*., 2013, 2015; Abhilash *et al*., 2014; Borah *et al*., 2015) and was originally run every 5 days using atmospheric and oceanic initial conditions from NCEP and provided predictions for 4 pentads. However, before implementation at IMD in 2017, some significant changes were made. These changes concerned the use of atmospheric and oceanic initial conditions from NCMRWF and INCOIS, respectively, instead of NCEP. In addition, the forecast schedule was changed from the 5-day interval to the Wednesday of each week. And finally, the model output was created for 4 weeks, as opposed to pentads. As can be seen, the operational ERF was able to predict very well the intra-seasonal variability of the monsoon, including the onset, withdrawal and the cycle of active interruption of the monsoon, during the recent monsoon seasons of 2017, 2018, 2019 and 2020 (Pattanaik *et al*., 2020, 2021 and 2022) at different spatial scales, starting from the all-India level to the met-subdivision level. Another very recent study has also shown how the bias-corrected ERF rainfall at the river basin level can improve the raw ERF during the monsoon season in India for reservoir operations (Praveen *et al*., 2022). As an example, we show here how the ERF could indicate the ISV of monsoon during the 2023 monsoon season. Fig. 5 shows the actual daily rainfall from 1 June to 30 September, which suggests suppressed monsoon rainfall activity during June and August and enhanced rainfall activity during most of July and September.

The predicted monsoon rainfall for week 1, week 2, week 3 and week 4 is shown in Fig. 6. The ERF system predicts the transition from active to weak periods and from weak to active periods quite well. The correlation coefficient (CC) for the predictions of the first week is 0.91, for the second week 0.71 and for the third week 0.45. Therefore, the IMD ERF produces quite accurate predictions of weekly precipitation activity. Based on this skilful extended-range forecasting system, IMD has also developed many applications for agriculture, water resources and the health sector. More details about the current ERF system can be found in Pattanaik *et al*. (2019).

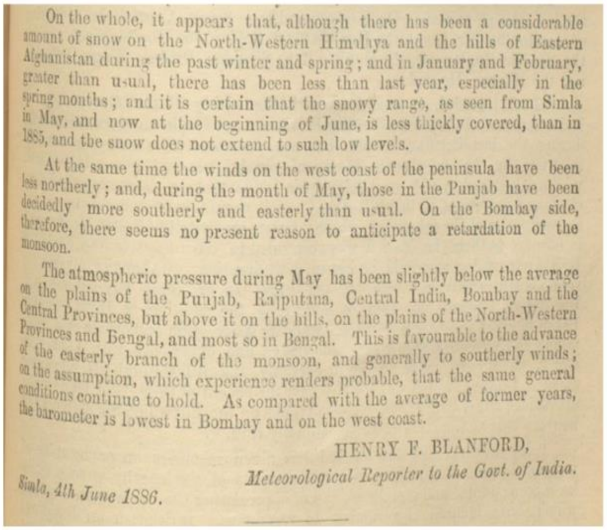
4. Monsoon Long-range forecasts

4.1. *Basic premise*

As we know, the predictability of daily weather patterns in the tropics is limited to 3-4 days (Lorenz 1963). Based on observations and numerical studies, Charney and Shukla (1981) documented that the seasonal mean monsoon circulation in the tropics is potentially more predictable than the mid-latitude circulation. Although daily variations in the tropics are small, interannual variations are related to changes in the boundary conditions of slowly fluctuating parameters such as sea surface temperature (SST), snow cover, albedo, soil moisture, *etc*. (Shukla 1987). The Charney-Shukla hypothesis has been the central paradigm for monsoon predictability research over the last 30-40 years.

4.2. *History of Long-range Forecasting in IMD*

After the Great Famine of 1877, the then-British government commissioned Henry F. Blanford to make long-term predictions for the rains of the Indian monsoon. The first long-term monsoon forecast was issued in 1886, based on the correlation between heavy winter and spring snowfalls in the Himalayas and summer monsoon droughts over India (Blanford 1886). However, it was the extensive and pioneering work of Walker (1918, 1923 and 1924) that led to the development of the first objective models based on statistical correlations between monsoon rainfall and antecedent global atmospheric, land and ocean parameters. In identifying potential predictors, Walker discovered the Southern Oscillation (SO), which is associated with the Walker Circulation. Walker (1923, 1924) developed several multiple regression (MR) equations to predict the seasonal monsoon rainfall averaged over two homogeneous sub-regions of India, namely NW India and the Peninsula. These regression equations have been revised periodically to incorporate new predictors as required. Since then, the IMD's operational Long-Range Forecasting (LRF) system has undergone changes in its approach and scope from time to time. There are many good reports/reviews on the LRF of the Indian Southwest Monsoon (ISMR) (Banerji, 1950; Normand 1953; Jagannathan 1960; Thapliyal and Kulshreshtha 1992; Hastenrath 1995; Kumar *et al*. 1995; Rajeevan *et al*. 2000; Rajeevan 2001; Gadgil *et al*. 2005, Pai *et al*. 2017). Normand (1953) suggested that these forecasts prepared by Walker have failed to correctly indicate the extreme monsoon years. Another interesting historical perspective (Carson 2021) on IMD's seasonal forecasts during the period 1886-1953 suggested that IMD continuously revised the methods of prediction using different predictors. However, all the methods failed to achieve accurate prediction. Nevertheless, the imperatives of economic administration, empire and public demand compelled IMD scientists to continue the annual publication of seasonal forecasts. The first long-range forecast issued by the IMD is shown in Fig. 7.



On the whole, it appears that, although there has been a considerable amount of snow on the North-Western Himalaya and the hills of Eastern Afghanistan during the past winter and spring; and in January and February, greater than usual, there has been less than last year, especially in the spring months; and it is certain that the snowy range, as seen from Simla in May, and now at the beginning of June, is less thickly covered, than in 1885, and the snow does not extend to such low levels.

At the same time the winds on the west coast of the peninsula have been less northerly; and, during the month of May, those in the Punjab have been decidedly more southerly and easterly than usual. On the Bombay side, therefore, there seems no present reason to anticipate a retardation of the monsoon.

The atmospheric pressure during May has been slightly below the average on the plains of the Punjab, Rajputana, Central India, Bombay and the Central Provinces, but above it on the hills, on the plains of the North-Western Provinces and Bengal, and most so in Bengal. This is favourable to the advance of the easterly branch of the monsoon, and generally to southerly winds; on the assumption, which experience renders probable, that the same general conditions continue to hold. As compared with the average of former years, the barometer is lowest in Bombay and on the west coast.

HENRY F. BLANFORD,
Meteorological Reporter to the Govt. of India.

Simla, 4th June 1886.

Fig.7. Excerpt from the first official IMD seasonal forecast by Blanford. From the 'Extract from the proceedings of the GOI in the Revenue & Agriculture Dept. of Meteorology, dated Simla, 10th June 1886', Supplement to the Gazette of India, 12 June 1886, p. 881. Courtesy of Library of Congress and Carson (2021)

Monsoon forecasts were then valued primarily for its supporting role in government budget administration and fiscal policy. Long-range forecasts acquired new scientific overtones, even if they remained reliably conservative. Monsoon forecasts, despite their widely criticized 'failures', allowed responsible governors to claim that their procedures accounted for the risks of drought (Carson 2021).

IMD continued to produce operational forecasts for Northwest (NW) India and the Peninsula using separate multiple regression models until 1987. These predictions were generally closer to the average than the observed values. The average error of the predictions for the peninsula was 12.33 cm and 9.9 cm for NW India during

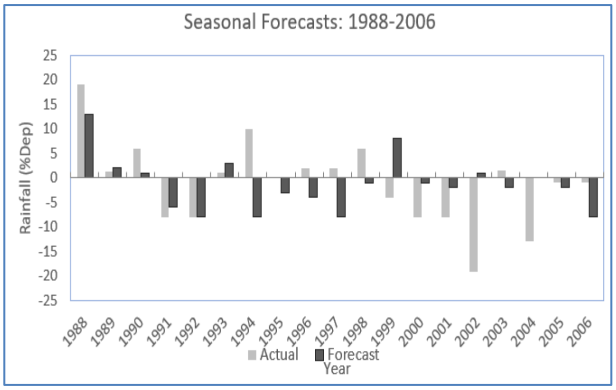


Fig. 8. Performance of IMD's operational seasonal forecasts for Indian Summer Monsoon Rainfall (ISMR) during the period 1988-2006 using the 16-Parameter power regression model. ISMR is shown as percent departures. Actual rainfall in light grey and predicted rainfall is in black colour

the period 1932-1987. However, the forecasts have not improved over the years despite repeated attempts to revise the forecast models based on rigorous and objective statistical methods (Gadgil *et al*. 2005).

In 1988, the IMD introduced new statistical models for forecasting monsoon rainfall over the entire country (ISMR) based on Parametric and Power Regression methods. During 1988-2006, the predictions for the entire country were based on the parametric and the power regression model with 16 parameters (Gowarikar *et al*. 1989, 1991). The parametric model was a purely qualitative model, while the power regression model is a quantitative model that considers the non-linear interactions of various important climatic influences with ISMR. A review of IMD operational forecasts from 1988 to 2006 (Fig. 8) showed that the mean square error during this period was 8.72%, while the standard deviation of ISMR was 8.58 %. The prediction error of the model was thus larger than the standard deviation during this period. The correlation between the actual and predicted rainfall during the period 1988-2006 was 0.25, which is statistically not significant. Fortunately, the ISMR was normal (in the range of 90% to 110%) during this period, with the exceptions of 2002 and 2004, but the IMD model failed to correctly predict these two droughts. The forecast error in 1994 was also very large.

4.3. *Statistical Ensemble Prediction System (ESPS) for ISMR*

IMD developed a new statistical ensemble forecast system (SEPS) for monsoon rains to support IMD's two-stage forecast system (Rajeevan *et al*. 2007), where the first forecast is released in mid-April and the updated forecast in late May. Because of the problems inherent in statistical models, such as epochal variations in the relationship between prediction and predictor and intercorrelation between predictors (Rajeevan 2001), it is necessary to subject the statistical models to constant scrutiny and modify them as necessary (Rajeevan *et al*. 2004). The main problem with the previous 16-parameter model of IMD was the use of up to 16 predictors (with many interconnected predictors) for model development and hence overfitting of the model (Delsole and Shukla, 2002). Therefore, the new prediction system was developed with a small number of predictors. The parameters used in the model development except that are related to ENSO were newly identified.

In the SEPS, nine predictors were considered that have a strong relationship with ISMR (Table 1). The first three predictors are included in both the April and May forecasts. As can be seen in Table 1, all predictors have a statistically significant correlation with ISMR. The physical significance of these predictors is discussed in detail in Rajeevan *et al*. (2005), Rajeevan *et al* (2007).

TABLE 1

List of 9 Predictors used in the Ensemble Statistical Prediction System

No	Parameter	Period	C.C with ISMR (1958-2000)
1	North Atlantic SST Anomaly	Dec+ Jan	-0.45**
2	Equatorial SE Indian Ocean SST	Feb + March	0.52**
3	East Asia Surface Pressure	Feb + March	0.36*
4	Europe land surface air temp	January	0.42**
5	NW Europe Surface Pressure	DJF (0)-SON (-1)	-0.40**
6	Warm Water Volume (WWV)	Feb + March	-0.32*
7	Nino 3.4 SST Tendency	MAM (0)- DJF(0)	-0.46**
8	N Atlantic Surface Pressure	May	-0.42*
9	North Central Pacific Zonal Wind at 850 hPa	May	-0.55**

* Significant at and above 5% level, ** Significant at and above 1% level

Two statistical methods were used to develop the model, Multiple Regression (MR) and Projection Pursuit Regression (PPR) (Rajeevan *et al*. 2007). The basis of the PP technique is the linear projection of the data and the attempt to identify the non-linear structures within the projections. All possible MR and PPR models were constructed with all possible combinations of predictors, rather than relying on a single model. If there are 'n' predictors, then there can be 2^n-1 models. From all the models developed in this way, the best models are selected using the generalised cross-validation (GCV) function and an ensemble mean is calculated. The final ensemble model is considered to have the lowest root mean square error (RMSE). Using a weighted ensemble average from a set of appropriately selected models with different predictor combinations for the model inferences effectively reduces the error resulting from using only one best model.

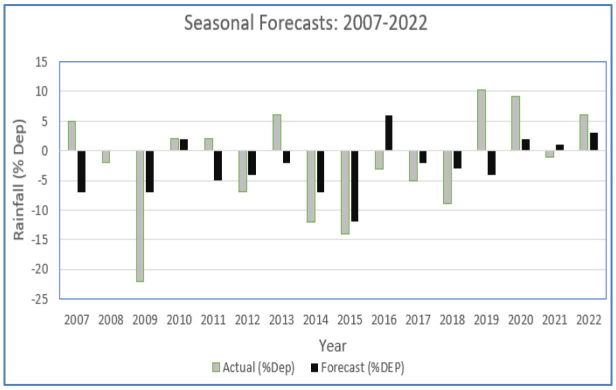


Fig. 9. Performance of IMD's operational seasonal forecasts for ISMR during the period 2007-2022 based on ESPS. ISMR is shown as percent departures. Actual rainfall in light grey and predicted rainfall is in black colour

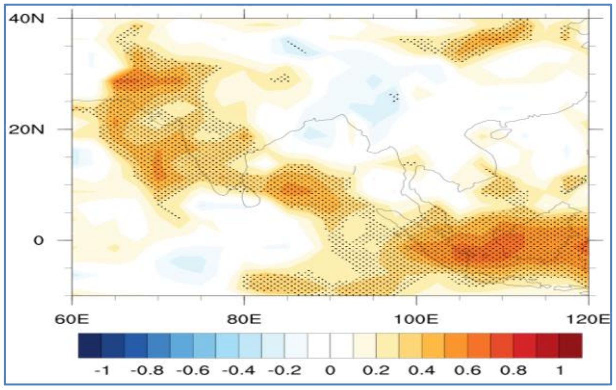


Fig. 10. Spatial distribution of Pearson's correlation coefficient between the MMCFS hindcasts and ISMR based on GPCP data for the period 1981-2022. Correlations which are significant at the 90% significance level are shown as black dots

The review of the ESPS predictions during the independent (operational) period (2007-2022) for the second stage of the forecast is shown in Fig. 9. The RMSE during the operational forecast period (2007-2022) was 7.57%, compared to a standard deviation of 8.99%. Thus, the forecast error was less than the standard deviation of monsoon rainfall during the same period. The correlation between the actual and predicted ISMR (0.49) is statistically significant. This is an impressive performance when compared to the previous forecasting system that was in operation during the period 1988-2006. Interestingly, ESPS predicted the correct sign for deficient monsoon years like 2009, 2014 and 2015. The prediction error in the deficient years of 2014 and 2015 was very low, indicating useful capability of the IMD statistical prediction system. Pai *et al*. (2017) discussed the 2015 seasonal monsoon forecasts in more detail and they found that the model forecasts were useful in warning the Indian government about the deficient monsoon.

4.4. *Dynamical Seasonal Prediction*

Statistical models are developed using empirical relationships based on past observations and may not perform satisfactorily in real-time forecasting due to over-fitting or longer-term non-stationarity (Gadgil *et al*. 2005). Moreover, statistical model predictions asymptotically approach the "mean" and largely miss the extremes (Gadgil *et al*. 2005). The secular fluctuations in the relationship between predictor and rainfall can be largely compensated by an optimal training period (Rajeevan *et al*. 2007). Statistical models may not be able to handle non-linear feedbacks and interactions in the coupled climate system that ultimately determine monsoon performance. Only a coupled ocean-atmosphere dynamic modelling framework can handle such non-linear interactions emerging during the monsoon season.

In India, systematic research and developmental work on dynamical seasonal prediction started with the launch of the project, namely "Seasonal Prediction of Indian Summer Monsoon" (SPIM) (Gadgil and Srinivasan 2011). They considered five Atmospheric General Circulation Model (AGCM) for this assessment study. The results revealed that none of the five models were able to simulate the correct sign of ISMR for all the extreme years considered. However, systematic efforts to make CGCMs for operational use were made under the ambitious Monsoon Mission, which was launched in 2012. The Monsoon Mission was launched by the Government of India with an objective to implement dynamical monsoon prediction systems for monsoon prediction in all time scales, from short-range to seasonal (Rao *et al*. 2019).

Under the Monsoon Mission, the NCEP CFSv2 model (Saha *et al*. 2014) was adopted and run at a high spatial resolution of 38 km for the atmosphere model. This model was chosen since it showed far better skill compared to other available coupled models. The hindcasts of the model with February initial conditions has shown better skill for summer monsoon rainfall (Pillai *et al*. 2017, Ramu *et al*. 2016). When the model resolution was increased from the original version of T126 to T382 (38 km), the skill improved from 0.48 to 0.55. The increase in the resolution of the atmospheric model also caused a reduced dry bias and a slight warm bias in the tropical ocean basins. The cold bias of the equatorial Pacific also became slight positive. Thus, the skill of Monsoon Mission CFS (MMCFS) model has shown a better skill (0.55) compared to the earlier generation coupled climate prediction system, namely ENSEMBLES (Rajeevan *et al*. 2012), which had a correlation of 0.46.

The spatial distribution of model skill of MMCFS for the period 1981-2022 is shown in Fig. 10. The time series of area-averaged rainfall over the Indian subcontinent from both prediction and observations is shown in Fig. 11.

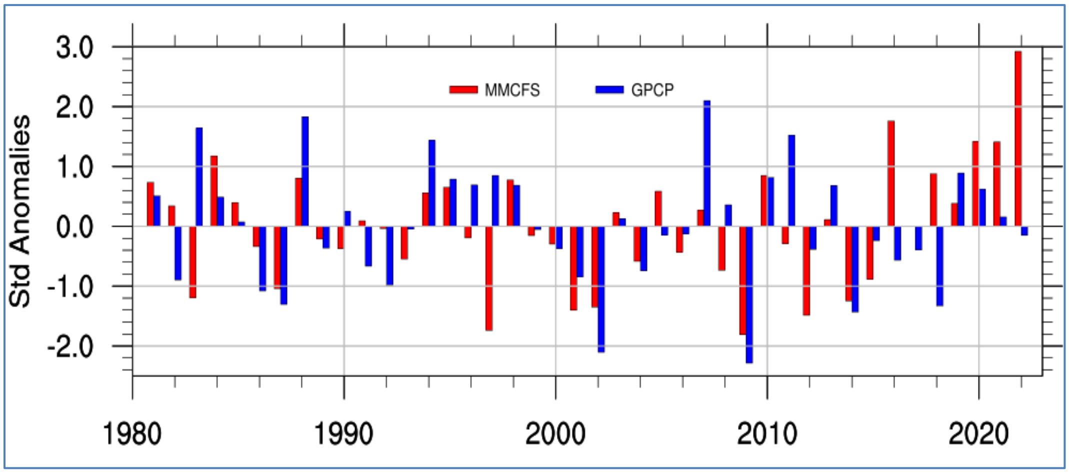


Fig. 11. Time series of MMFCS predictions (red) and observed ISMR based on GPCP data (blue) for the period 1981-2022. Seasonal rainfall is shown as standardized anomalies

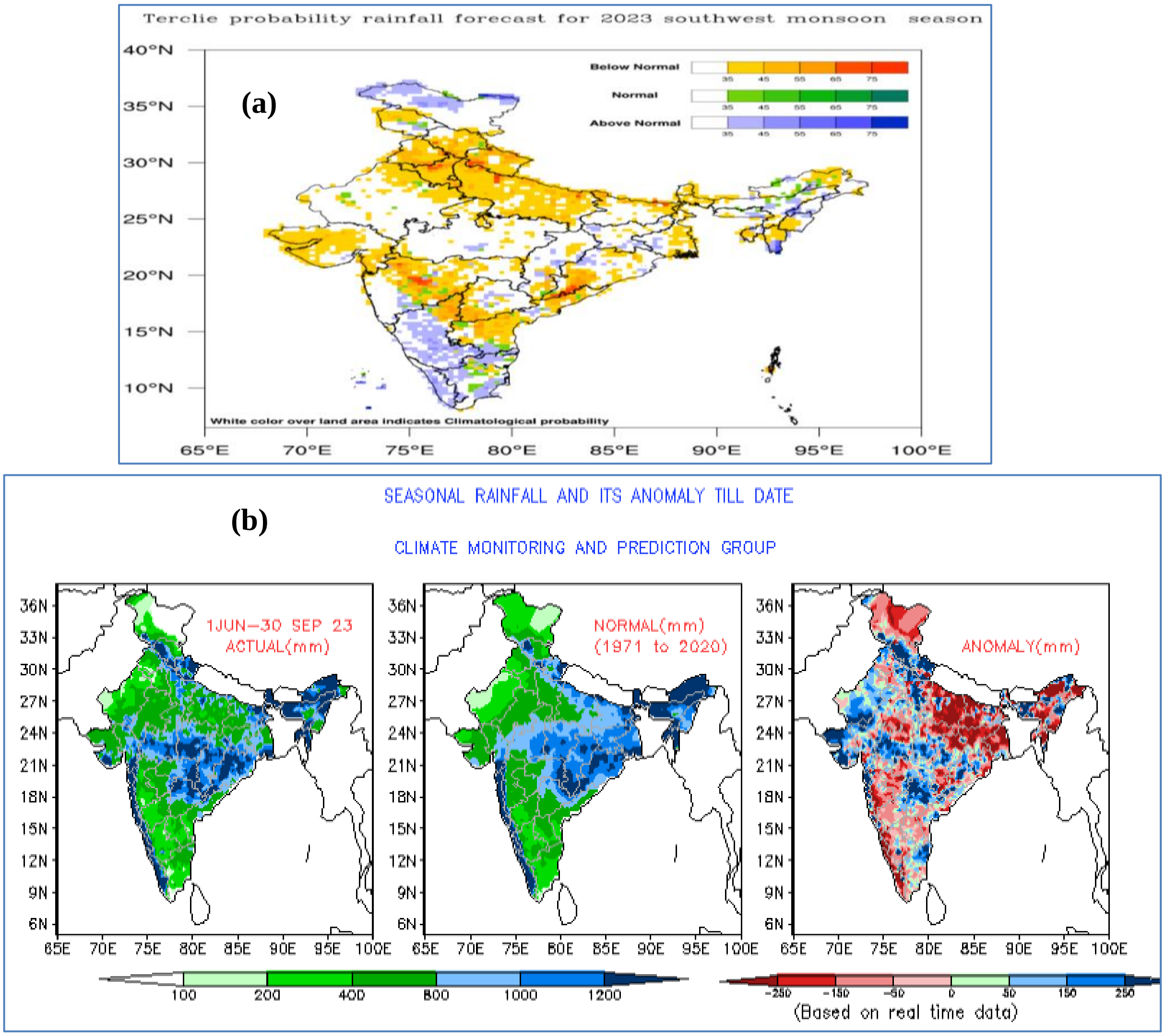


Fig.12. Probabilistic Forecasts of IMD based on the new ensemble dynamical prediction system for the 2023 monsoon rainfall and verification. a) Spatial distribution of tercile forecasts b) observed seasonal rainfall in 2023 (left), long-term normal (middle) and anomaly in mm (right). (Source: IMD)

The spatial distribution of the skill (correlation) (Fig. 10) shows that the MMCFS has positive correlations over south peninsula, parts of central India and northwest India. Over northeast India, the model skill is very poor. Another notable feature is the poor skill over the monsoon core region (Rajeevan *et al*. 2010). The rainfall variability over the monsoon core region truly represents the all-India variability and also linked strongly with agricultural crop yield. The time series of predicted and actual ISMR (Fig 11) shows that the model satisfactorily predicts the IAV of ISMR with a correlation of 0.55, significant at the 99% significance level. The model could predict deficient monsoon years like 1987, 2002, 2009 and 2014. The model also could predict satisfactorily above normal monsoon years like 1988, 1994 and 2019-2021. However, the model failed to predict the years like 1983, 1986 and 1994. Rajeevan *et al*. (2012) discussed the failure of forecasts from ENSEMBLES system in 1983 and 1994 and the possible reasons in terms of SST anomalies over the equatorial Pacific. The models failed to predict the spatial distribution of SST anomalies over the central Pacific accurately. Since MMCFS has shown reasonable skill in predicting ISMR, the model was made operational in 2017 at the India Meteorological Department (IMD) for generating operational seasonal forecasts. The operational seasonal forecasts for next 9 months, based on MMCFS, updated every month are available at https://www.imdpune.gov.in/prediction.php.In 2021.

In 2021, IMD introduced a dynamic multi-model ensemble prediction system to generate probabilistic forecasts of spatial distribution of monsoon rainfall over India. This new strategy was developed using eight different coupled models from different countries and using the hindcast data from 1981-2020. The models considered for the multi-model ensemble forecasts are CanCM4i (NMHS, Canada), GEM-NEMO (NMHS, Canada), NCAR-CCSM4 (NCAR, USA), GEOSS2S (NASA/USA), JMA (NMHS, Japan), NCEP-CFS2 (NMHS, USA), MMCFS (IMD, India) and ECMWF SEAS-5 (ECMWF). The probabilistic forecast for the 2023 monsoon season based on this ensemble system and its verification are shown in the following Fig.12. The prediction system, however, could not predict the spatial distribution of rainfall anomalies that accurately. Model prediction was good for eastern parts of Uttar Pradesh and Bihar and parts of Maharashtra.

5. Summary

Over the last 150 years, the IMD's ability to monitor the monsoon on a daily and sub-daily scale and to forecast the monsoon on different time scales has improved considerably. Starting with a few rain gauges before 1875, the IMD observational network has improved with the installation of more rain gauges, upper air radiosondes, Doppler weather radasrs and Agromet and Hydromet observatories. The IMD is now able to assess monsoon performance at the district level on a daily basis. This information is extensively used by government officials to make appropriate policy decisions.

The IMD's forecasting capability has also improved significantly thanks to timely investments in augmenting computing capacity and doing systematic research on weather and climate forecasting. The monsoon mission launched by the Ministry of Earth Sciences has helped IMD to expand and strengthen its forecasting capabilities. The IMD now has a state-of-the-art ensemble short to medium range, extended range and seasonal forecasting systems. The extended-range forecasting system is capable of accurately predicting the transition from the active to the break phase of the monsoon and vice versa at least two weeks in advance. Based on these skilful forecasts, IMD has also developed many applications in the fields of agriculture, water resources, energy and health.

The IMD began its seasonal monsoon forecasting initiatives with the first forecast published on 4 June 1886. Since then, the scope and capabilities of the monsoon forecasting system have improved. The statistical forecasting system has been the backbone of IMD's seasonal forecasts. However, in 2017, IMD introduced a dynamic forecasting system based on a coupled model developed by IITM Pune. In 2021, IMD went ahead and developed a multi-model ensemble forecasting system for seasonal monsoon forecasting.

There is ample scope for IMD to improve the monitoring and forecasting systems. The current observation network should be upgraded by installing more observations over the data deficient regions like the Himalayas. Rain gauges should be available at taluka level to accurately monitor the performance of the monsoon. The ERF system should be further improved so that even the forecasts for the third week are quite good and useful. More and better data assimilation could be useful to improve the extended range forecasts. For better seasonal forecasts, the dynamical models should be improved by improving the systematic errors/biases and teleconnectivity with the global climate modes such as ENSO. The expectations of different user communities are increasing day by day. IMD should respond appropriately to their demands.

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