

Evolution of operational extended range forecast system of IMD : Prospects of its applications in different sectors

D. R. PATTANAİK, A. K. SAHAI*, RAJU MANDAL*, R. PHANI MURALIKRISHNA*, AVIJIT DEY*,
RAJIB CHATTOPADHYAY*, SUSMITHA JOSEPH*, AMAR DEEP TIWARI** and VIMAL MISHRA**

India Meteorological Department, New Delhi – 110 003, India

**Indian Institute of Tropical Meteorology (IITM), Pune – 411 008, India*

***Indian Institute of Technology, Gandhinagar – 382 355, India*

E mail: drpattanaik@gmail.com

सार – इस शोध पत्र में भारत मौसम विज्ञान विभाग में प्रचलनात्मक विस्तारित अवधि पूर्वानुमान (ERF) प्रणाली का विकास 2009 से 2016 की अवधि में आनुभविक मॉडल्स, गतिशील मॉडल्स और मल्टी मॉडल एनसेंबल (MME) के प्रयोग से आरंभ होकर 2016 में युग्मित मॉडल के प्रचालन में पूर्णतः कार्यान्वयन पर चर्चा की गई है। भारत मौसम विज्ञान विभाग में कार्यान्वित युग्मित मॉडल जलवायु पूर्वानुमान प्रणाली वर्जन-2 (CFSv2) है। इसमें दक्षिणी-पश्चिमी मॉनसून, पूर्वोत्तर मॉनसून, बंगाल की खाड़ी (BoB) में चक्रवात की उत्पत्ति और 2009 से 2018 की अवधि के दौरान अधिकतम और न्यूनतम तापमान के लिए इ आर एफ के निष्पादन का विभिन्न क्षेत्रों जैसे: कृषि, जल विज्ञान, स्वास्थ्य, बिजली आदि में इसके अनुप्रयोग की संभावनाओं पर चर्चा की गई है और विश्लेषण भी किया गया है।

दक्षिणी-पश्चिमी मॉनसून ऋतुओं के लिए विस्तारित अवधि पूर्वानुमान का निष्पादन मॉनसून की अंतरा-मौसमी परिवर्तिता के लिए स्पष्ट रहा जिसमें मॉनसून के विलंब से/पहले आगमन, मॉनसून के सक्रिय/व्यवधान होने और वास्तविक समय पर मॉनसून की वापसी सहित भिन्न-भिन्न अनुप्रयोगों के लिए मार्गदर्शन दिए गए। एम एम ई आधारित ई आर एफ उत्तरी हिंद महासागर में अक्टूबर से दिसम्बर (अक्टूबर-नवम्बर-दिसम्बर) के दौरान पूर्वोत्तर मॉनसून और चक्रवात बनने की क्षमता के बारे में 2/3 सप्ताह तक उपयोगी मार्ग दर्शन प्रदान करने के लिए उत्साहजनक परिणाम भी प्रदान करता है और गर्मी तथा सर्दियों के दौरान उष्ण लहर (लू) तथा शीत लहर को 2 सप्ताह तक सांख्यिकीय रूप से महत्वपूर्ण सहसंबंध गुणांक (CC) प्रदान करता है। कृषि क्षेत्र में अनुप्रयोगों के लिए मौसम विज्ञान उपखंड स्तर के पूर्वानुमान कृषि परामर्श के उद्देश्य से दो सप्ताह के लिए तैयार किए जाते हैं।

कृषि और जल विज्ञान में अनुप्रयोग के लिए नियमित रूप से ई आर एफ उत्पादों के अलावा मानकीकृत वर्षा सूचकांक (SPI), धरातलीय जल विज्ञान उत्पाद जैसे-मृदा नमी और अपवाह परिवर्तन, कृषि, जल विज्ञान और स्वास्थ्य क्षेत्रों में अनुप्रयोगों के लिए वेक्टर जनित रोगों आदि के ट्रांसमिशन विंडोज उत्पाद तैयार करना है।

ABSTRACT. The evolution of operational extended range forecast (ERF) system of IMD starting from use of empirical models, dynamic models and the Multi-model Ensemble (MME) from 2009 to 2016 till the operational implementation of fully coupled model in 2016 is discussed. The coupled model implemented in IMD is the Climate Forecast System version 2 (CFSv2). The performance of ERF for southwest monsoon, northeast monsoon, cyclogenesis over the Bay of Bengal (BoB) and maximum and minimum temperature during the period from 2009 to 2018 have been discussed along with its prospects of its application in different sectors like, agriculture, hydrology, health, power etc. are also analysed.

The performance of extended range forecasts for the southwest monsoon seasons clearly captured the intra-seasonal variability of monsoon including delay/early onset of monsoon, active/break spells of monsoon and also withdrawal of monsoon in the real time in providing guidance for various applications. The MME based ERF also provides encouraging results to provide useful guidance upto 2/3 weeks about northeast monsoon and cyclogenesis potential during October to December (OND) over the north Indian Ocean, heat wave, cold wave during summer and winter with statistically significant correlation coefficient (CC) upto two weeks. For applications in agriculture sector meteorological subdivision level forecasts are prepared for two weeks for the purpose of agro advisory.

In addition to the regular ERF products for application in agriculture and hydrology, additional products are being prepared like, Standardised Precipitation Index (SPI), land-surface hydrology products like soil moisture and runoff change, transmission windows products for vector borne diseases etc for applications in agriculture, hydrology and health sectors.

Key words – Multi model ensemble, Cyclogenesis, Madden Julian oscillation, Climate forecast system.

1. Introduction

Extended range forecast (ERF) covering the time scale from one week to about a month in the tropics are one of the most challenging tasks in atmospheric sciences. It fills the gap between medium-range weather forecasting and seasonal forecasting. The ERF time scale is certainly a difficult time range of weather forecasting, as the timescale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost and on the other hand, monthly mean time average is not large enough for the atmospheric signal associated with the ocean anomalies to emerge over the atmospheric noise. Though the seasonal forecast of monsoon has its own relevance for the policy maker the forecast of monsoon in intermediate time scale are critical for the optimization of planting and harvesting (Webster and Hoyos, 2004). Thus, the forecasting of monsoon break in the extended range time scale, 2 to 4 weeks in advance is of great importance for agricultural planning (sowing, harvesting, etc.), which can enable tactical adjustments to the strategic decisions that are made based on the longer-lead seasonal forecasts and also will help in timely review of the prevailing monsoon conditions for providing outlooks to farmers.

Just like the inter-annual variability of monsoon rainfall the Indian summer monsoon precipitation during June to September (JJAS) is driven by many convectively coupled oscillations like ENSO (El Nino-Southern Oscillation) and Indian Ocean Dipole (IOD), the intra-seasonal variation of monsoon is driven by propagation of large-scale convective anomalies northward from the equator with in the season. This northward propagation is known to be accompanied by eastward propagation of convective activity along the equator (Madden Julian Oscillation; MJO) through the Rossby wave propagation. The MJO is the leading mode of tropical intra-seasonal climate variability and is characterized by organization on a global spatial scale with a period typically ranging from 30-60 days (Madden and Julian, 1971&1994; Zhang, 2005). The active/break cycles of monsoon are manifestations of sub-seasonal fluctuations of the northward propagating inter-tropical convergence zone (ITCZ; Sikka and Gadgil, 1980; Krishnamurti and Subrahmanyam, 1982; Pattanaik, 2003; Goswami, 2005). The agriculture sectors like farmers are very much benefited if accurate outlook of monsoon conditions are provided in the extended range.

It is not only the agriculture sector which is benefited from the proper outlook of extended range forecast (Tyagi and Pattanaik, 2012; Pattanaik *et al.*, 2013a), a skilful extended range forecast can also be very useful for reservoir operation in managing floods. Pattanaik and Das (2015) have recently demonstrated usefulness of extended range forecast in a pilot study over the Mahanadi River basin in Odisha in case of 2011 flood. In addition to monsoon associated heavy rainfall over India during JJAS, the post monsoon season from October-December (OND) are known to produce tropical cyclones (TCs) of severe intensity in the north Indian Ocean, which after crossing the coast can cause damages to life and property over India and neighbourhood surrounding the Bay of Bengal. The strong winds, heavy rains and large storm surges associated with tropical cyclones are the factors that eventually lead to loss of life and property. Heavy rains associated with cyclones are another source of damage. The combination of a shallow coastal plain along with a thermodynamically favourable environment allow TCs to impart high surface winds, torrential rains and significant wave heights (wave setup plus storm surge) as these systems move inland. In addition, the world's highest population density coupled with low socio-economic conditions in the region has resulted in several land-falling TCs becoming devastating natural disasters. The forecasting of genesis of tropical cyclone and associated rainfall in the extended range time scale (about 2 weeks in advance) is also very useful for applications in disaster risk reduction (Pattanaik *et al.*, 2013b; Pattanaik & Mohapatra, 2014). The post-monsoon cyclone season during OND is also known as the northeast monsoon season. The withdrawal of southwest monsoon and commencement of northeast monsoon is linked to one another. The five meteorological subdivisions where the northeast monsoon activity occurred are Coastal Andhra Pradesh, Rayalaseema, South interior Karnataka and Kerala and Tamil Nadu with Tamil Nadu is the main area where most of the annual rainfall occurred during this period of northeast monsoon season. As shown by Tyagi and Pattanaik (2012) the skill of ERF of northeast monsoon rainfall over Tamil Nadu can provide very useful guidance for different sectors.

Like the utility of ERF of Indian monsoon rainfall, cyclogenesis, northeast monsoon, the ERF of surface air temperature (including the heat wave and cold wave) for two to four weeks has a wide range of applications in

agriculture, energy, health, insurance, power, financial sector etc. In May 2003 the heat wave claimed over 1,600 lives throughout the country with some 1,200 individuals died in the state of Andhra Pradesh alone. Like in 2003, during 2005 also India was under the grip of severe heat wave towards the third week of June due to stagnation of monsoon and recently in 2015 India witnessed large number of death due to severe heat wave over many parts of India. The prediction of heat waves and cold waves with significant accuracy can save lives and prevent damage to property from these dangerous weather events.

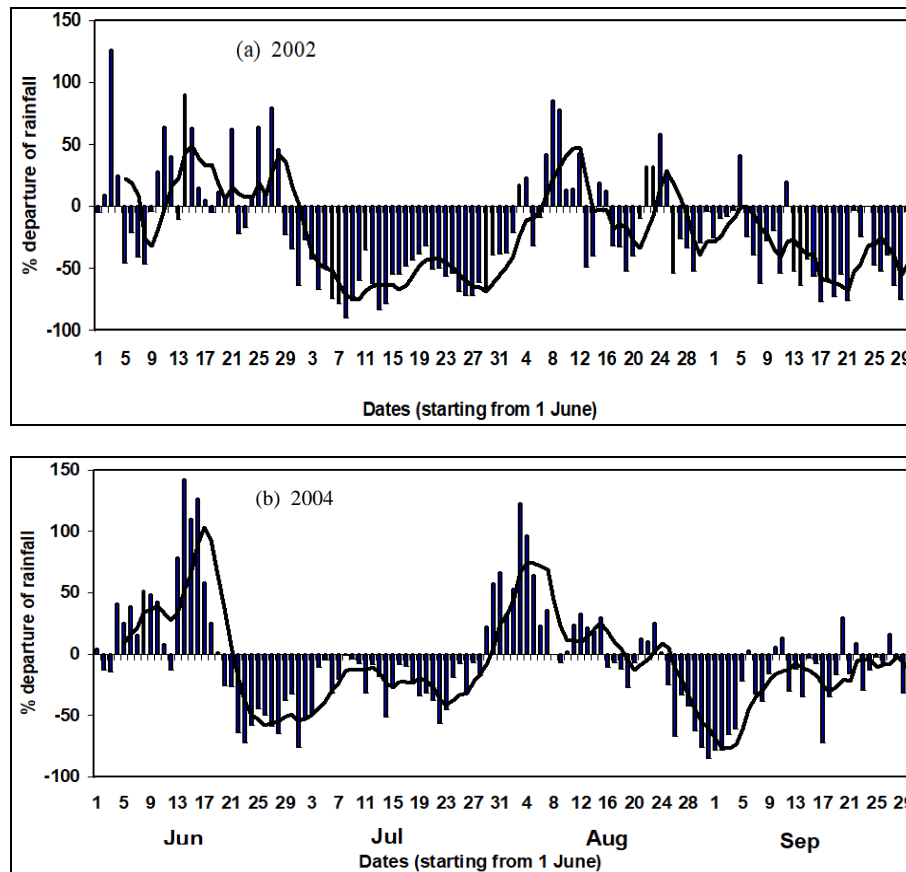
In last few decades, many groups throughout the world are working in developing empirical models for predicting the MJO signals, which can be utilized for the monitoring and prediction of intra-seasonal fluctuation of rainfall over India. In addition, there are many global modeling centers like European Centre for Medium Range Weather Forecasting (ECMWF), National Centre for Environment Prediction (NCEP), Japan Meteorological Agency etc. are also running atmospheric General Circulation Model and coupled atmosphere-ocean models operationally. The latest generation coupled models are found to be very useful in providing skilful guidance of extended range forecast (Saha *et al.*, 2014). IMD has been issuing ERF since 2008, initially by using available products from statistical as well as dynamical model outputs from various centres in India and abroad and very recently by the use of fully coupled model implemented in IMD. In the present article a review of the evolution of operational ERF system of IMD since its inception in 2008 along with prospects of its application in different sectors are presented. The different products based on ERF that can be used for sectoral applications are also presented. Further, a short review is also presented highlighting the evolution of Numerical Weather Prediction (NWP) for short/medium and long range weather forecasting in IMD.

2. Evolution of NWP for short-medium and seasonal forecast systems in IMD

Since its establishment in 1875, India Meteorological Department (IMD) has been involved in monitoring and providing weather and climate services to different users communities. With respect to the NWP, the dawn of it may be traced back to 1958 when the first paper entitled "Numerical prediction of the movement of Bay depressions" was published in the Indian Journal of Meteorology and Geophysics authored by Dr. P. K. Das and his collaborator (Das and Bose, 1958). The evolution of NWP in India and in IMD during the period from 1958 to 2008 is documented very well by a comprehensive book published by IMD (Tyagi and Pattanaik, 2008). NWP entered a new era in India with the establishment of

the National Center for Medium Range Weather Forecasting (NCMRWF) with a supercomputing facility Cray-XMP/14. This gave a much needed boost to NWP research and facilitated development of a full-fledged NWP system for operational short range (up to 3 days) forecasting. Once the medium range forecast (Up to a week to 10 days) system of NCMRWF went in to full production mode, the limited area system of IMD was linked with the NCMRWF's global model outputs for obtaining the lateral boundary conditions to run the limited area model as a routine. With gradual up-gradation in the high power computing power as a part of the modernization programme of IMD started in 2006, the Ministry of Earth Sciences (MoES) has commissioned a very high resolution (12 km) global forecast system model for deterministic weather prediction for generating operational weather forecasts by IMD. Both operational and research aspects for these services are implemented through its constituent units IMD, NCMRWF, Indian Institute of Tropical Meteorology (IITM) and Indian National Centre for Ocean Information System (INCOIS). This high resolution Global Forecast System (GFS) model has been operational in IMD from January, 2017, which is being used for medium range weather forecasting. For further improvement in the forecasting of extreme weather like heavy rainfall, heat wave, cold wave etc., IMD in 2018 has implemented with the joint efforts of the MoES constituents, a new Ensemble Prediction Systems (EPS) at 12 km grid scale across India to provide probabilistic weather forecasts up to next 10 days. The probabilistic forecasts of severe weather events at 12 km grid scale across India will help disaster management authorities in making better emergency response decisions.

Like the evolution of short/medium range weather forecasting in IMD using NWP models the seasonal forecast of monsoon in IMD during June to September also has a long history. The beginning of the long-range forecasting of Indian summer monsoon rainfall was initiated more than a century ago by Blanford (1884). In last few decades, many statistical (Gowariker *et al.*, 1991; Rajeevan *et al.*, 2003) and dynamical models (Shukla *et al.*, 2000; Saha *et al.*, 2006) have been developed for prediction of seasonal summer monsoon rainfall. Atmospheric General Circulation Models (AGCM) and Coupled GCMs (CGCMs) are the main tools for dynamical seasonal scale prediction as it is boundary value problem and not the initial value problem. The Climate Forecasting System (CFS), which is the coupled modeling system of the NCEP is generating the seasonal forecast operationally (Saha *et al.*, 2006 & 2014). Through the Monsoon Mission programme of MoES coordinated by IITM, the Climate Forecast System (CFS) coupled model has been implemented in IMD very recently for the dynamical seasonal forecast of monsoon.



Figs. 1(a&b). % departure of all India daily rainfall for the country as a whole from 1 June to 30 September for (a) 2002 and (b) 2004. The moving averages of 5 days mean are superposed

3. Evolution of Extended Range Forecast System of IMD (2008-2016)

The ERF of weather using numerical model requires the role of ocean and thereby a coupled model is most appropriate for the same. For the forecasting of monsoon on this time scale, models must simulate the statistics (amplitude, phase propagation and frequency spectra) of the Intra Seasonal Oscillation (ISO) correctly. Unlike the short-medium and seasonal forecast systems of IMD, which have long histories, the ERF system of IMD is very new. During the initial decade of 21st century there were three drought years *viz.*, 2002, 2004 and 2009. The 2002 drought year was associated with long dry spell of July (with departure of -51%) as shown in Fig. 1(a) with all India seasonal rainfall departure of -19%. None of the model could predict this long dry spell of July and ultimately the seasonal forecast of 2002 was also not correctly predicted (Kalsi *et al.*, 2004; Pattanaik and Rajeevan, 2007). Similarly, the monsoon drought of 2004 was also associated with long dry spell of July as shown in Fig. 1(b) (Pattanaik *et al.*, 2005). These two drought years

in quick succession associated with long dry spells of monsoon was instrumental for IMD to think about the prediction of active-break cycle of monsoon in the real time. However, due to the non-availability of proper tools and also of very low predictive skill it was very challenging to start the monsoon intra-seasonal forecast operationally. However, considering the importance and demand of extended range forecast, IMD started to generate operationally in house the forecast products of precipitation and temperature based on available model products from different centres in India and abroad from 2008 onwards. Initially some empirical models were used and subsequently the available dynamical model outputs were also used for the same. The two groups of products as highlighted in Pattanaik (2015) used since 2008 are presented below.

3.1. Empirical models used for real time ERF in IMD

During the initial period of ERF in IMD many products based on empirical models were used

operationally *viz.*, the outgoing long-wave radiation (OLR) pentad forecasts based on the method adopted by Xavier and Goswami (2007), the pentad OLR anomaly forecast based on Jones *et al.* (2004), Multivariate MJO indices based on Wheeler and Hendon (2004), rainfall forecast based on the Self Organising Map (SOM) technique used by Sahai and Chattopadhyay (2006). Sahai and Chhappadhyay (2006) used the dynamical indices from the NCEP data in real time mode for the forecast of rainfall anomalies.

3.2. *Dynamical models products used for real time ERF in IMD*

In addition to the available products from the empirical models the dynamical model outputs available from the NCEP's CFS version 1 (CFSv1), JMA's ensemble prediction system and European Centre for Medium Range Weather Forecasting (ECMWF) monthly forecast system etc were also used. After the initial few years during 2008 and 2009, with the improvement in dynamical models, multi-model ensemble (MME) based on these dynamical models only are used for the preparation of real time extended range forecast during the period from 2010 to 2015. A review article by Pattanaik (2015) has documented the performance of ERFs during the earlier periods before the implementation of operational coupled model in IMD.

3.2.1. *ECMWF monthly forecast system*

The products from the ECMWF monthly forecasting system is based on 32-day coupled ocean-atmosphere integrations set up at ECMWF. This system has run routinely since March 2002. The GCM used in this study has a much finer resolution (T639L62 for first 10 days and T319L62 beyond 10 days). The ECMWF monthly forecasting system is forced by persisted SSTs for first 10 days and the atmosphere-ocean coupling started beyond days 10 and is having 51 ensemble members. The details about the ECMWF monthly forecast system along with its skill over the different geographical regions have been discussed in Frederic (2004).

3.2.2. *NCEP's Climate Forecast System (CFSv1 & CFSv2)*

MJO monitoring and prediction was also carried out at Climate Prediction Centre, NCEP by using the dynamical model outputs from CFSv1. The atmospheric component of the operational CFSv1 is the NCEP atmospheric GFS model (T62L64). The oceanic component is the GFDL Modular Ocean Model V.3 (MOM3), which is a finite difference version of the ocean primitive equations under the assumptions of Boussinesq

and hydrostatic approximations. 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 CFSv1 is a fully coupled "tier-1" forecast system. Many recent studies have demonstrated the forecast skill CFSv1 for the prediction of Indian monsoon on the seasonal and monthly scale (Pattanaik and Kumar, 2010; Pattanaik *et al.*, 2012). The second version of the NCEP Climate Forecast System (CFSv2) was made operational at NCEP in March 2011. This version has upgrades to nearly all aspects of the data assimilation & model components of the system. The atmospheric model has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 Km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. The CFSv2 runs with 16 members per day in operations (Saha *et al.*, 2014; Pattanaik and Kumar, 2014).

3.2.3. *Ensemble Prediction System (EPS) from JMA*

The numerical prediction model used in the Ensemble Prediction System (EPS) for extended-range forecasting is an atmospheric general circulation model (AGCM) that is a low-resolution version (TL159) of the Global Spectral Model (GSM) used for short and medium range forecasting with 50 ensemble members. Like in the ECMWF model the Japan Meteorological Agency (JMA) model also generate forecasts for 32 days based on every Thursday.

3.2.4. *Multi-Model Ensemble (MME)*

Based on the respective hindcasts climatology of each of the three models the weekly anomaly field is calculated from ECMWF, CFSv2 and JMA model with forecast period valid for days 5-11, days 12-18 and days 19-25 based on every Thursday. The anomalies fields from NCEP CFSv2, JMA and ECMWF are converted into uniform latitude-longitude grid (0.5°×0.5°) and the MME is prepared with giving equal weights to all the three models. The forecast is generated on every Friday with forecast anomaly for week 1 (Monday to Sunday) to week 3 (subsequent Monday to Sunday). The intra-seasonal monsoon forecast during recent years show useful skill in MME (Tyagi and Pattanaik, 2012; Pattanaik *et al.*, 2013a; Pattanaik, 2014). The MME ERF products are also prepared on smaller spatial domains (4 homogeneous regions of India and 36 met-subdivisions) during the southwest monsoon season from June to September for the preparation of Agromet advisory. During the period from 2008 to 2016, IMD was involved in preparing the ERF using these available models outputs from different centres as discussed above.

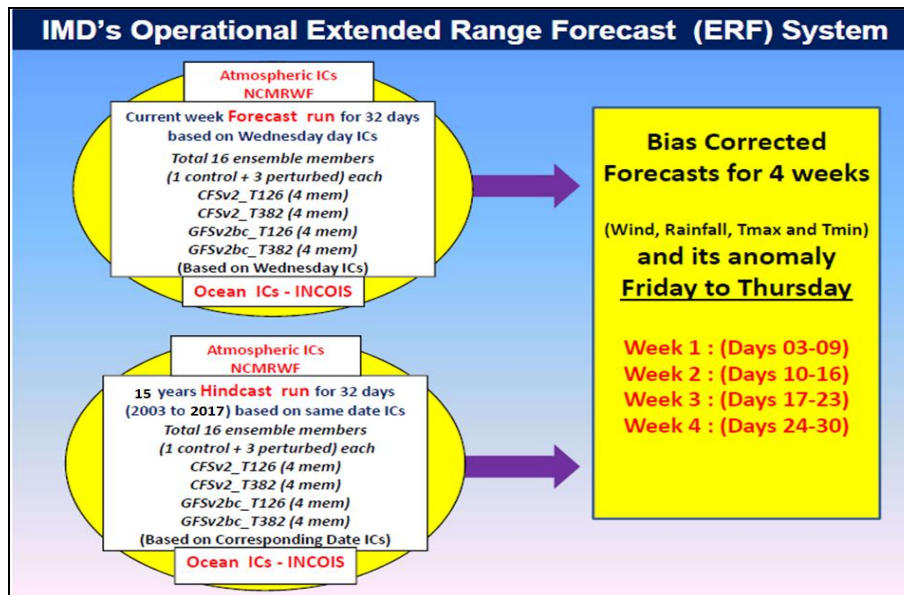


Fig. 2. IMD's Operational Extended Range Forecast (ERF) System

3.3. Current operational ERF system of IMD (2017)

At present the ERF system at IMD is running operationally once in a week every (Wednesday) and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on. The current operational ERF modelling system is a suite of models at different resolutions based on the CFSv2 coupled model adopted from NCEP (Fig. 2). The operational suite is ported in ADITYA HPCS at IITM Pune for day-to-day operational run. As demonstrated in Fig. 2, the Multi-model ensemble (MME) out of the above 4 suite of models are run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126. The oceanic component is the GFDL Modular Ocean Model V.4 (MOM4). The operational suite of models consists of (i) CFSv2 at T382 (≈ 38 km) (ii) CFSv2 at T126 (≈ 100 km) (iii) GFSbc (bias corrected SST from CFSv2) at T382 and (iv) GFSbc at T126 with 4 members each (Total 16 members). This is based on the Ensemble Prediction System (EPS) of IITM developed by Abhilash *et al.* (2014b) and Abhilash *et al.* (2015). For 2018 operational forecast the hindcast run is performed for 15 years (2003 to 2017) as shown in Fig. 2. Similarly, the year 2018 is added into hindcast run for the forecast of 2019. The average ensemble forecast anomaly of all the 4 set of models runs of 4 members each (total 16 members) based on every Wednesday is calculated by subtracting corresponding 15- year model hindcast climatology on every Thursday, which is valid for 4 weeks for days 3-9 (week1; Friday to Thursday), days 10-16 (week2; Friday

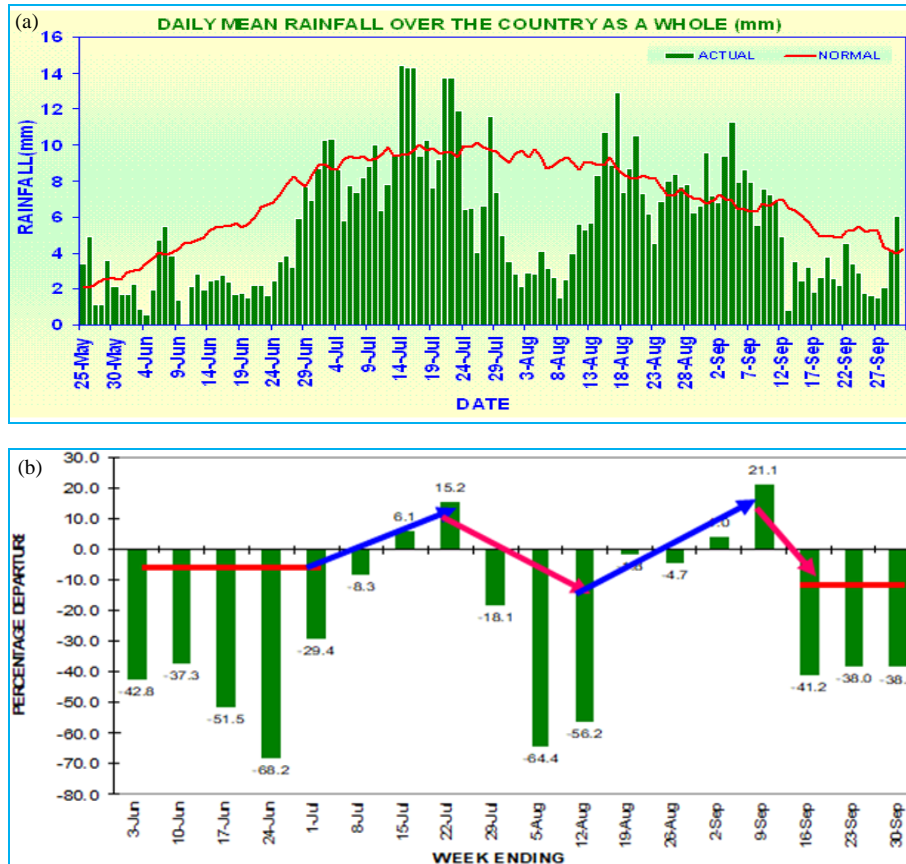
to Thursday), days 17-23 (week3; Friday to Thursday) and days 24-30 (week4; Friday to Thursday). This ERF system has the capability of predicting active-break cycle of monsoon which can be used for various applications. The performance of ERF forecast for 2017 monsoon is available in Pattanaik & Sahai (2018). Another report highlighting verification of ERF forecast skills for monsoon, cyclogenesis, heat wave, cold wave etc for the entire year 2017 is also published by IMD (Pattanaik and Sahai, 2018) and also available online (http://nwp.imd.gov.in/ERF_Report_2017.pdf).

The model was initially developed at IITM (Sahai *et al.*, 2013; Abhilash *et al.*, 2014a; Borah *et al.*, 2015; Sahai *et al.*, 2015), which was run using the atmospheric and oceanic initial conditions available from NCEP once in every 5 days with forecast for 4 pentads. However, three major changes were carried out before it is implemented in IMD during 2016 such as the hindcast and forecast runs are carried out with atmospheric and oceanic initial conditions available from NCMRWF and INCOIS respectively and not from NCEP. Secondly, the forecast day was fixed on Wednesday of every week and not at the interval of 5 days. Finally, the outputs are prepared for 4 weeks and not the pentads.

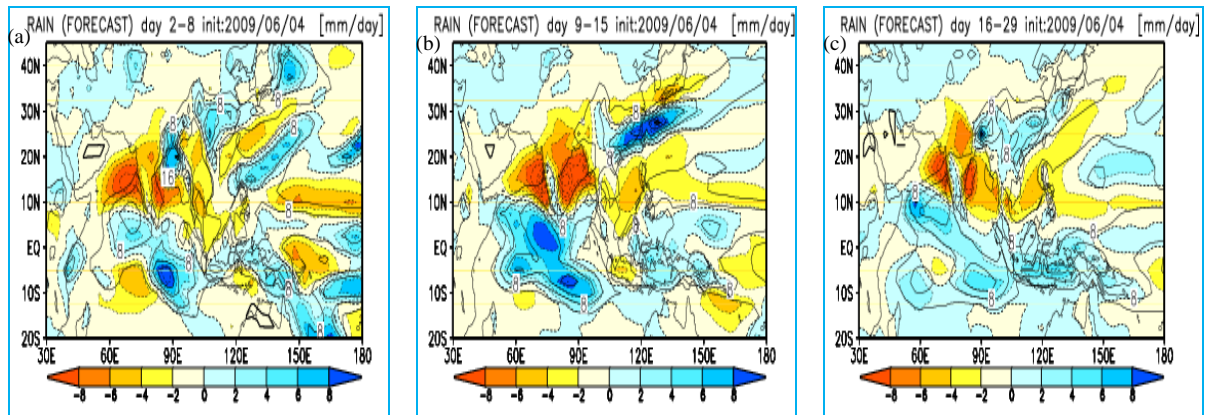
4. Operational extended range forecast of some monsoon cases during 2008-2017

4.1. Long breaks of 2009 monsoon

Although IMD had started preparing the operational ERF from 2008 onwards, the real success of ERF was



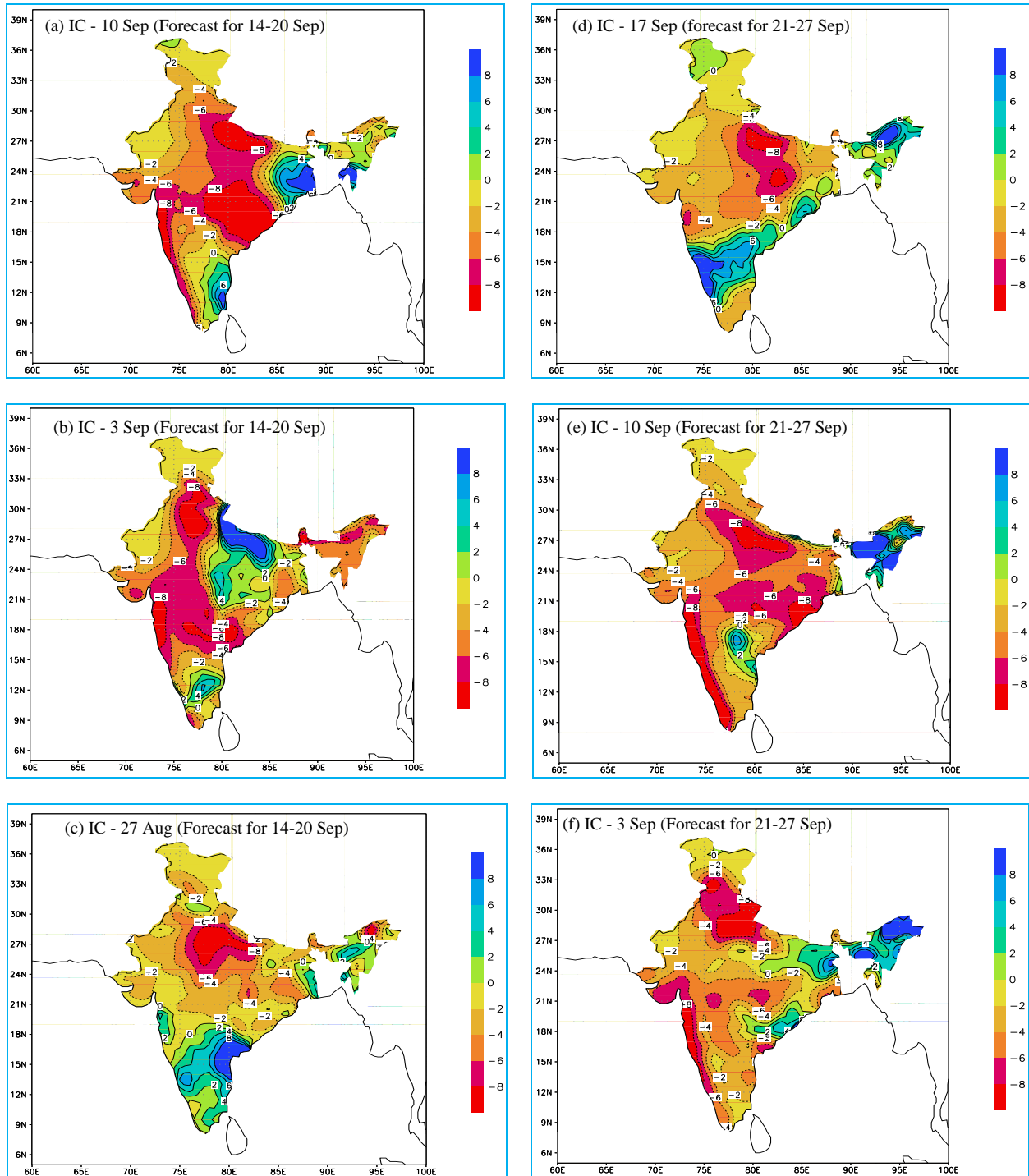
Figs. 3(a&b). (a) Daily actual and normal rainfall averaged over Indian as a whole during 2009 monsoon season from June to September. (b) Same as ‘a’ but for weekly rainfall departure during 2009



Figs. 4(a-c). Forecast rainfall anomaly for 28 days (from JMA) based on initial condition of 4th June, 2009. (a) for week 1 valid for 5-11 June, (b) for week 2 valid for 12-18 June, (c) for week 3&4 valid for 19 June - 3 July, 2009

visible in predicting the dry spells of 2009 monsoon season. The 2009 monsoon season during JJAS witnessed large deficiency in the seasonal total rainfall (-22% of long period average). The drought year of 2009 was associated with many dry spells of monsoon and some transition phases of monsoon from weak phases to active phases and *vice versa* [Fig. 3(a&b)].

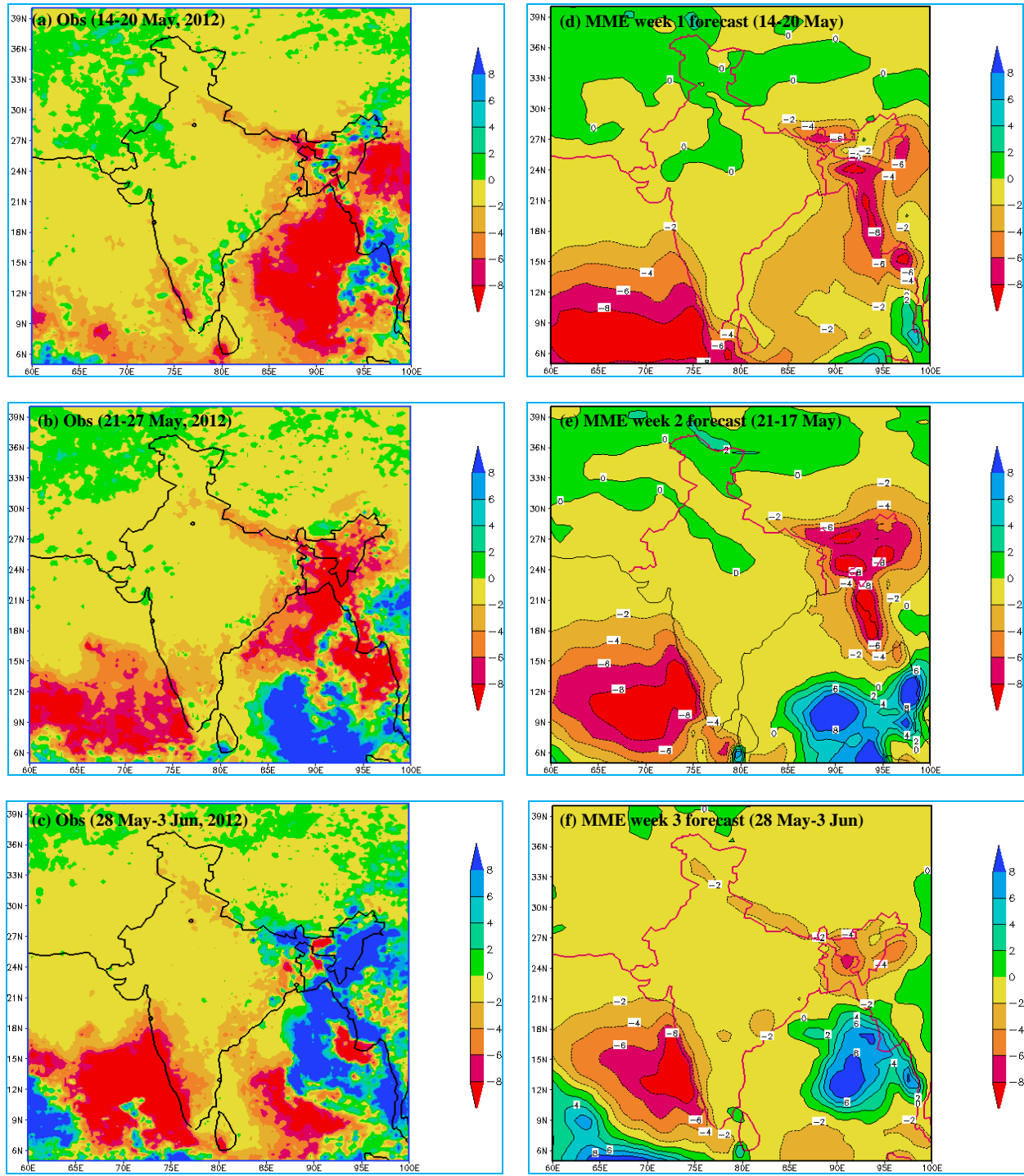
It was noticed that various climate research centers in India and abroad using statistical and dynamical models could not forecast the extent of deficiency of 2009 seasonal monsoon rainfall. However, a proper monitoring of intra-seasonal fluctuation of monsoon rainfall during 2009 monsoon season by IMD was quite useful in assessing the extent and gravity of drought situation of the



Figs. 5(a-f). (a) to (c) MME ERF valid for week 1 to week 3 forecasts rainfall anomaly (mm/day) for the period from 14-20 September, 2009 with different lead times. (d) to (f) same as from (a) to (c) but for the forecast period valid for 21-27 September, 2009

country (Tyagi and Pattanaik, 2010). As shown by them the intra-seasonal prediction of active-break cycles of monsoon 2009 were well captured by the numerical models. It is seen that the dry spells of monsoon during almost the entire June, 1st half of August and 2nd half of

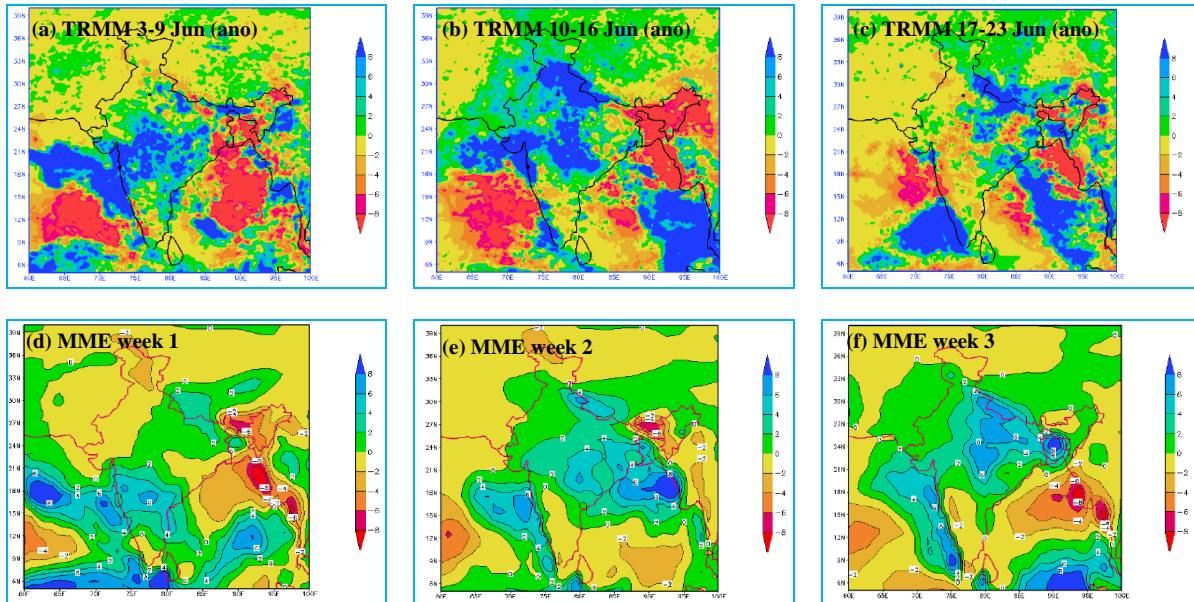
September 2009 were well anticipated in the model forecasts, thus, were very useful in the real time forecasting of these dry spells of monsoon 2009. As shown by them and also shown here in Figs. 4(a-c), the long dry spell of June was very much predicted by the



Figs. 6(a-f). Observed rainfall anomaly for (a) 14-20 May, (b) 21-27 May and (c) 28 May-3 June, 2012. MME forecast rainfall anomalies based on 10th May, 2012 and valid for (d) week 1 (14-20 May), (e) week 2 (21-27 May) and (f) week 3 (28 May-3 June)

model from the beginning of June (initial condition of 4th June). Similarly the dry spell of September (14-27 September) also captured in the MME ERF two to three weeks in advance as indicated in the figure with negative rainfall anomaly for two weeks forecasts based on Initial

Conditions (ICs) of 10th September, 3rd September and 27th August, 2009 for forecast period of 14-20 September, 2009 [Figs. 5(a-c)] and ICs of 17th September, 10th September and 3 September for the forecast period of 21-27 September, 2009 [Figs. 5(d-f)].



Figs. 7(a-f). Observed (TRMM) and forecasts rainfall anomaly (mm/day) from MME based on 30 May, 2013 and valid for week-1 (3-9 June), week-2 (10-16 June) and week-3 (17-23 June)

4.2. Operational extended range forecast during year 2010-2017

The verification of real-time ERF during the period from 2008 to 2017 have been documented in monsoon reports published each year by IMD. Some of these episodes along with their performance have been discussed here.

4.2.1. MME forecast of delayed onset and delayed withdrawal of monsoon during 2012

The monsoon season of 2012 witnessed a delay in onset over southern tip of India (Kerala) with the onset date of 5 June, 4 days later than its normal onset date of 1 June (Khole *et al.*, 2013). The observed weekly rainfall anomalies obtained from TRMM during the period from 14-20 May, 21-27 May and 28 May to 3 June, 2012 [Figs. 6(a-c)] indicated no likely onset of monsoon till 3rd June as indicated by large negative anomalies of rainfall over Kerala coast over southern tip of India and adjoining Arabian Sea. It is also seen from Fig. 6(b) that the positive anomalies over the Andaman Sea during the period from 21-27 May, 2012 indicated onset of monsoon over the Andaman Sea during the week with actual onset of monsoon over Andaman Sea occurred on 23 May. The corresponding MME ERF rainfall anomalies patterns based on the initial condition of 10 May, 2012 and valid for week 1, week 2 and week 3 forecasts coinciding from 14 May to 3 June, 2012 [Figs. 6(d-f)] also indicated the delayed onset of monsoon over southern tip of Kerala. The forecast rainfall anomalies clearly indicated no onset of monsoon till week ending on 3 of June 2012.

The withdrawal of southwest monsoon during 2012 was also delayed with large positive departure of rainfall continuing till 23 September. During 2012 the withdrawal of monsoon from west Rajasthan (Northwestern state of India) commenced only on 24 September compared to its normal date of 1 September (Khole *et al.*, 2013). The active September with positive anomalies for three weeks were very much captured in MME ERF based on the initial condition of 30 August 2012 with no indication of withdrawal till 23 of September, 2012 (Pattanaik, 2014).

4.2.2. Rapid progress of monsoon and heavy rainfall over Uttarakhand during 2013

One of the unusual features of monsoon 2013 is the rapid progress of monsoon northward after the onset of monsoon over Kerala. The southwest monsoon normally sets in over Kerala around 1st June and it advances northwards, usually in surges and covers the entire country around 15 July. The pace of advance of southwest monsoon in 2013 had been the fastest during the period 1941-2013 as it took only 15 days to cover the entire country after its normal onset on 1st June. This type of rapid advance of monsoon with vigorous rainfall activity is associated with movement of a monsoon low from NW Bay of Bengal across central India to NW India during this period (Pattanaik *et al.*, 2015). The rainfall anomaly during these periods from 3 June to 23 June, 2013 indicate positive rainfall anomalies over entire northern and western parts of India during the period from 10-16 June, 2013 indicating the coverage of monsoon over entire India by 16th June, 2013 [Figs. 7(a-c)]. The week during

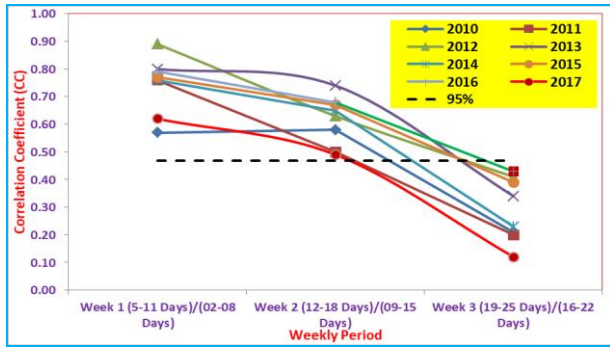
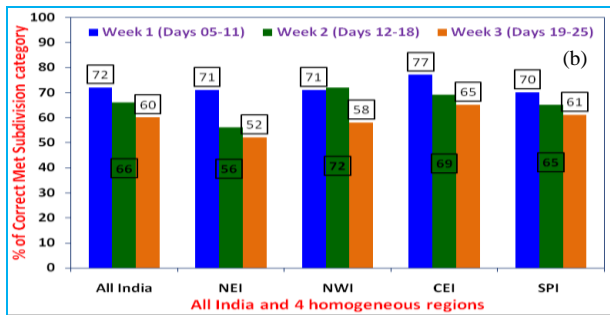
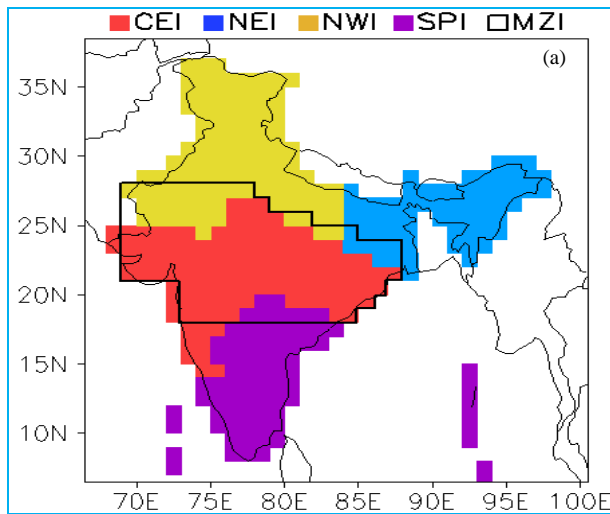


Fig. 8. Correlation Coefficients (CCs) for week 1 to week 3 forecast of all India monsoon rainfall during 2010 monsoon season to 2017 monsoon season



Figs. 9(a&b). (a) The four homogeneous regions of India with Central India (CEI), Northeast India (NEI), Northwest India (NWI) and South peninsular India (SPI). (b) Met-subdivision level forecast skill over India and four homogeneous regions as per the classification given in Table 1

10-16 June also indicated heavy rainfall over Uttarakhand and adjoining region as also seen in Figs. 7(a-f). As discussed by Pattanaik *et al.*, (2015) the MME based ERF had captured this unusual behaviour. The MME ERF based on the initial condition of 30th May also clearly indicated rapid progress of monsoon and coverage over

TABLE 1

Classification of forecast category for the met-subdivision level based on rainfall departure over a met-subdivision

Forecast → Actual ↓	Excess (E) or Normal (N) (Moist State)	Deficient (D) or Scanty (S) or No Rain (NR) (Dry state)
(Excess; E) : +20% or more or (Normal; N) : -19% to +19%	Correct (C)	Wrong (W)
(Deficient; D) : -20% to -59% (Scanty; S) : -20% to -59% (No Rain; NR)	Wrong (W)	Correct (C)

the entire country by 16th June, 2013 as seen from the anomaly plots of rainfall shown in Figs. 7(d-f). Thus, the unusual behaviour of rapid progress of monsoon during 2013 was very much captured in the coupled models. However, on sub-division level over Uttarakhand the positive departure of rainfall forecasted by the model was much less than that of observed departure. The underestimation of heavy rainfall in the model is due to the fact that it could not capture the interaction of upper level westerly trough with the low level convergence in the model.

4.2.3. *Quantitative forecast skill over the India and smaller spatial domains*

As discussed in previous section, IMD started preparing monitoring and forecasting of monsoon in extended range time scale from 2008 onwards using both empirical and dynamical models outputs. From 2010 monsoon season onwards IMD also started preparing the ERF operationally using MME of all dynamical models operationally available. The operational MME ERF forecast is prepared each year and is documented in the report published by IMD Pune. The all India averaged monsoon rainfall forecast for three weeks during the monsoon season from 2010 to 2017 is shown in Fig. 8. During the initial period from 2010 to 2012 when the ECMWF monthly forecast system data was available to IMD the initial condition was used for every Wednesday and the forecast was valid for week 1 (Days 5 -11), week 2 (Days 12-18) and week 3 (Days 19-25) that is coinciding from every Monday to Sunday. However, after the ECMWF monthly forecast system data was not available the forecast period was for Days 2-8, Days 9-15 and Days 16-22 for week 1, week 2 and week 3 respectively based on every Wednesday initial condition and valid for Friday to Thursday and so on.

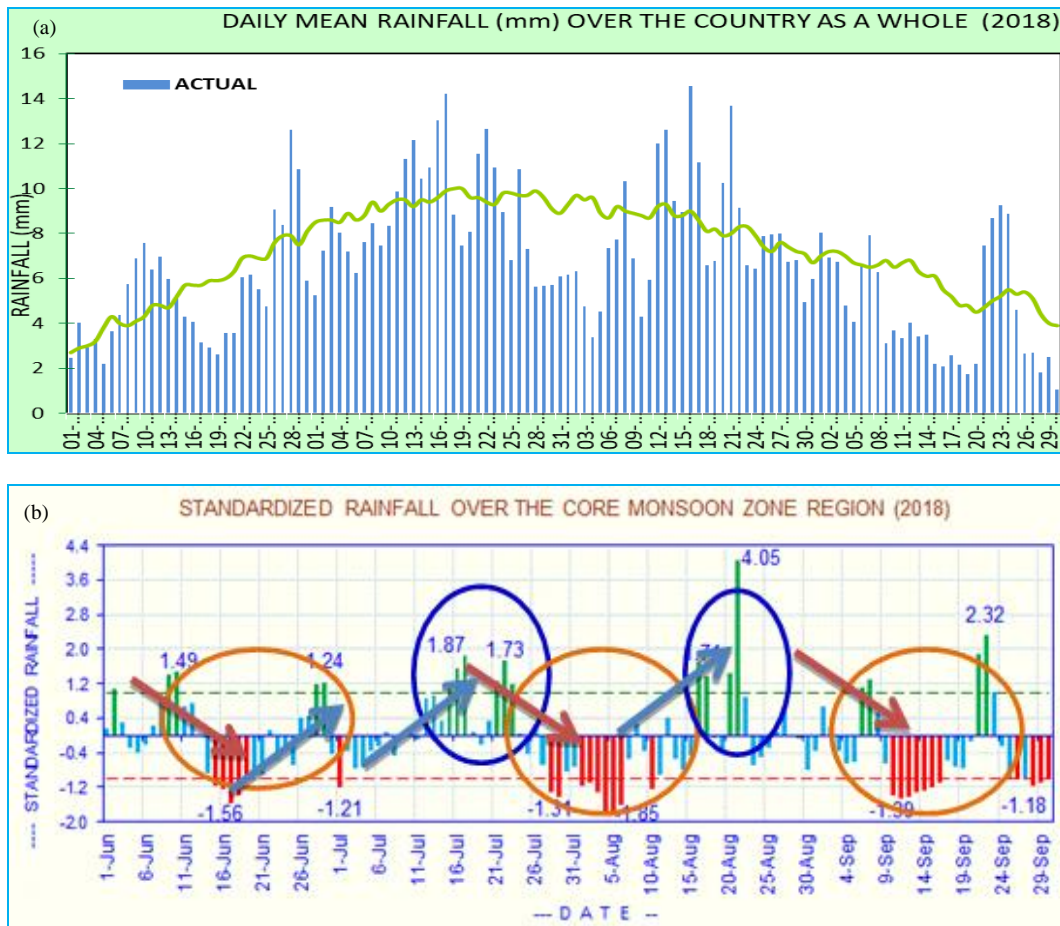


Fig. 10(a&b). (a) The daily all India rainfall (actual and normal) and (b) Daily actual and normal rainfall over core monsoon region along with its daily departure during June to September, 2018

As seen from Fig. 8 the ERF forecast skill shows significant correlation coefficient (CC) for two weeks (15 to 18 days) with week 3 forecast (22 to 25 days) also indicates positive value, although not statistically significant.

Though the extended range forecast of monsoon on all India level is very useful, due to the spatial inhomogeneity of the rainfall distribution it is useful to analyse the skill of the monsoon forecast on smaller spatial domains. The country as a whole is divided into 4 homogeneous regions *viz.*, (i) Northeast (NE) India, (ii) Northwest (NW) India, (iii) CE India and (iv) South Peninsular (SP) India, consisting of 7, 9, 10 and 10 met-subdivisions respectively as shown in Fig. 9(a). The ERF over 36 met-subdivisions can provide forecast outlook at regional level for application in Agriculture and other sectors. As shown by Pattanaik (2014) the forecast skill differs from one region to other region and broadly it shows significant CCs (above 95% level) over CE India, SP India and NW India till 2 weeks (up to 18 days) except

in case of NE India, which shows significant CC for week 1 only. For the met sub-division level forecast the observed rainfall departure is compared with the forecast category of the met-subdivision like Excess (E), Normal (N), Deficient (D) and Scanty (S) as per the classification shown in Table 1. Pattanaik (2014) based on detailed analysis of met-subdivision level forecast for 2012 monsoon season found that the MME ERF has the skill better than climatology forecast skill.

In case of application of extended range forecast in Agriculture it is not only the rainfall forecast which matters, but the other parameters like temperature, solar radiation and the moisture stress are very crucial. In view of that the category forecast based on rainfall in terms of "excess", "normal", "deficient" and "scanty or no rain" can be combined into two broad categories as (i) moist state and (ii) dry state by combining "excess" and "normal" into former category and "deficient" and "scanty or no rain" into the latter category as indicated in Table 1. In this case the contingency table for verification is given

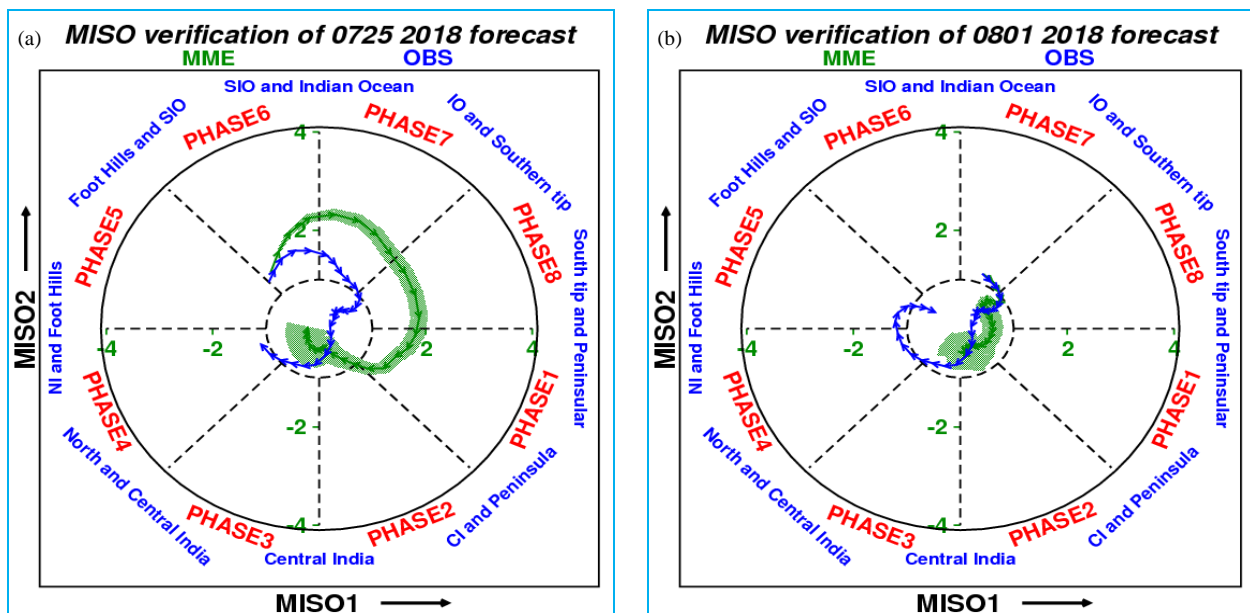


Fig. 11(a&b). The phase diagram of the observed and extended range forecast Monsoon Intra-Seasonal Oscillation (MISO) for 4 weeks based on IC of 25 July and (b) 1 August, 2018

in Table 1 with only two categories *viz.*, either correct or wrong. As shown by Pattanaik (2014) the mean percentage of correct forecast from MME ERF for 18 weeks of 2012 monsoon season for week 1 to week 3 forecasts over India as a whole and 4 homogeneous regions are given in Fig. 9(b). As seen from Fig. 9(b) for the country as a whole (consisting of 36 met-subdivisions) the met-subdivision level forecast indicates 72% correct during week 1 followed by 66% in week 2 and 60% in week 3. It is to be interpreted that if it is 50% correct means 18 out of 36 met-subdivisions the forecast category matches with the observed category as per the contingency Table 1. As seen from Fig. 9(b) the percentage of correct forecast over CE India and NW India is found to be about 70% or more up to week 2, whereas over the SP India the correct category is found to be 70% for week 1 and 65% for week 2. Over the NE India the week 1 forecast shows correct category of 71% followed by only 56% and 52% for week 2 and week 3 forecasts respectively. Another interesting aspect is that over the CE India the week 3 forecast also indicated 65% correct category. Characterizing the extended range prediction of Indian monsoon is a vexing problem, as it encompasses complex, multi-scale variability, the MME based predictions for 2 to 3 weeks provide skilful results & can provide useful guidance to the farming sector of India.

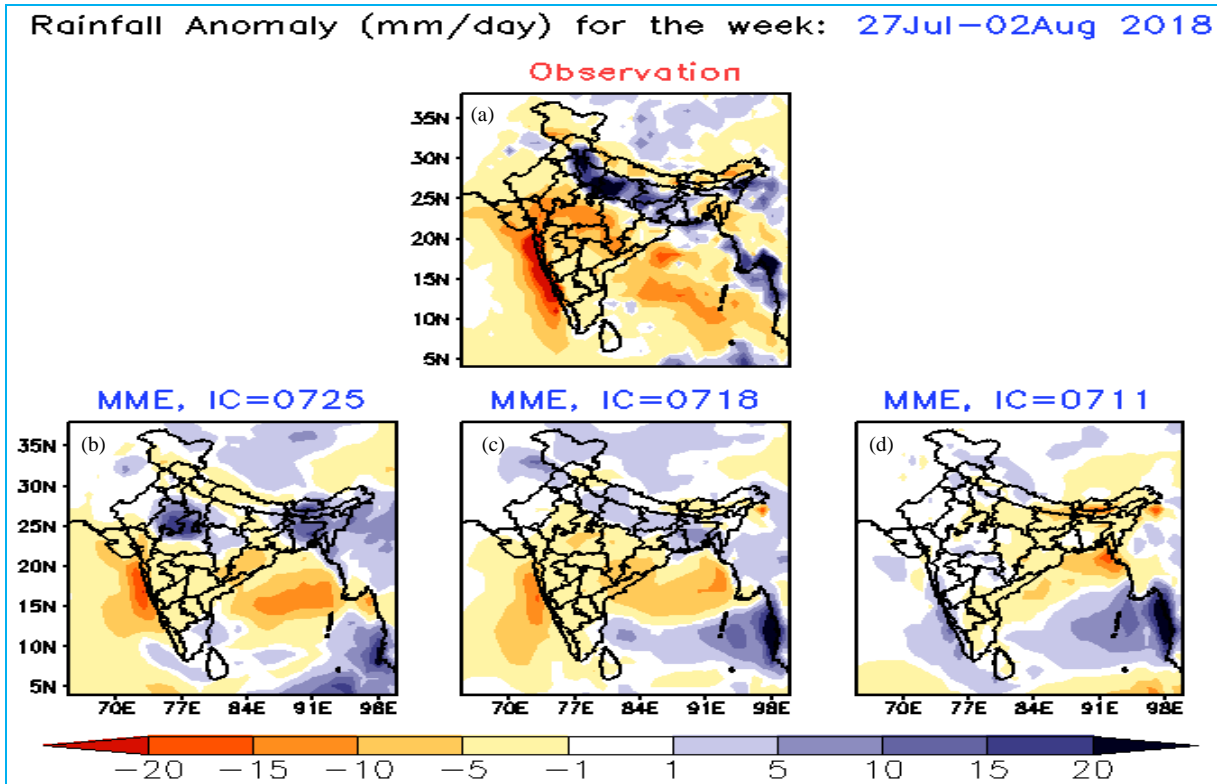
5. Active-break cycle prediction of monsoon during 2018

During 2018 the southwest monsoon onset over Andaman Sea and Nicobar Islands was on 25th May

(5 days later than its normal date), but further advance was relatively faster with Kerala onset was on 29th May, 3 days ahead of its normal date. Thereafter monsoon progressed rapidly and covered the entire country in one month (on 28th June) well ahead of its normal schedule. As seen from the daily rainfall and its departure over India as a whole and core monsoon region [as demarcated in Fig. 9(a)], the season witnessed normal to below normal rainfall during many days along with transition from active to break and *vice versa* during the season [Figs. 10(a&b)]. The intra-seasonal episodes for 2018 monsoon seasons indicated following transitions *viz.*, (i) Slight early onset of monsoon over southeast Bay of Bengal and Kerala, (ii) Progress of monsoon to north India with better monsoon condition in 1st half of June followed by weak rainfall in end of June, (iii) Transition into normal to active phase of monsoon during 3rd and 4th week of July, (iv) Transition of monsoon from active phase towards the end of July to long dry spell during first 10 days of August and (v) Weak monsoon condition during 2nd and 3rd week of September, 2018.

5.1. Transition of monsoon from active phase towards the end of July to long dry spell during first 10 days of August.

The general intra-seasonal patterns of monsoon indicate transition of active to break and break to active phase of monsoon particularly during the peak phase of monsoon. During 2018, after the two weeks active phase of monsoon from 13-26 July, 2018 it entered into weak phase with most of the days the rainfall is below



Figs. 12(a-d). (a) Observed weekly rainfall anomaly for the period 27 July-2 August, 2018. The lower panel (b)-(d) : The ERF rainfall anomaly for the same target week with ICs of 25 July, 18 July and 11 July, 2018

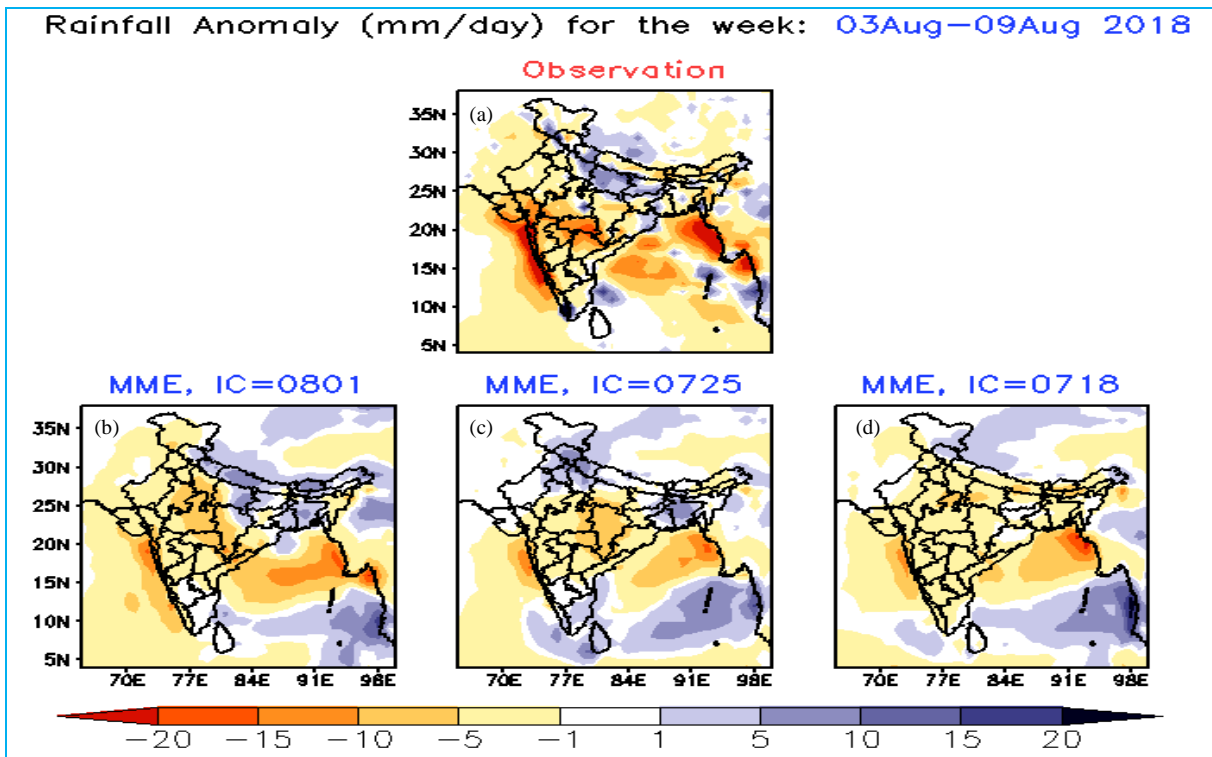
normal [Figs. 10(a&b)]. The Monsoon Intra-Seasonal Oscillation (MISO) leading to this transition from normal/active phase of monsoon to weak/break phase of monsoon can be seen from the MISO phase diagram. To see the northward progress of monsoon the phase diagram of the observed and extended range forecast of MISO for 4 weeks based on IC of 25 July and 1 August, 2018 is shown in Figs. 11(a&b). As seen from these two figures the northward propagation was very weak particularly, with regard to the initial condition of 1st August, 2018.

The weak phase of monsoon can also be seen from the observed negative rainfall anomaly during the two weeks period from 27 July-2 August [Fig. 12(a)] and 3-9 August, 2018 [Fig. 13(a)]. During this two weeks period most of central India witnessed large negative rainfall with some meteorological subdivisions over the Indo-Gangetic plain received positive rainfall anomaly. In order to see the MME ERF forecast in capturing this break monsoon condition, the forecast with three weeks lead time for the target weeks of 27 July-2 August and 3-9 August, 2018 is shown in Figs. 12(b-d) and Figs. 13(b-d) respectively. As shown in both the figures the break phase of monsoon associated with the large negative anomaly of rainfall over most of India was well captured with three weeks lead time with ICs of 25 July, 18 July and 11 July

for the target week of 27 July-2 August and with ICs of 1 August, 25 July and 18 July for the target week of 3-9 August, 2018. Thus, the model could capture the transition from active to break phase of monsoon very well.

5.2. Quantitative verification of ERF forecasts of monsoon over India during 2018

In order to see the quantitative verification of extended range forecast over the country as a whole and 4 homogeneous regions of India the observed weekly rainfall departure for four weeks period during 2018 monsoon season is correlated with the corresponding MME ERF forecasts rainfall for four weeks averaged over India as a whole and the central India. The MME ERF rainfall departures along with observed rainfall departures for the country as a whole and central India with different lead time along with CC is shown in Figs. 14(a&b). As seen the ERF forecast did capture the observed intra-seasonal variability of monsoon rainfall during different phases of monsoon in most of the period during the season with significant CCs upto three weeks. Only during the two weeks from 29 June-5 July and 6-12 July, 2018 the slight negative departure of observed rainfall, predicted as slight positive rainfall in the ERF forecast. Over the main monsoon belt of central (CE) India the transition of



Figs. 13(a-d). (a) Observed weekly rainfall anomaly for the period 27 July-2 August, 2018. The lower panel (b)-(d) : The ERF rainfall anomaly for the same target week with ICs of 25 July, 18 July and 11 July, 2018

monsoon from active to weak phase, weak to active phase and the long weak spells of July, August and early September was captured very well in the MME forecast [Fig. 14(b)]. Like in all India rainfall case shown in Fig. 14(a) the central India, where the active-break cycle is more prominent, also shows significant CCs for three weeks with ERF forecasting capturing the active and weak phases of monsoon along with its transition from one phase to other about 3 weeks in advance [Fig. 14(b)]. The CC between observed and forecast rainfall departure over CE India is found to be significant till three weeks with CC of 0.87 in week 1, 0.66 in week 2 and 0.42 in week 3.

5.3. Met sub-division forecast for 2018

In order to see the forecast skill of extended range forecast for smaller spatial domains the 36 met-subdivisions of India is considered for forecast verification. Based on the observed weekly rainfall departure over each met- subdivisions during the monsoon season of 2018 the CC is calculated with the corresponding met-subdivision forecast rainfall during the entire monsoon season of 2018. The meteorological sub-division wise CC map is prepared for four weeks forecasts (Fig. 15). As seen from Fig. 15 the week 1 forecast is mostly skilful over all the met-subdivisions of India except J & K in the extreme north and Arunachal Pradesh

in Northeast India. The forecast skill for week 2 forecast is also encouraging and skilful with many subdivisions with higher CCs, except some met subdivisions in north and northeast India, which have very poor skill. During week 3 and week 4 forecasts cases, parts of central India, northwest India and peninsula India are having higher skill and many met-subdivisions in eastern, northeast and northern India are with very lower skill. Thus, on met-subdivision level the forecast for at least two weeks can be used for various applications including the agriculture sector.

In order to use the extended range forecast for agromet applications, the forecast for 36 met subdivisions of India is prepared for two weeks with categorising the subdivisions as below normal (BN), normal (NN) or above normal (AN) category depending on the rainfall departure during the week. As per the classification a met-subdivision is considered to be 'AN' if rainfall departure $\geq 20\%$; 'NN' if it is between $+19\%$ to -19% and 'BN' if it is $\leq -20\%$. The active to break transition of monsoon from above normal week of 20-26 July to below normal weeks of 27 July-2 August and 3-9 August, 2018 can be seen in Fig. 10(b). The observed met-subdivision level rainfall for this three weeks period is shown in Figs. 16(a-c). The corresponding forecast rainfall for two weeks based on the ICs of 18 July, 25 July and 1 August, 2018 is shown

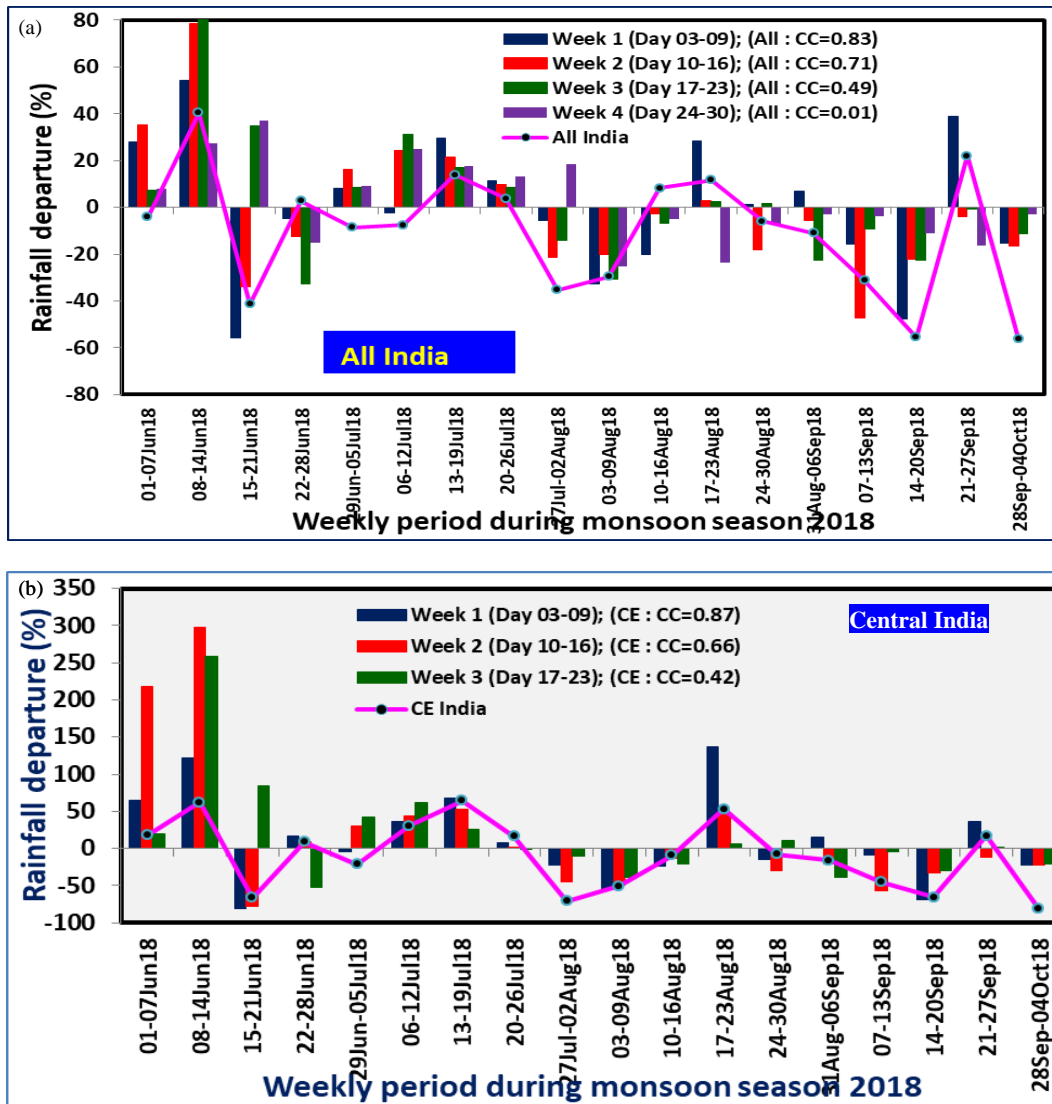


Fig. 14(a&b). (a) Weekly observed all India weekly rainfall departure during the monsoon season 2018 along with corresponding extended range forecast rainfall departure with lead time of week 1 week 4. (b) Same as 'a' but for the central India rainfall with verification up to three weeks forecasts

in Figs. 16(d-f). As seen from Figs. 16(a-c) the observed rainfall departure over most of the meteorological subdivisions in central and northwest India changed from AN/NN categories during 20-26 July into BN category during 27 July-2 August and 3-9 August, 2018 indicating the transition from active phase of monsoon into break phase of monsoon. The MME ERF based on ICs of 18th July and valid for next two weeks (20-26 July and 27 July-2 August) well captured this transition and hence was very useful in providing Agromet advisory to farmers [Fig. 16(d&e)]. For the quantitative verification of met-subdivision level forecast a 3×3 contingency table is considered with three categories (AN; NN and BN) shown in Table 2. If the forecast category matches with observed category it is correct (C) forecast and if it is one category

out it is termed as partially correct (PC) forecast and if it is two categories out it is wrong (W) forecasts. When compared quantitatively the week 1 forecast valid for 20-26 July shown in Fig. 16(a) and Fig. 16(d) indicated correct forecast of 58% (21 out of 36 Met subdivisions), partially correct forecast of 36% (13 out of 36 Met subdivisions) and wrong forecast of 6% (2 out of 36 Met subdivisions). In case of week 2 forecast valid for the week from 27 July-2 August shown in Fig. 16(b) and Fig. 16(e) indicated 72% correct, 20% partially correct and 8% wrong forecast. Similarly the week 2 forecast based on IC of 25th July and valid for the period from 3-9 August, 2018 as shown in Fig. 16(c) and Fig. 16(f) indicated 47% correct, 45% partially correct and 8% wrong forecast. Thus, the present skill of met-subdivision

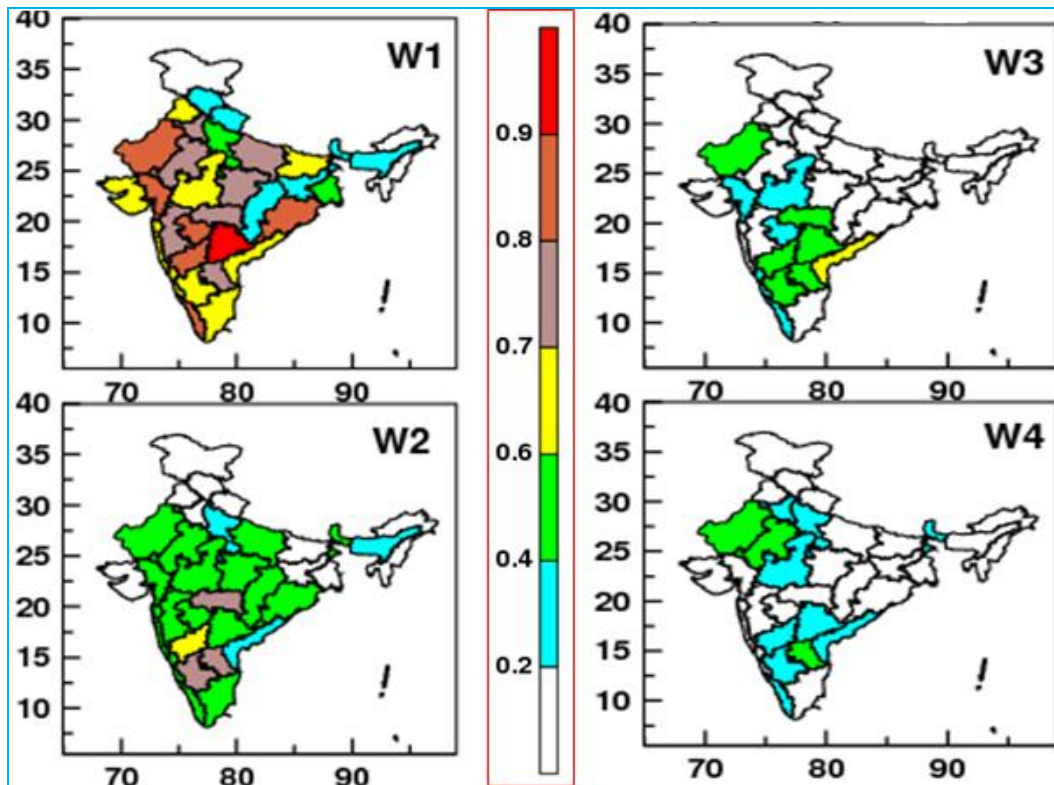


Fig. 15. Met-subdivision level forecast between observed rainfall and MME ERF rainfall departure for week 1 to week 4 forecast during the monsoon season 2018

level ERF forecasts could provide useful guidance to farmers for two weeks.

6. Extended range forecast of heat wave, cold wave and health sector

6.1. Extended range forecast of heat wave

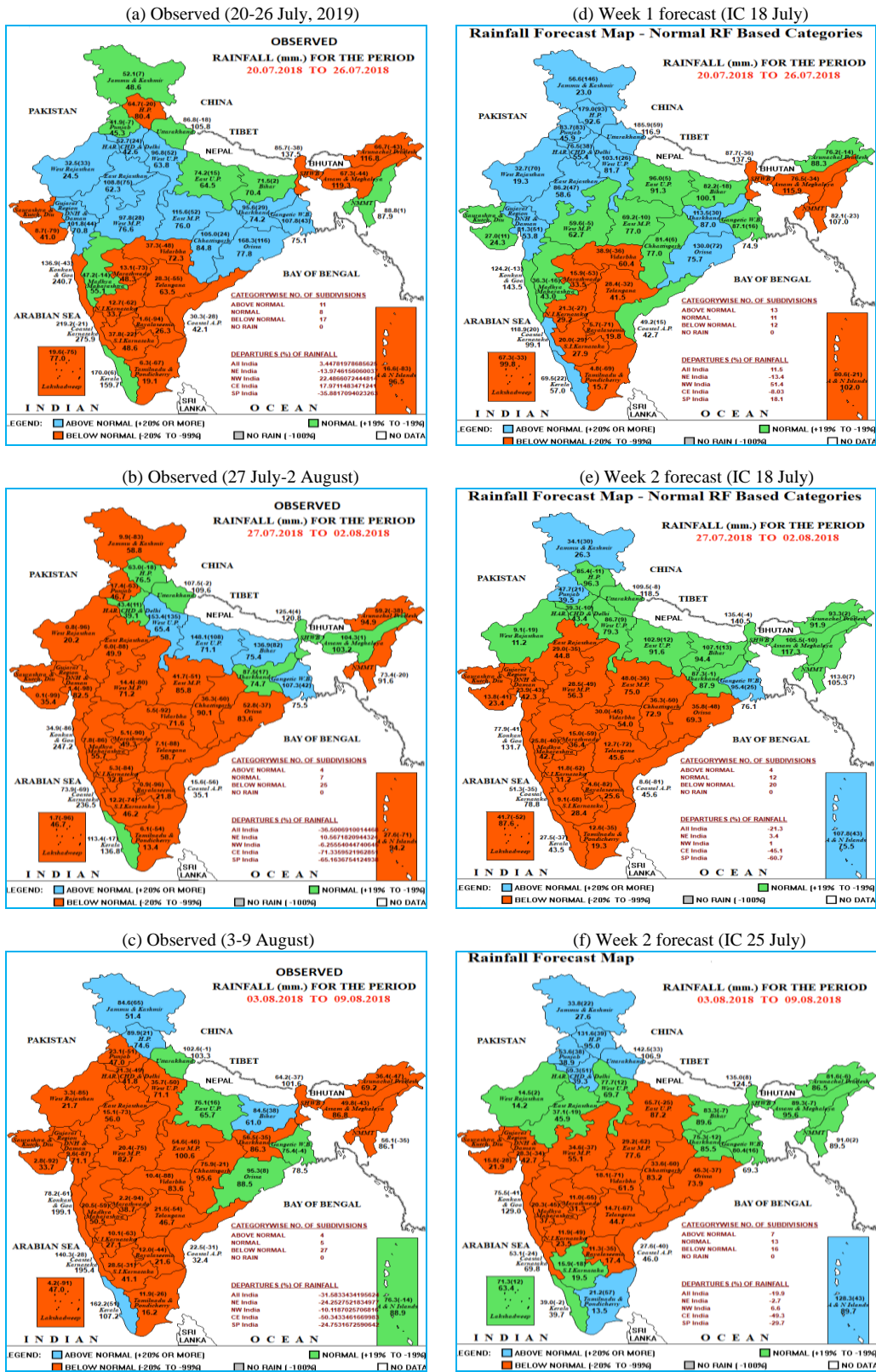
Hot winds known as “loo” are the marked feature of summer in northern India. Extremely hot weather is common in India during late spring preceding the climatological onset of the monsoon season in June. The climatology pattern (Pattanaik and Mukhopadhyay, 2012) of maximum temperature (Tmax) in April over India indicates a small pocket of Tmax exceeding 40 °C over central India and by May, the Tmax increases and exceeds 40 °C over large parts of India covering north-western parts of the country extending towards the Indo-Gangetic plain, whereas, in June, though the monsoon currents cool the southern parts of the country, the Tmax remains more than 40 °C in north-western parts of the country. During summer, most areas of India experience episodes of heat waves almost during every year causing sunstroke, dehydration and death. It is not only the loss of life associated with ‘HW’ is important but also the continuous higher temperatures during critical growth stages of rabi

TABLE 2

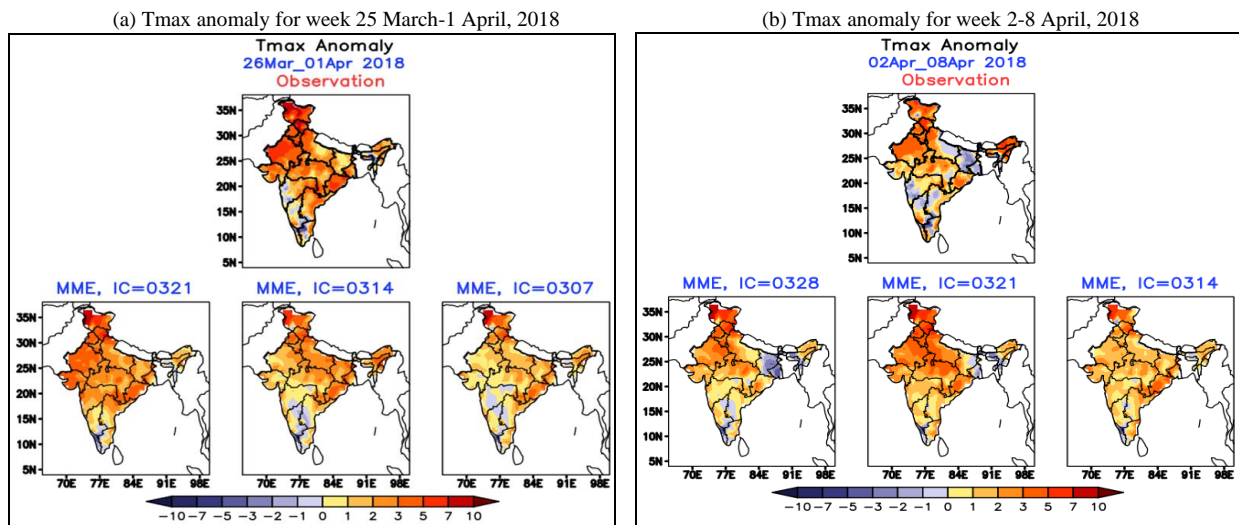
Classification of forecast category for the met-subdivision level based on rainfall departure over a met-subdivision

Forecast → Actual ↓	Above Normal (AN)	Normal (NN)	Above Normal (BN)
Above Normal (AN) Rainfall Dep : ≥ +20%	Correct (C)	Partially Correct (PC)	Wrong (W)
Normal (NN) Rainfall Dep : -19% to +19%	Partially Correct (PC)	Correct (C)	Partially Correct (PC)
Below Normal (BN) Rainfall Dep : ≤ -20%	Wrong (W)	Partially Correct (PC)	Correct (C)

crops reduces the crop yields considerably. Change in the characteristics of temperature extremes of different intensities and duration has significant impact on sectors like agriculture and health. Heat wave can kill birds in the poultry firm. It is estimated that about 20 lakhs birds died in May & June 2003 with an estimated loss of 27 Crores in Andhra Pradesh (Rao, 2012).



Figs. 16(a-f). (a-c) Observed met-subdivision level rainfall with three categories, (d-e) MME ERF based on 18th July and valid for week 1 and week 2 forecasts coinciding with 20-26 July and 27 July-2 August and (f) Week 2 forecast based on IC of 25th July and valid for 3-9 August, 2018



Figs. 17(a&b). (a) For the target week of 26 Mar-1April, 2018 the observed Tmax anomaly along with ERF forecasts with ICs of 21st, 14th and 7th March (b) Same as ‘a’ but for the target week of 2-8 April, 2018 with ERF forecasts from 28th, 21st and 14th March

Recently, many studies highlighting different aspects of HW over India in recent times have been carried out (Mohapatra *et al.*, 2001; De *et al.*, 2005; Bhadram *et al.*, 2005; Pai *et al.*, 2013, Ratnam *et al.*, (2016), etc). As shown by Pai *et al.* (2013) the spatial variation of seasonal climatology of ‘HW’ days experienced over the country expressed as average ‘HW’ days per season during last fifty years from 1961 to 2010 during March to July. They have shown that except over northeast India and large parts of Peninsula (South of ~21° N & west of 80° E), most areas of the country have experienced on an average ≥2 HW days. The present criteria used by IMD for defining heat wave are given in Table 3.

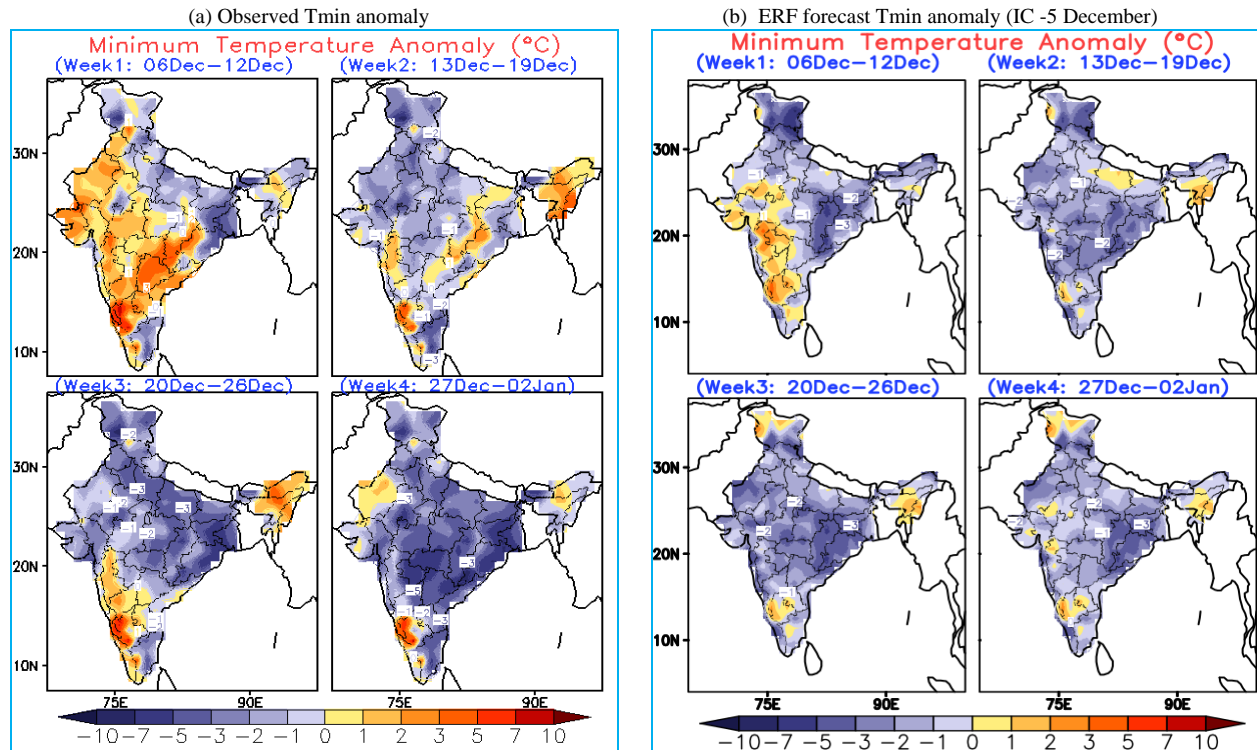
As shown by Pattanaik and Hatwar (2006) the ‘HW’ during the middle of June in 2005 was due to such stagnation in monsoon progress over the region. In its detailed study of the deadly 2010 heat wave in Ahmedabad, the Indian Institute of Pubic Heath (IIPH) found that the number of deaths caused by heat strokes were highly under-reported and that the most vulnerable populations were construction workers and children, the elderly and women from slum settlements. In May 2015, India was also severely impacted by a severe heat wave with casualties of more than 2,400 people in many meteorological subdivisions over central, eastern coastal regions, north and north-western parts of the country (Pattanaik *et al.*, 2016). In 2016, number of casualties came down drastically from 1111 deaths in 2016 (reduced 46%) as compared to deaths that recorded in 2015. Heat wave also caused death of wildlife, birds, poultry in states and most of the zoos in India (Source; NDMA). However, after the heat action plans implemented over many states of the country the number of death related to heat wave have been decreased substantially in India from 2016 onwards.

TABLE 3

Present criteria used by IMD for defining heat wave

1. Heat wave is considered if maximum temperature (Tmax) of a station reaches at least 40 °C or more for Plains and at least 30 °C or more for Hilly regions	
<i>Based on Departure of Tmax from Normal</i>	<i>Based on Actual Tmax</i>
Heat Wave (HW) : Departure is 4.5 °C to 6.4 °C	Heat Wave (HW) : Actual Tmax ≥ 45 °C
Severe Heat Wave (SHW) : Departure is > 6.4 °C	Severe Heat Wave (SHW) : Actual Tmax ≥ 47 °C
2. Heat Wave Over Coastal Stations is defined when maximum temperature departure is 4.5 °C or more from normal provided the actual Tmax ≥ 37 °C	

The operational ERF issued by IMD shows higher predictive skill of heatwave (Pattanaik, 2015). The medium to extended range forecast (2 to 4 weeks) of such extreme high temperature has a wide range of applications in agriculture, energy, health, insurance, power, financial sector etc. The prediction of heat waves with significant accuracy can save lives and prevent damage to property from these dangerous weather events. Now it is to be tested how this present generation coupled model can predict the heat wave, which is now considered to be a deadly disaster like cyclones and floods. Pattanaik *et al.*, (2016) have shown the skill of extended range forecast of recent heatwave episode over Telangana and Odish during 2015. In order to see the performance of current operational ERF system of IMD in capturing the heat wave over India, the recent two weeks heat wave period from 25 March to 8 April of 2018 is considered. In this regard the observed maximum temperature (Tmax) anomaly for the target week of 25 March - 1 April, 2018



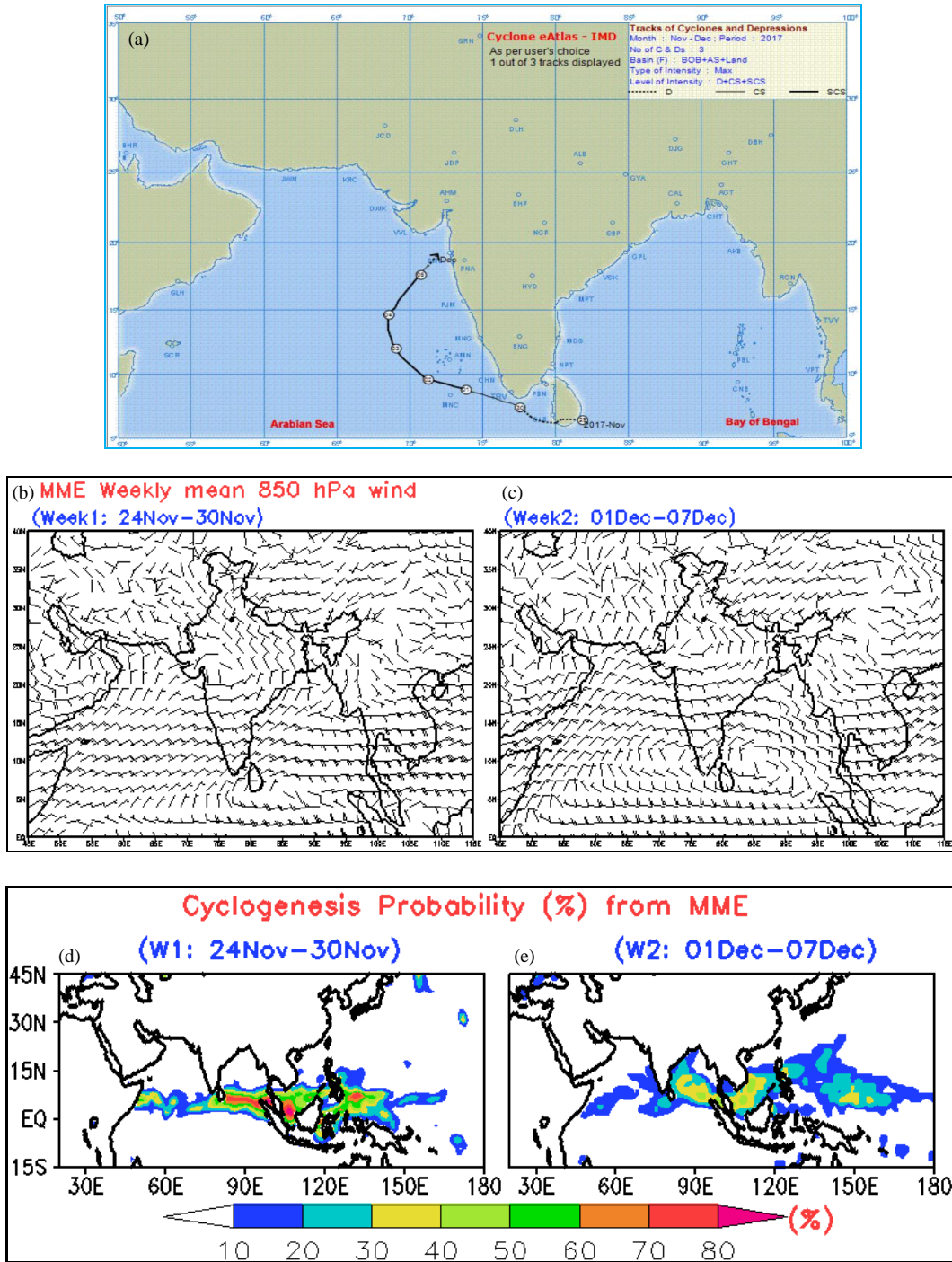
Figs. 18(a&b). (a) Observed minimum temperature (T_{min}) anomaly during 4 weeks from 6th December, 2018 to 2nd January, 2019, (b) The corresponding ERF forecast T_{min} anomaly for 4 weeks based on the initial condition of 5th December, 2018

with ERF T_{max} anomaly with different lead time is shown in Fig. 17(a). Similarly, for the target week of 2-8 April, 2018 the observed T_{max} anomaly and ERF T_{max} anomaly with three different lead time are shown in Fig. 17(b). As shown in Figs. 17(a&b) the ERF could capture the observed T_{max} anomaly during the heat wave period from 25 March to 8 April, 2018. Thus, the real time forecast is accurately provided the guidance in for the heat wave. Heat wave probability of occurrence, hot day, Heat wave (HW) & Severe Heat Wave (SHW) are also prepared operationally based on the ERF forecast. As shown in Pattanaik and Sahai (2018) the Heat Wave and Hot days during the hot weather season of April-May 2017 over North-western and central parts of India is very well predicted in the ERF forecast.

6.2. Extended range forecast of cold wave

Like the heat wave the northern parts of India, especially the hilly regions and adjoining plains are affected by the cold waves, although cold wave conditions are reported from central Indian states like Maharashtra and Karnataka. At times, the northern parts of South Peninsula also experience the cold episodes. The maximum number of cold waves occur over Jammu and Kashmir, followed by Himachal Pradesh, Punjab, Bihar, Haryana and Uttar Pradesh. Cold waves in India occur

during boreal winter (December-February) due to extreme low temperature in association with incursion of dry cold winds from north into the sub-continent. Cold waves over northern and north-western parts of India are often associated with the Western Disturbances. Extreme of cold has a broad and far-reaching set of impacts on the nation. These include significant loss of life and illness, economic costs in transportation, agriculture, production, energy and infrastructure. The ERF well in advance about the impending cold wave can be very helpful to disaster managers to take proper actions to minimize the adverse impact on various sectors like health, power, agriculture etc. The current ERF system of IMD is able to predict the cold wave very well. During the 2018-19 winter season there was long cold wave over north India, adjoining central India from 13th December, 2018 to 2nd January, 2019 as seen from the observed minimum temperature (T_{min}) during the period with negative T_{min} over large parts of India [Fig. 18(a)]. The corresponding MME ERF based on the initial condition of 5th December, 2018 clearly captured this long cold wave with negative T_{min} anomaly prevailing over the region from week 2 to week 4 forecast valid from 13 December 2018 to 2 January, 2019 [Fig. 18(b)]. As shown in Pattanaik and Sahai (2018) cold condition of 2017-18 seasons is also very well captured in the present ERF system of IMD.

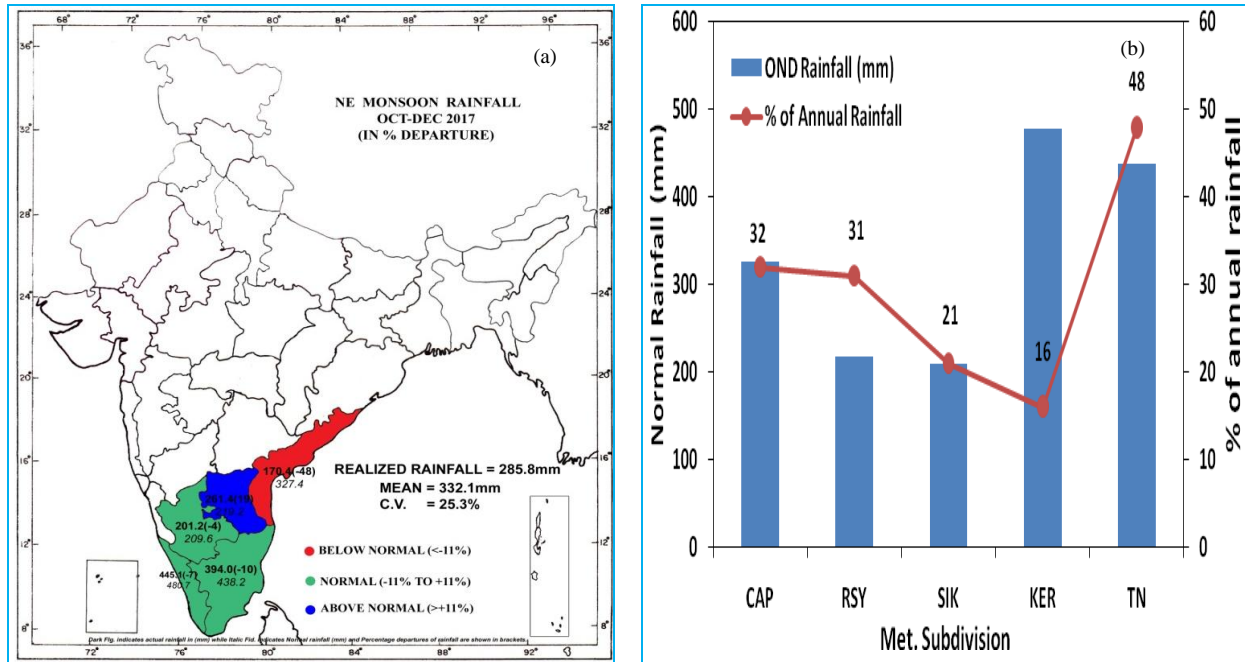


Figs. 19(a-e). (a) Track of Very Severe Cyclonic Storm (VSCS) Ockhi during 29 November-6 December, 2017, (b&c) based on 22nd November the weekly mean wind ERF at 850 hPa valid for (24-30 November) and (1-7 December), 2017, (d&e) Same as (b&c) but for cyclogenesis probability for two weeks valid for same period

6.3. *Experimental climate information product for health sector*

It has been found from many recent studies that certain favourable weather conditions associated with

favourable temperature and humidity can have some impacts of human health conditions. Thus, in addition to heat wave, cold wave, high heat index (combined effect of high temperature and high humidity) as discussed in Pattanaik *et al.*, (2013c) certain combination of minimum



Figs. 20(a&b). (a) Met-subdivisions of northeast monsoon rainfall and (b) The normal northeast monsoon rainfall over these five met-subdivisions along with its percentage contribution

temperature, maximum temperature and humidity is more suitable for the transmission of vector borne diseases like Malaria, Dengue etc. Pattanaik and Mukhopadhyay (2012) have discussed the vulnerability analysis of two transmission windows (TW1 and TW2) products for vector borne diseases over India during different seasons based on climatological data of meteorological variables. The two windows are defined as TW1; $T_{max} \leq 35$; $T_{min} \geq 20$; $RH \geq 55\%$ and TW2; $25 \leq T \leq 30^\circ C$; $60 \leq RH \leq 80\%$. Considering such favourable windows of temperature and humidity which helps in transmission of vector borne disease, IMD has started preparing the Climate Information products for Health sector experimentally based on extended range forecast. The temporal evolution of spatial distribution of transmission window for Vector borne disease, based on extended range weather forecasts are being prepared experimentally for sharing with state government officials.

7. Extended range forecast of cyclogenesis potential

With respect to the forecasting of Tropical Cyclone (TC) genesis using dynamical models, there have been considerable improvement in the forecast skill of TCs over the NIO, particularly in the short range up to 72 hrs (Mohapatra *et al.*, 2013a&b), which could be due to the improvement in numerical model and use of wide range of non-conventional data in the assimilation system of the model (Pattanaik and Rama Rao, 2009; Mohanty *et al.*, 2010; Osuri *et al.*, 2012, etc). Some earlier studies

(Pattanaik *et al.*, 2003; Kotal *et al.*, 2009) have also discussed the genesis parameters of formations of TCs over North Indian Ocean (NIO) based on dynamical variables in the medium range time scales. Also, there have been some efforts to forecast the genesis of TCs over the Bay of Bengal (BoB) in the extended range time scale (2-3 weeks) using latest generation coupled model outputs (Belanger *et al.*, 2010; Pattanaik *et al.*, 2013b; Pattanaik and Mohapatra, 2014) over the NIO. IMD has started to use the real time ERF for converting into cyclogenesis potential based on Kotal *et al.* (2009). The Genesis Potential Parameters (GPP) of TC genesis is being prepared operationally with $GPP = (\xi_{850} * M * I) / S$, where ' ξ_{850} ' is low level relative vorticity, 'S' being the vertical wind shear between 200 hPa and 850 hPa, 'I' being the middle tropospheric instability and 'M' is the middle tropospheric relative humidity. Based on the operational ERF forecast the GPP is prepared both for day to day animation plot and also the weekly average. As discussed in Pattanaik and Sahai (2018) the real-time GPP guidance prepared based on operational ERF forecast had captured reasonably well the cyclogenesis potential of TCs that formed during 2017. While discussing the cyclogenesis potential as discussed in Kotal *et al.* (2009) the probability of tropical cyclone is calculated based on a threshold value >20 . At each grid point, ensemble members exceeding the threshold value is counted. Probability at each grid point = total count of members exceeding threshold/total member.

To see the performance ERF for the cyclogenesis the Very Severe Cyclonic Storm (VSCS), Ockhi over Bay of Bengal during formed during 29 November-6 December, 2017 is considered, which originated from a low pressure area over southwest Bay of Bengal. Under favourable environmental conditions, it concentrated into a Depression over southwest Bay of Bengal off southeast Sri Lanka coast in the morning of 29th November [Fig. 19(a)]. Moving westwards, it crossed Sri Lanka coast after some time. Continuing its westward movement, it emerged in Comorin Area in the evening of 29th and intensified into a Deep Depression (DD) in the early hrs of 30th. It further moved northwestwards intensified into Cyclonic Storm (CS) in the morning of 30th November, into a Severe Cyclonic Storm (SCS) over Lakshadweep area in the early morning of 1st December and VSCS over Southeast Arabian Sea to the west of Lakshadweep in the afternoon of 1st December. Finally, it crossed South coast of Gujarat between Surat and Dahanu as a WML around early morning of 6th December.

For the genesis of VSCS “Ockhi” the extended range forecast of low level wind based on the initial conditions of 22nd November, 2017 and 29th November, 2017 are considered. As seen in Figs. 19(b&c) the week 1 and week 2 forecast of low level mean wind based on the initial condition of 22nd November, 2017 indicates closed cyclonic circulation off the Sri Lanka coast in week 1 forecast valid for 24-30 November, 2017 which extends westward into the Arabian Sea in week 2 forecast valid for the period from 1-7 December, 2017. The cyclogenesis probability forecast for week 1 indicate >70% over the Southeast Arabian Sea and adjoining Sri Lanka coast based on the initial condition of 22nd November and valid for the period from 24-30 November, 2017 [Fig. 19(d)]. The week 2 forecast valid for the period from 1-7 December, 2017 indicated cyclogenesis probability of about 40% (mainly over the Bay of Bengal; Fig. 19(e)). Based on 29th November initial condition the cyclogenesis probability was between 30% to 50% over the southeast Arabian Sea and also over the western part of Bay of Bengal (Fig. not shown). Thus, the cyclogenesis probability over the Bay of Bengal off Sri Lanka coast during the period from 24-30 November, 2017 (coinciding with the period of Ockhi cyclone) based on 22nd November initial condition was reasonably indicated in the week 1 forecast.

8. Extended range forecast of northeast monsoon

The post-monsoon season during October to December (OND) is referred to as Northeast Monsoon (NEM) season over peninsular India, which was earlier also referred to as “Retreating southwest Monsoon Season”. It is associated with the seasonal reversal of

surface and lower tropospheric winds from south-westerlies (during the southwest monsoon season of June-September) to north-easterlies which set in over the Indian region in October [India Meteorological Department (IMD) 1973]. The reversal from south-westerlies to north-easterlies in the peninsula in October is a prelude to the establishment of northeast monsoon over the southern Indian peninsula. The five meteorological subdivisions of India that received NEM rainfall during OND is shown in Fig. 20(a), which constitute Coastal Andhra Pradesh (CAP), Rayalaseema (RYS), South Interior Karnataka (SIK), Kerala (KER) and TN (including the union territory of Pondicherry as well). Tamil Nadu is the main rainy season accounting for about 48% of the annual rainfall. Coastal districts of the State get nearly 60% of the annual rainfall and the interior districts get about 40-50% of the annual rainfall. The climatological rainfall over the 5 met-subdivisions based on 50 years of data from 1951 to 2000 (IMD, 2010) during OND season is shown in Fig. 20(b). The met-subdivision “Tamil Nadu” is the main meteorological subdivision, which accounts for 48% (OND, 438 mm) of its annual rainfall of 914 mm making this state/sub-division, the major beneficiary of NEM. The met-subdivision ‘Tamil Nadu’ is also the lone met-subdivision of India where rainfall realized during NEM is significantly more than that during the southwest monsoon season from June to September (317 mm).

As shown in the previous study the current generation coupled models are able to provide useful guidance about the active and weak phase of NEM with a lead time of about 1 to 2 weeks during 2010 and 2011 post-monsoon season (Pattanaik, 2015). During 2015, associated with strong El Nino the southwest monsoon rainfall over India during June to September was very deficit, while the NEM during OND, 2015 over southern peninsula was very active particularly during November and early December. Associated with this active phases of NEM the southeast India, especially Tamil Nadu and Puducherry experienced unprecedented rainfall activity during November and early December 2015 leading to devastating floods over Tamil Nadu. The megacity of Chennai was worst affected during the heavy rainfall spells of November and early part of December, 2015. The outlook of such active or weak phase of NEM, 2 to 3 weeks in advance was discussed by Pattanaik and Mohapatra (2017) will be very useful to different users. Considering the skilful forecast of southwest monsoon rainfall and NEM in the extended range time scale the performance of real time extended range forecast of active phases of NEM over Tamil Nadu and other met-subdivisions during the 2017 post-monsoon season based on multi-model ensemble has been discussed. The onset of northeast monsoon over Tamilnadu during 2017 was on 27th October and the withdrawal was on 15th January, 2018.

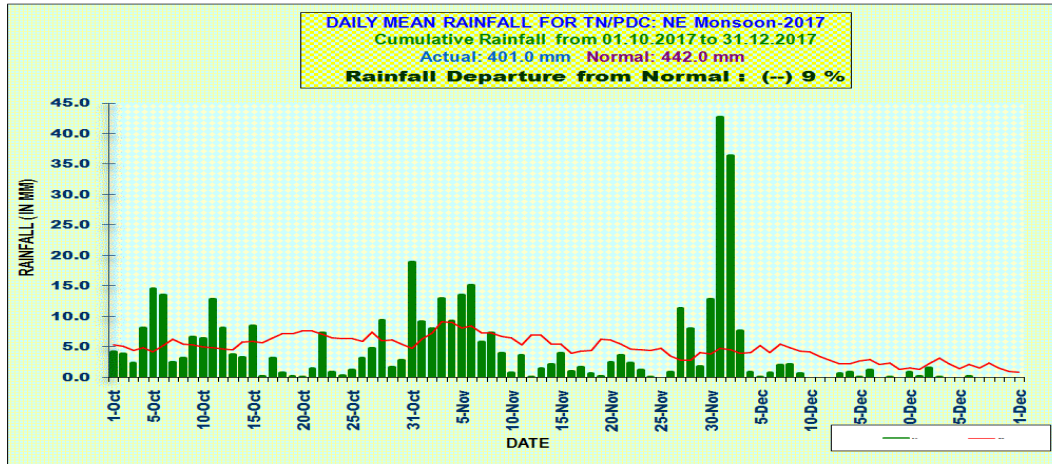


Fig. 21. Daily actual and normal rainfall over Tamil Nadu subdivision during October to December, 2017

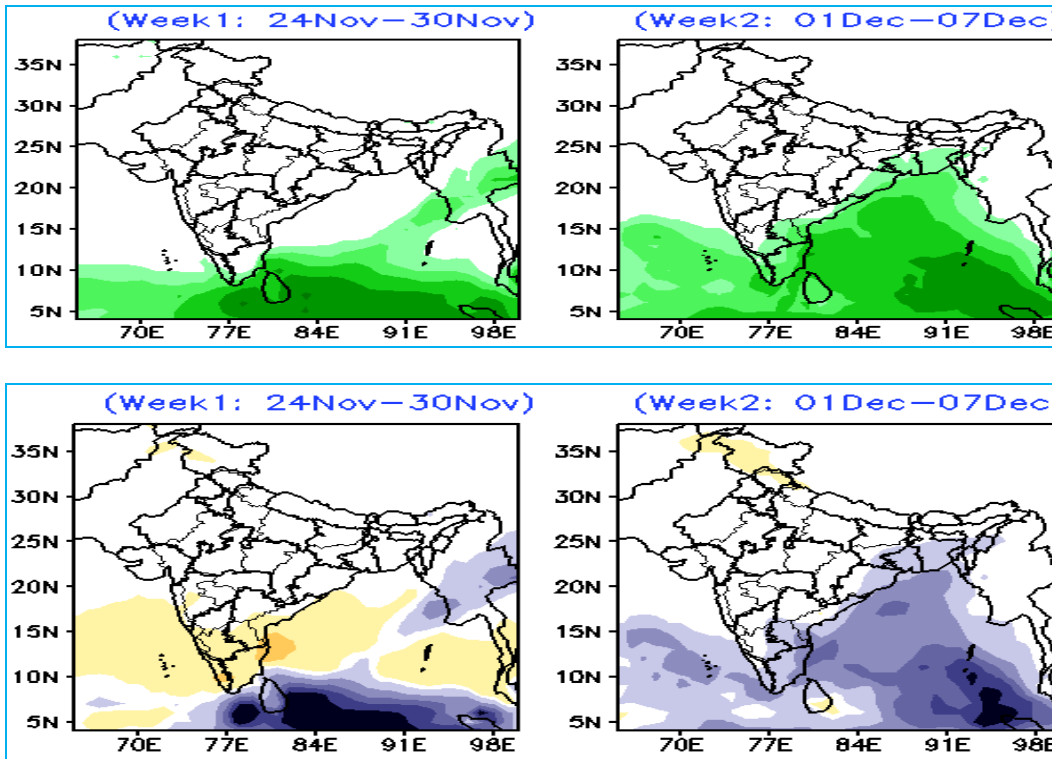
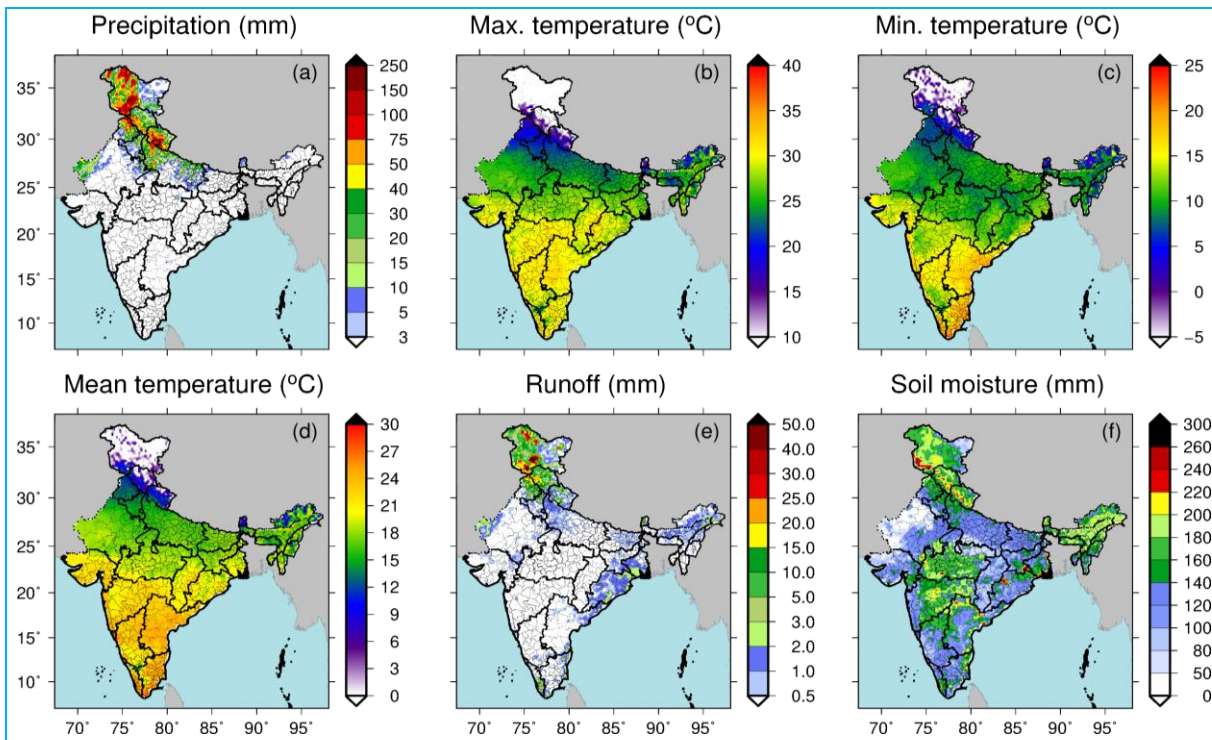


Fig. 22. Subdivision wise two weeks forecast rainfall based on 22 November and 29 November, 2017 and valid for 24-30 November, 2017, (1-7 December) and (8-14 December, 2017)

The observed intra-seasonal variability of rainfall over Tamilnadu meteorological subdivision during 2017 post-monsoon season from October to December is shown in Fig. 21. As seen from Fig. 21 the rainfall over Tamil Nadu during October to December 2017 witnessed normal to above normal rainfall during the period from beginning of October to about two weeks of October. The other active spells of monsoon over Tamilnadu was during last week of October to beginning of November and last week of

November to beginning of December, 2017 associated with cyclone “Ockhi” with a weekly rainfall departure of about 230% during the week from 1-7 December, 2017.

The operational ERF of north-east monsoon rainfall during 2017 northeast monsoon season could capture the intra-seasonal variability very well (Pattanaik and Sahai, 2018). The active phase of NEM over Tamil Nadu region associated with OCKHI cyclone is well predicted in the



Figs. 23(a-f). Weekly observed conditions from 18-24 January, 2019 for (a) Accumulated weekly precipitation, (b) weekly average maximum temperature, (c) weekly average minimum temperature, (d) weekly average mean temperature, (e) weekly average runoff and (f) weekly average soil moisture

operational ERF based on the initial condition of 22nd November, 2017 valid for two weeks from 24-30 November and 1-7 December, 2017 (Fig. 22).

9. Land surface hydrology for agrometeorology and hydrological applications

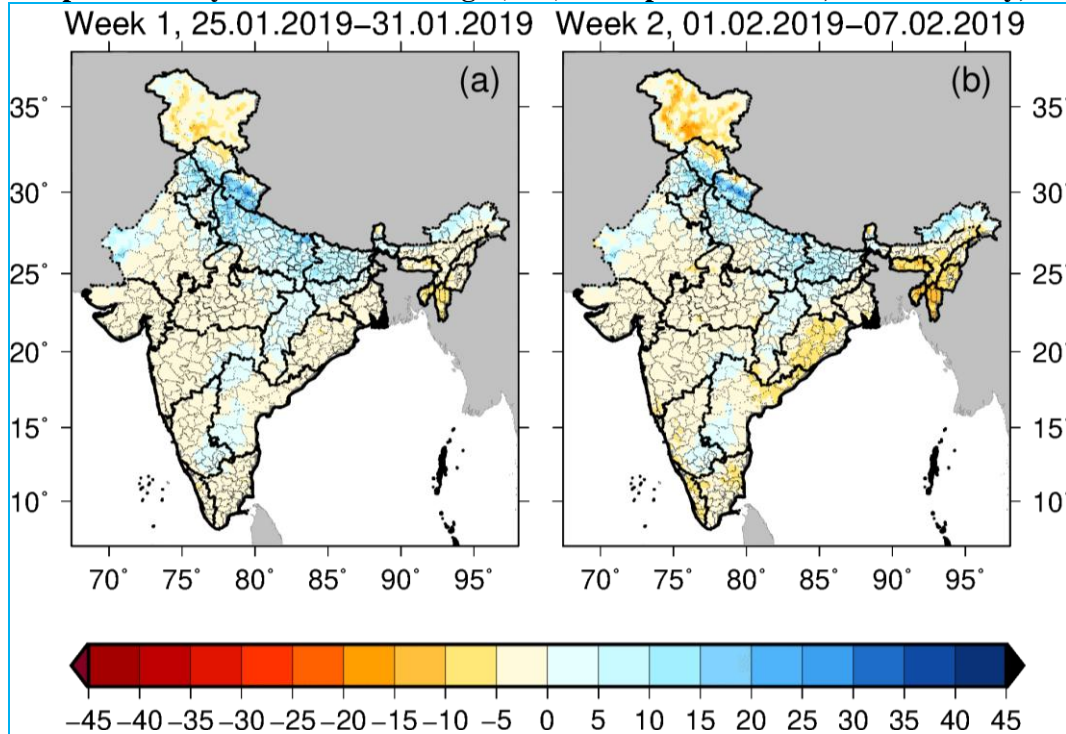
IMD in collaboration with IIT Gandhinagar has recently implemented a well calibrated Variable Infiltration Capacity Model (VIC) for land surface products such as Soil moisture, Runoff, etc. for application in Agriculture and also for hydrologic assessment. The real-time forecasts from the global model in medium range time scale and coupled models in extended range time scale run at IMD are used along with observed temperature and rainfall for preparing these products. The observed conditions of precipitation, maximum, minimum and mean temperature, runoff and soil moisture in term of weekly average is prepared for the assessment of observed land-surface conditions. The precipitation and temperature plots are obtained based on observed conditions available from IMD, whereas, the Runoff and soil moisture conditions are obtained using VIC model simulations.

The Variable Infiltration Capacity (Liang *et al.*, 1994) macroscale hydrology model has been used, which

simulates water and energy fluxes by taking soil and vegetation parameters and meteorological forcing as inputs. The VIC model has been widely applied for soil moisture drought assessments at various spatial scales (Andreadis and Lettenmaier, 2006; Mishra *et al.*, 2018, 2014; Shah and Mishra, 2016; Sheffield *et al.*, 2004). Shah and Mishra (2016) simulated soil moisture and runoff using the VIC model in near-real time to estimate the agricultural and hydrological droughts severity and areal extent. Moreover, Shah and Mishra (2016) used the VIC model to observe changes in the hydroclimatic variables in the Indian sub-continental basins for a larger time scale. In the Indian context Dadhwal *et al.* (2010) worked on Mahanadi river basin and recently, Hengade and Eldho (2016) worked on Ashti Catchment (sub-catchment of Godavari Basin in India) using VIC model as a case study to assess the impacts on hydrological variables due to Land Use Land Cover (LULC) changes and rainfall trends. Other than water budget estimates, very recently VIC model has also been used to access the role of Irrigation and climate change impacts on hydropower in India [Ali *et al.* (2018); Shah *et al.* (2019)].

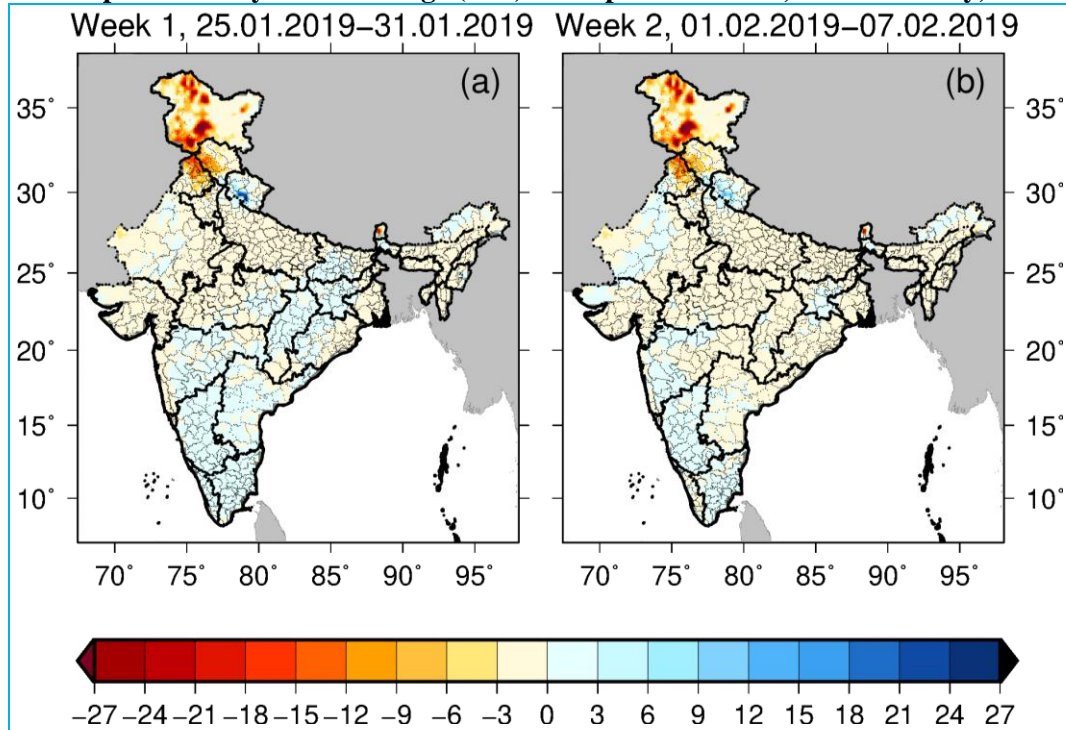
The VIC model is applied at daily time-scale for each 0.25° grid from 1st January, 1951 to 28th February, 2018 and made a state file which is the initial condition

Anticipated weekly soil moisture change (mm) w.r.t. previous week, 18-24 January, 2019

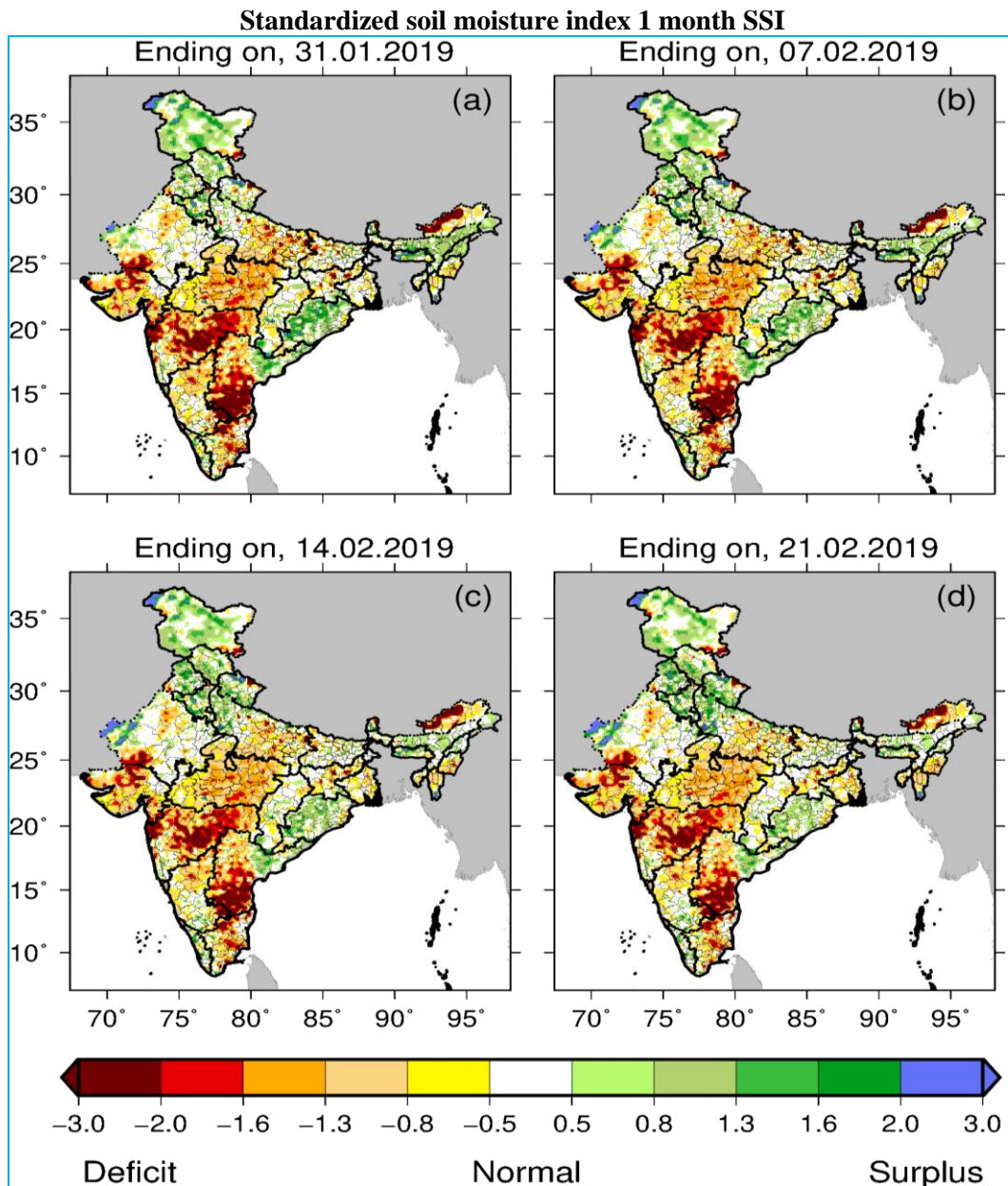


Figs. 24(a&b). Anticipated weekly soil moisture change (mm) for 2 forecasted weeks (a) 25-31 January, 2019 and (b) 1-7 February, 2019 with respect to observed week 18-24 January, 2019

Anticipated weekly runoff change (mm) w.r.t. previous week, 18-24 January, 2019



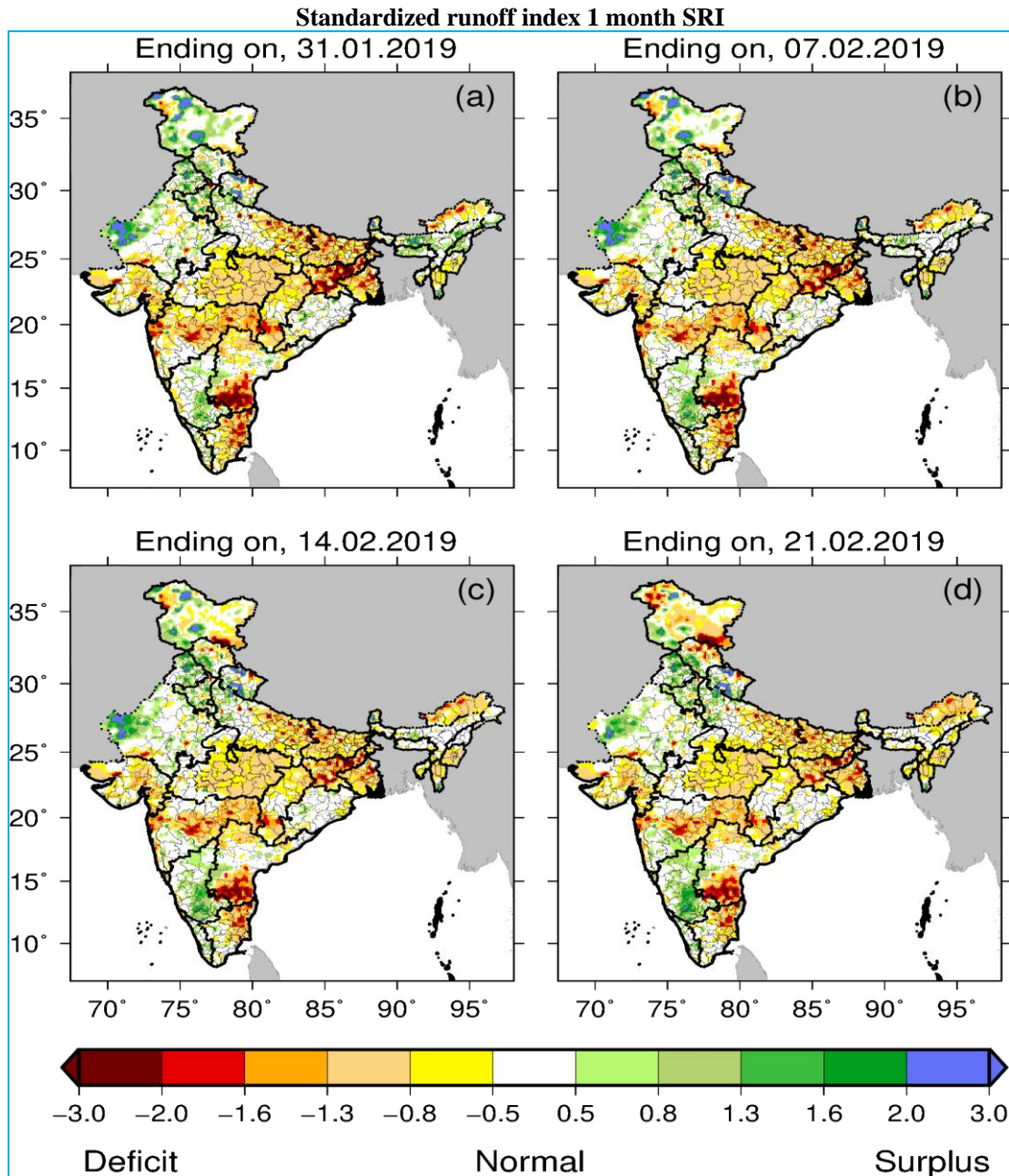
Figs. 25(a&b). Anticipated weekly runoff change (mm) for 2 forecasted weeks (a) 25-31 January, 2019 and (b) 1-7 February, 2019 with respect to observed week 18-24 January, 2019



Figs. 26(a-d). 1 month Standardized Soil moisture Index (SSI) ending on 4 forecasted weeks, (a) 31st January, 2019, (b) 7th February, 2019, (c) 14th February, 2019 and (d) 21st February, 2019

for the VIC model simulation from 1st March, 2018. The VIC model runs weekly from 1st March, 2018 till 32 days future forecast from the extended range forecast date for IMD ERF data using the initial condition of 28th February, 2018. The aggregated daily soil moisture and daily runoff for each grid using the VIC model are calculated. The weekly observed conditions for the previous week from 18-24 January, 2019 is shown in Figs. 23(a-f). Observed conditions of the previous week (18-24 January) show that there has been rainfall only in the north part of India (J&K, Punjab, Haryana, Himachal Pradesh, Uttarakhand

& in north Uttar Pradesh; UP) and little rainfall in some part of Rajasthan [Fig. 25(a)]. Average day temperature (maximum temperature) of the previous week is less than 20 °C in the northern states (J&K, Punjab, Haryana, Himachal Pradesh, Uttarakhand) [Fig. 23(b)]. Rajasthan, UP., Madhya Pradesh (MP), Bihar, Jharkhand, West Bengal and eastern states show maximum temperature around 25 °C. In Gujarat, Maharashtra, Chhattisgarh, Odisha and southern states experience a maximum temperature of around 30 °C. Average night temperature (minimum



Figs. 27(a-d). 1 month Standardized Runoff Index (SRI) ending on 4 forecasted weeks, (a) 31st January, 2019, (b) 7th February, 2019, (c) 14th February, 2019 and (d) 21st February, 2019

temperature) of the previous week is less than 5 °C in the northern states (J&K, Himachal Pradesh, Uttarakhand) [Fig. 23(c)] and around 15 °C in Gujarat, Maharashtra and southern states where, in the rest part of India it is around 10 °C [Fig. 23(c)]. The spatial distribution of mean temperature is similar to maximum temperature [Fig. 23(d)]. Runoff and soil moisture also takes account of the previous rainfall occurred in the upstream area. According to the rainfall occurred in J&K, Himachal Pradesh, Uttarakhand and Punjab, we find high runoff compared to UP, some northern states, Odisha, West

Bengal and Kerala [Fig. 23(e)]. Similarly, soil moisture condition of J&K, Himachal Pradesh, Uttarakhand, north-eastern Punjab, all north-eastern states, MP & Maharashtra is higher than other parts of India [Fig. 23(f)].

9.1. Anticipated soil moisture and runoff change

Based on the real-time extended range forecast of 23rd January, 2019 initial condition the forecasts land surface variables are calculated for application in hydrology and also agriculture. In this case, the VIC

model is simulated from 1st March, 2018 till 24th February, 2019, where from 1st March, 2018 to 23rd January, 2019 the observed data is used and then for next 32 days we used model forecasted data using the state file (initial condition) of 28 February, 2018 which is generated by simulation of VIC from 1st January, 1951 till 28th February, 2018. Though the forecasted soil moisture & runoff is calculated for 4 weeks the anticipated change with respect to the previous week observed condition is shown here for two weeks considering the skillful forecast up to two weeks [Figs. 24(a&b) & 25(a&b)].

The anticipated weekly runoff change & anticipated weekly soil moisture change for the upcoming two weeks (25-31 January, 2019 & 1-7 February, 2019) with respect to the previous week (18-24 January, 2019) are evaluated. As seen from Figs. 24(a&b), very little improvements in soil moisture condition in Punjab, Uttarakhand, UP, Bihar, Chhattisgarh, North Jharkhand and Arunachal Pradesh are most likely in upcoming weeks (In other parts of India it is expected to decrease in soil moisture for upcoming two weeks. Especially J&K, Odisha, Meghalaya, Tripura, Mizoram and Kerala are expected to face more decrease in soil moisture in the 2nd forecasted week [Fig. 24(b)].

Runoff condition for J&K, southwest Himachal Pradesh and northeast Punjab is expected to decrease significantly for upcoming two weeks (25-31 January, 2019 and 1-7 February, 2019) with respect to the previous week (18-24 January, 2019) as shown in Figs. 25(a&b). However, in the other part of India, there is not much change in runoff condition for the upcoming two weeks.

9.2. *Extended range forecasted one month Standardised Soil moisture Index (SSI) and one month Standardised Runoff Index (SRI).*

We evaluated 1-month SSI and 1-month SRI for the 4 forecasted weeks. This 1-month SSI and 1-month SRI show the condition of the current soil moisture and runoff respectively in the country with respect to last 68 years (from 1951) at the same time of each year. Based on the ERF of initial condition 23rd January, 2019 the 4 weeks Standardised Soil moisture Index (SSI) is calculated for week 1 (25-31 January, 2019), week 2 (1-7 February, 2019), week 3 (8-14 February, 2019) and week 4 (15-21 February) and is shown in Figs. 26(a-d).

To understand Fig. 26(a) indicated 1 week forecasted soil moisture for the week 25-31 Jan, 2019 superposed with previously observed 3 weeks soil moisture data. Similarly Fig. 26(b) indicated the two weeks forecasted soil moisture from 25 January to 7 February with previously observed 2 weeks soil moisture similarly Figs. 26(c&d) indicated 3 weeks forecasted soil moisture

ending on 14 February, 2019 & one previous week observed and 4 week forecasted soil moisture ending on 21 February, 2019. As it is seen, Maharashtra and south Andhra Pradesh are facing extreme drought condition. Some areas in UP, MP, Gujarat, some areas of Karnataka and some areas of Tamilnadu are facing droughts. J&K, Punjab, Haryana, Himachal Pradesh, Uttarakhand, Odisha, east Andhra Pradesh, Assam and Meghalaya states are showing good soil moisture condition. At the end of the 4th forecast week, soil moisture condition of south Andhra Pradesh is expected to improve [Fig. 26(d)].

Similarly, the Figs. 27(a-d) indicated one month Standardised Runoff Index (SRI). It is seen that almost similar results in terms of 1-month SRI as compared to 1-month SSI. We found that Maharashtra, Jharkhand and south Andhra Pradesh are facing drought according to SRI. In all these 3 states at the end of 4th forecast week, the drought condition is expected to improve [Fig. 27(d)].

10. Summary

The evolution of operational extended range forecast (ERF) system of IMD since it started experimentally in 2008 till the implementation of the fully coupled model in 2016 is discussed. Initially, empirical models and multi-model ensemble (MME) based on available dynamical models outputs *viz.*, NCEP Climate Forecast System version 1 (CFSv1), Japan Met. Agency model and ECMWF monthly forecast system were used for the experimental forecast. Finally, during 2016 a fully coupled modelling system with 16 ensemble members is implemented in IMD, which is based on NCEP Climate Forecast System version 2 (CFSv2) coupled model. The performance of ERF for southwest monsoon, northeast monsoon, cyclogenesis over the Bay of Bengal (BoB) and maximum and minimum temperature during the period from 2009 to 2018 have been discussed along with its prospects of its application in different sectors like Agriculture, hydrology, health, power etc. are also analysed. The major dry spells of 2009 monsoon were very well captured by the empirical and dynamical models, giving major boost to carry out the work for subsequent years.

The performance of operational extended range forecasts for the southwest monsoon seasons clearly captured the intra-seasonal variability of monsoon including delay/early onset of monsoon, active/break spells of monsoon and also the withdrawal of monsoon in the real-time in guiding various applications during 2010 to 2018 monsoon seasons. Some of the events like late onset and the late withdrawal of monsoon during 2012, rapid progress of monsoon to north India during 2013, active to break transition during 2017 and 2018 monsoons

were very well captured in the ERF forecasts with statistically significant correlation coefficient (CC) up to two weeks. Quantitatively, over the country as a whole and over the homogeneous regions of India the MME forecast provided useful guidance with central India indicating more promising results with the CC between observed and forecast rainfall departure is found to be significant till two weeks. The met. subdivision wise forecasts for 36 met. subdivisions for two weeks are being used for preparing agromet advisory to farmers.

The MME based ERF also provides encouraging results to provide useful guidance upto 2/3 weeks about northeast monsoon and cyclogenesis potential during October to December (OND) over the north Indian Ocean, heat wave, cold wave during summer and winter.

In addition to the regular ERF products for application in agriculture and hydrology, other products are being prepared like, Standardised Precipitation Index (SPI), land-surface hydrology products like soil moisture and runoff change, transmission windows products for vector-borne diseases, etc. for applications in agriculture, hydrology and health sectors respectively.

Acknowledgement

The first author is very much thankful to Dr. M. Rajeevan, Secretary, MoES and Dr. K. J. Ramesh, Director General, IMD for their encouragements and for providing all supports to work together with other institutes. Thanks are also due to CRS Pune for making available the gridded data. The real-time extended range forecast capability of IMD is being strengthened through the collaborative efforts of the MoES institutions viz., the IITM, NCMRWF, INCOIS and NCEP. The CFSv2/GFSbc customised at IITM, was implemented in IMD for the operational run.

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.

References

- Abhilash, S., Sahai, A. K., Borah, N., Joseph, S., Chattopadhyay, R., Sharmila, S., Rajeevan, M., Mapes, B. E. and Kumar, A., 2015, "Improved Spread-Error Relationship and Probabilistic Prediction from the CFS-Based Grand Ensemble Prediction System", *J. Appl. Meteor. Climatol.*, **54**, 1569-1578, <https://doi.org/10.1175/JAMC-D-14-0200.1>
- Abhilash, S., Sahai, A. K., Pattnaik, S., Goswami B. N. and Kumar Arun, 2014a, "Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System", *Int. J. Climatol.*, **34**, 98-113, doi:10.1002/joc.3668.
- Abhilash, S., Sahai, A. K., Pattnaik, S., Goswami, B. N. and Kumar, A., 2014b, "Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System", *Int. J. Climatol.*, **34**, 98-113, doi:10.1002/joc.3668.
- Ali, S. A., Aadhar, S., Shah, H. L. and Mishra, V., 2018, "Projected Increase in Hydropower Production in India under Climate Change", *Scientific Reports*, **8**, 1, <https://doi.org/10.1038/s41598-018-30489-4>.
- Andreadis, K. M. and Lettenmaier, D. P., 2006, "Trends in 20th century drought over the continental United States", *Geophys. Res. Lett.*, **33**, 1-4, <https://doi.org/10.1029/2006GL025711>.
- Belanger James, I., Curry, J. A. and Webster, P. J., 2010, "Predictability of North Atlantic tropical cyclone activity on intraseasonal time scales", *Mon. Wea. Rev.*, **138**, 4362-4374, doi: 10.1175/2010MWR3460.1.
- Bhadram, C. V. V., Amatya, B. V. S. and Pant, G., B., 2005, "Heat waves over Andhra Pradesh: A case study of summer 2003", *Mausam*, **56**, 385-394.
- Blanford, H. F., 1884, "On the connection of the Himalayan snowfall with dry winds and seasons of droughts in India", *Proceedings of the Royal Society of London*, **37**, 3-22.
- Borah, N., Sahai, A. K., Abhilash, S., Chattopadhyay, R., Joseph, S., Sharmila, S. and Kumar, A., 2015, "An assessment of real-time extended range forecast of 2013 Indian summer monsoon", *Int. J. Climatol.*, **35**, 2860-2876, doi:10.1002/joc.4178.
- Dadhwal, V. K., Aggarwal, S. P. and Mishra, N., 2010, "Hydrological simulation of Mahanadi river basin and impact of land use/land cover change on surface runoff using a macro scale hydrological model", In: Wagner W., Székely, B. (eds.): ISPRS TC VII Symposium – 100 Years ISPRS, Vienna, Austria, July 5-7, 2010, IAPRS, Vol. XXXVIII, Part 7, 165-170.
- Das, P. K. and Bose, B. L., 1958, "Numerical prediction of the movement of Bay depressions", *Ind. Journal of Met. Geophys.*, **9**, 225-232.
- De, U. S., Singh, Arun and Pandey, S. N., 2005, "Heat and cold waves affecting India during recent decades", *International J. of Meteorology*, **30**, 323-331.
- Frederic, Vitart, 2004, "Monthly Forecasting at ECMWF", *Mon. Wea. Rev.*, **132**, 2761-2779.
- Goswami, B. N., 2005, "South Asian Monsoon", In: Lau, W. K. M. and Waliser, D. E. (eds) Intraseasonal variability in the atmosphere-ocean climate system, **Chap. 2**, 19-61.
- Gowariker, V., Thapliyal, V., Kulshrestha, S. M., Mandal, G. S., Sen Roy, N. and Sikka, D. R., 1991, "A power regression model for long range forecast of southwest monsoon rainfall over India", *Mausam*, **42**, 125-130.
- Hengade, N. and Eldho, T. I., 2016, "Assessment of LULC and climate change on the hydrology of Ashti Catchment, India using VIC model", *Journal of Earth System Science*, **125**, 8, 1623-1634.
- India Meteorological Department (IMD), 1973, "Northeast Monsoon", FMU Report No. IV-18.4, 197.
- Jiang, X., Waliser, D. E., Wheeler, M. C., Jones, C., Lee, M. and Schubert, S. D., 2008, "Assessing the Skill of an All-Season Statistical Forecast Model for the Madden-Julian Oscillation", *Mon. Wea. Rev.*, **136**, 1940-1956.

- Jones, C., Carvalho, L. M. V., Higgins, W., Waliser, D., Schemm, J. K., 2004, "A Statistical Forecast Model of Tropical Intra-seasonal Convective Anomalies", *J. Climate*, **17**, 2078-2095.
- Kalsi, S. R., Hatwar, H. R., Jayanthi, N., Subramanian, S. K., Shyamala, B., Rajeevan, M. and Jenamani, R. K., 2004, "Various aspects of unusual behaviour of monsoon 2002", *IMD Met. Monograph, Synoptic Meteorology No. 2/2004*, National Climate Centre, India Meteorology Department, Lodi Road, New Delhi, India.
- Khole, M., Yadav, B. P. and Devi, S. S., 2013, "Onset, advances and withdrawal of southwest monsoon", In Pai, D. S. and Bhan, S. C., (Ed), Monsoon 2012 - A Report, *IMD Met. Monograph, Synoptic Meteorology No. 13/2013*, 1-14.
- Kotal, S. D., Kundu, P. K. and Roy Bhowmik, S. K., 2009, "Analysis of cyclogenesis parameter for developing and non-developing low-pressure systems over the Indian Sea", *Nat. Hazards*, **50**, 389-402.
- Krishnamurti, T. N. and Subrahmanyam, D., 1982, "The 30-50 day mode at 850 mb during MONEX", *J. Atmos. Sci.*, **39**, 2088-2095.
- Liang, X., Lettenmaier, D. P., Wood, E. F. and Burges, S., 1994, "A simple hydrologically based model of land surface water and energy fluxes for general circulation models", *J. Geophys. Res.*, **99**, 14415-14428, <https://doi.org/10.1029/94JD00483>.
- Madden, R. and Julian, P., 1971, "Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific", *J. Atmos. Sci.*, **28**, 702-708.
- Madden, R. and Julian, P., 1994, "Observations of the 40-50 day tropical oscillation: A review", *Mon. Wea. Rev.*, **112**, 814-837.
- Mahapatra, M., Daastidar, S. K. and Gupta, D. C., 2001, "Some aspects of recent heat waves over India", *Tropmet Proceeding*, India Meteorological Society, 189-195.
- Mishra, V., Shah, R., Azhar, S., Shah, H., Modi, P., and Kumar, R., 2018, "Reconstruction of droughts in India using multiple land-surface models (1951-2015)", *Hydrol. Earth Syst. Sci.*, **22**, 2269-2284, <https://doi.org/10.5194/hess-22-2269-2018>, 2018.
- Mohanty, U. C., Osuri, K. K., Routray, A., Mohapatra, M. and Sujata, P., 2010, "Simulation of Bay of Bengal tropical cyclones with WRF model: Impact of initial and boundary conditions", *Mar. Geodesy*, **33**, 294-314.
- Mohapatra, M., Bandyopadhyay, B. K. and Nayak, D. P., 2013b, "Evaluation of operational tropical cyclone intensity forecasts over north Indian Ocean issued by India Meteorological Department", *Nat. Hazards*, **68**, 2, 433-451.
- Mohapatra, M., Nayak, D. P., Sharma, R. P. and Bandyopadhyay, B. K., 2013a, "Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department", *J. Earth System Sci.*, **122**, 3, 589-601.
- Osuri Krishna, K., Mohanty, U. C., Routray, A., Kulkarni, M. A. and Mohapatra, M., 2012, "Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over north Indian Ocean", *Nat. Hazards*, **63**, 1337-1359.
- Pai, D. S., Smitha, Anil Nair and Ramatathan, A. N., 2013, "Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010)", *Mausam*, **64**, 585-604.
- Pattanaik, D. R., Pai, D. S. and Mulhopadhyay, B., 2015, "Rapid northward progress of monsoon over India and associated heavy rainfall over Uttarakhand: A diagnostic study and real time extended range forecast", *Mausam*, **66**, 3, 551-568.
- Pattanaik, D. R. and Das, Ashok Kumar, 2015, "Prospect of application of extended range forecast in water resource management : A case study over the Mahanadi River basin", *Natural Hazards*, **77**, 575-595.
- Pattanaik, D. R. and Hatwar, H. R., 2006, "Analysis and impact of delayed onset of monsoon over northeast India during 2005", *Vayu Mandal*, **32**, 3-9.
- 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. and Kumar, Arun, 2014, "Comparison of intra-seasonal forecast of Indian summer monsoon between two versions of NCEP coupled models", *Theoretical and Applied Climatology*, **118**, 331-345.
- Pattanaik, D. R. and Mohapatra, M., 2014, "Multi-model ensemble based extended range forecast of tropical cyclogenesis over the north Indian Ocean", In: Monitoring and prediction of tropical cyclones in the Indian Ocean and climate change (Eds.) Mohanty, U. C., Mohapatra, M., Singh, O. P., Bandyopadhyay, B. K. and Rathore, L. S., doi: doi.org/10.1007/978-94-007-7720-0_17, 203-216.
- Pattanaik, D. R. and Mohapatra, M., 2017, "Active Northeast Monsoon over India during 2015 - An Assessment of Real-Time Extended Range Forecast", *Current Science*, **112**, 11, 2253-2262.
- Pattanaik, D. R. and Mukhopadhyay, B., 2012, "Indian Climatology in the context of human health", In book "*Climate change and disease dynamics in India*", Eds: Nitish Dogra and Sangeet Srivastava, ISBN: 9788179934128, 71-110, TERI press, TERI, New Delhi.
- Pattanaik, D. R. and Rajeevan, M., 2007, "North-west pacific tropical cyclone activity and July rainfall over India", *Met. Atmos. Physics*, **95**, 63-72.
- Pattanaik, D. R. and Rama Rao, Y. V., 2009, "Track prediction of very severe cyclone "Nargis" using high resolution weather research forecasting (WRF) model", *J. of Earth System Science*, **118**, 309-330.
- Pattanaik, D. R. and Sahai, A. K., 2018, "Evaluation of Real-Time Extended Range Forecast (ERF) of southwest monsoon, heat wave, cold wave, cyclogenesis and northeast monsoon during 2017", *IMD Technical Report*, IMD No. ESSO/IMD/NWP-Extended Range Forecast (ERF) Report No. 1 (2018)/05, 1-142.
- Pattanaik, D. R., 2003, "The northward moving low frequency mode : A case study of 2001 monsoon season", *Mausam*, **54**, 937-940.
- Pattanaik, D. R., 2014, "Meteorological subdivisional-level extended range forecast over India during southwest monsoon 2012", *Meteorology and Atmospheric Physics*, doi: [10.1007/s00703-014-0308-6](https://doi.org/10.1007/s00703-014-0308-6).
- Pattanaik, D. R., 2015, "Operational extended range forecast activity in IMD and its application in different sectors", *Vayu Mandal*, **40**, 44-70.
- Pattanaik, D. R., Kalsi, S. R. and Hatwar, H. R., "Evolution of convection anomalies over the Indo-Pacific Region in Relation to Indian monsoon rainfall (2005)", *Mausam*, **56**, 811-824.

- Pattanaik, D. R., Kumar, Gajendra, Bhatla, R., Soni, V. K., Bist, Sanjay, Bhan, S. C. and Mukhopadhyay, B., 2013c, "Heat index outlooks over the Indian region using general circulation model outputs", *IMS Bulletin (Vayu Mandal)*, **39**, 12-24.
- Pattanaik, D. R., Mohapatra, M., Mukhopadhyay, B. and Tyagi, Ajit, 2013b, "A preliminary study about the prospects of extended range forecast of tropical cyclogenesis over the North Indian Ocean during 2010 post-monsoon season", *Mausam*, **64**, 171-188.
- Pattanaik, D. R., Mohapatra, M., Srivastava, A. K. and Kumar, Arun, 2016, "Heat wave over India during summer 2015: An assessment of real time extended range forecast", *Meteorology Atmospheric Physics*, DOI 10.1007/s00703-016-0469-6.
- Pattanaik, D. R., Mukhopadhyay, B. and Kumar, Arun, 2012, "Monthly Forecast of Indian Southwest Monsoon Rainfall Based on NCEP's Coupled Forecast System", *Atmospheric and Climate Sciences*, **2**, 479-491. doi: 10.4236/acs.2012.24042.
- Pattanaik, D. R., Phani Muralikrishna, R., Mandal, Raju, Dey, Avijit, Joseph, Susmitha, Chattopadhyay, Rajib, Mohapatra, M. and Sahai, A. K., 2018, "Performance of real time extended range forecast during southwest monsoon 2017", Eds: O. P. Sreejith, D. S. Pai and M. Mohapatra, *IMD Met. Monograph*, No. ESSO/IMD/Synoptic Met./01(2018)/22, 226-2656.
- Pattanaik, D. R., Rathore, L. S. and Kumar, Arun, 2013a, "Observed and Forecasted Intraseasonal Activity of Southwest Monsoon Rainfall over India During 2010, 2011 and 2012", *Pure Appl. Geophys.*, doi: 10.1007/s00024-013-0670-1.
- Pattanaik, D. R., Thapliyal, V. and Mujumdar, M., 2003, "Dynamical features associated with intensification of cyclonic disturbances over Bay of Bengal", *Proceedings of DAE-CEP Symposium*, IGCAR, Kalpakkam, India, 50-57.
- 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", *Current Science*, **86**, 422-430.
- Rao, V. U. M., 2012, "Impacts of climate change on Indian Agriculture", (available from <http://www.cseindia.org/userfiles/VUM-CSE-Delhi-16-11-12.pdf>, accessed on 6 July, 2015).
- Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M. and Yamagata, T., 2016, "Anatomy of Indian heatwaves", *Scientific Reports*, doi: 10.1038/srep24395.
- 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.
- Saha, Suranjana, Moorthi, Shrinivas, Wu, Xingren, Wang, Jiande, Nadiga, Sudhir, Tripp, Patrick, Hua-Lu Pan, Behringer, David, Hou, Yu-Tai, Chuang, Hui-ya, Iredell, Mark, Ek, Michael, Meng, Jesse, Yang, Rongqian, Dool, Huug van den, Zhang, Qin, Wang, Wanqiu and Chen, Mingyue, 2014, "The NCEP Climate Forecast System Version 2", *Journal of Climate*, **27**, 2185-2208, doi: <http://dx.doi.org/10.1175/JCLI-D-12-00823.1>.
- Sahai, A. K. and Chattopadhyay, R., 2006, "An objective study of Indian summer monsoon variability using the self organizing map algorithms", *IITM Research Report*, No.113.
- Sahai, A. K., Chattopadhyay, R., Joseph, S., Mandal, R., Dey, A., Abhilash, S., Krishna, R. P. M. and Borah, N., 2015, "Real-time performance of a multi-model ensemble-based extended range forecast system in predicting the 2014 monsoon season based on NCEP-CFSv2", *Current Science*, **109**, 10, 802-1813.
- Sahai, A. K., Sharmila, S., Abhilash, S., Chattopadhyay, R., Borah, N., Krishna, R. P. M., Joseph, S., Roxy, M., De, S., Pattanaik, S. and Pillai, P., 2013, "Simulation and extended range prediction of monsoon intraseasonal oscillations in NCEP CFS/GFS version 2 framework", *Current Sciences*, **104**, 1394-1408.
- Shah, H. L., Zhou, T., Huang, M. and Mishra, V., 2019, "Strong influence of irrigation on water budget and land surface temperature in Indian sub-continental river basins", *Journal of Geophysical Research Atmospheres*, DOI: 10.1029/2018JD029132.
- Shah, R. D. and Mishra, V., 2016, "Utility of Global Ensemble Forecast System (GEFS) Reforecast for Medium-Range Drought Prediction in India", *J. Hydrometeorol.*, **17**, 1781-1800, <https://doi.org/10.1175/JHM-D-15-0050.1>.
- Sheffield, J., Ziegler, A. D., Wood, E. F. and Chen, Y., 2004, "Correction of the high-latitude rain day anomaly in the NCEP-NCAR reanalysis for land surface hydrological modeling", *J. Clim.*, **17**, 3814-3828, [https://doi.org/10.1175/1520-0442\(2004\)017<3814:COTHRD>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<3814:COTHRD>2.0.CO;2).
- 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", *Bulletin of the American Meteorological Society*, **81**, 2593-2606.
- Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Mon. Wea. Rev.*, **108**, 1840-1853.
- Tyagi, Ajit and Pattanaik, D. R. (Editors), 2008, "Five Decades of Numerical Weather Prediction (NWP) in India", *India Met. Deptt., New Delhi*, 1-172.
- Tyagi, Ajit and Pattanaik, D. R., 2010, "Real Time monitoring and forecasting of intra-seasonal monsoon rainfall activity over India during 2009", *IMD Met. Monograph*, Synoptic Meteorology No. **10/2010**.
- Tyagi, Ajit and Pattanaik, D. R., 2012, "Real time extended range forecast activities in IMD - Performance Assessments & Future Prospects", *IMD Met. Monograph*, No. ERF 01/2012, 1-132.
- Webster, P. J. and Hoyos, C. D., 2004, "Prediction of Monsoon Rainfall and River Discharge on 15-30 day Time Scales", *Bull. American Met. Soc.*, **85**, 1745-1765.
- Wheeler, M. and Hendon, H., 2004, "An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction", *Mon. Wea. Rev.*, **132**, 1917-1932.
- Xavier, P. K. and Goswami, B. N., 2007, "An Analog Method for Real-Time Forecasting of Summer Monsoon Subseasonal Variability", *Mon. Wea. Rev.*, **135**, 4149-4160.
- Zhang, C., 2005, "Madden-Julian Oscillation", *Reviews of Geophysics*, **43**, 1-36.