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Understanding the intraseasonal variability over Indian region and development of an operational extended range prediction system

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सार – भारतीय क्षेत्र में मौसमी पैमाने से हटकर उप-मौसमी परिवर्तिता का विस्तारित अवधि पूर्वानुमान देना जलवायु पूर्वानुमान अनुप्रयोग में अति महत्वपूर्ण घटक है। मौसमी पैमाने से हटकर आगे के पूर्वानुमान में सुधार लाने के लिए वर्ष 2013 में WCRP द्वारा उप-मौसमी से मौसमी (s2s) परियोजना आरंभ की गई जो अनुसंधान एवं प्रचालनात्मक पूर्वानुमान के क्षेत्र में एक चुनौतीपूर्ण अंतराल है। इस उप-मौसमी से मौसमी (s2s) परियोजना का प्राथमिक उद्देश्य भिन्न-भिन्न अग्रकाल (लीड टाइम) में उप-मौसमी से मौसमी पूर्वानुमान उपलब्ध कराना है।

भारतीय उष्णकटिबंधीय मौसम विज्ञान संस्थान (IITM) में विस्तारित अवधि का पूर्वानुमान परियोजना की कल्पना एक दशक से अधिक समय से पहले की है जिससे इस पैमाने पर हितधारकों की माँग का देखते हुए परिष्कृत प्रचालनात्मक पूर्वानुमान देने के लिए एक बेहतर शोध पृष्ठभूमि तैयार की जा सके। विस्तारित अवधि का पूर्वानुमान 2-3 सप्ताह के लीड टाइम में देने का अर्थ है। भारतीय उष्णकटिबंधीय मौसम विज्ञान संस्थान में पिछले एक दशक में विस्तारित अवधि पूर्वानुमान को बेहतर बनाने के लिए कई प्रयास किए गए हैं। वर्तमान अध्ययन में आई एम डी में प्रचालनात्मक कार्यान्वयन के लिए विस्तारित अवधि पूर्वानुमान प्रणाली के विकास का सारांश प्रस्तुत किया गया है। इसमें विस्तारित अवधि पूर्वानुमान के विकास के लिए अनुसंधान और विकास को सबसे पहले संक्षेप में प्रस्तुत किया गया है। इसमें मॉनसून के अंतरामौसमी दोलनों के सांख्यिकीय गुणों को स्थापित करने, पूर्वानुमान क्षितिज स्थापित करने, अत्याधुनिक जलवायु मॉडल में दोलनों का प्रतनिधित्व करने और अंत में अत्याधुनिक तकनीक विकसित करने के लिए किए गए प्रयासों का वर्णन किया गया है। यह तकनीक अब भारत मौसम विज्ञान विभाग में प्रचालनात्मक रूप से लागू हो गई है।

यह अध्ययन मौसम विज्ञान के संदर्भ में विस्तारित अवधि पूर्वानुमान के संभावित अनुप्रयोगों को सारांश में प्रस्तुत करता है। इस पूर्वानुमान प्रणाली का प्राथमिक उपयोग विस्तारित अवधि समय पैमाने पर समूचे देश के लिए प्रचालनात्मक पूर्वानुमान उत्पाद का विकास करना है। इस पूर्वानुमान का उपयोग मौसम विज्ञान, जल मौसम विज्ञान, स्वास्थ्य क्षेत्र जैसे कई संबद्ध क्षेत्रों में किया जा सकता है। इस शोध पत्र में इन क्षेत्रों में इस पूर्वानुमान के संभावित उपयोग के विषय में संक्षिप्त चर्चा की गई है।

ABSTRACT. Extended range forecast of sub seasonal variability beyond weather scale is a critical component in climate forecast applications over Indian region. The sub-seasonal to seasonal (s2s) project, undertaken by WCRP, started in 2013 to improve the forecast beyond weather scale which is a challenging gap area in research and operational forecast domain. The primary objective of this s2s project is to provide the sub-seasonal to seasonal forecast in various lead times.

Extended range forecast project at Indian Institute of Tropical Meteorology (IITM) is envisioned more than a decade ago in this way, keeping in view of the demands from the stakeholders to create a robust research background required for improved delivery of operational forecast in this scale. Extended range forecast implies an outlook with a lead-time of 2-3weeks. Several efforts have been undertaken to improve the extended range forecast in the past decade or so at IITM. The current study summarizes the development of extended range prediction system for operational implementation at IMD. The research and development that lead to the development of extended range prediction are summarized at first. It describes the efforts that were undertaken to establish the statistical properties of monsoon intraseasonal oscillations, establish the predictability horizon, represent the oscillations in state-of-art climate models and finally develop the latest state-of-art forecast technique. This technique is now operationally implemented at India Meteorological Department.

The study then summarizes potential applications of extended range forecast in meteorological perspective. The primaryuse of this forecast system is the development of an operational country-wide forecast product in the extended range time scale. The application of this forecast can be made in several allied fields like agro-meteorology, hydrometeorology, health sector etc. A brief discussion is made relating the potential use of this forecast to these fields.

Key words – ISO, MJO, MISO.

1. Introduction

Indian subcontinent gets most of its rainfall during the southwest monsoon (June - September) months. The Indian economy is immensely influenced by the spatio-temporal variation of monsoon rainfall over the region such that it could be termed as a gamble on the monsoon rains. Indian summer monsoon (ISM) fluctuates on a broad range of temporal and spatial scales. The temporal variability can range from daily to synoptic, biweekly, intraseasonal, seasonal, interannual, decadal and inter decadal time scales.

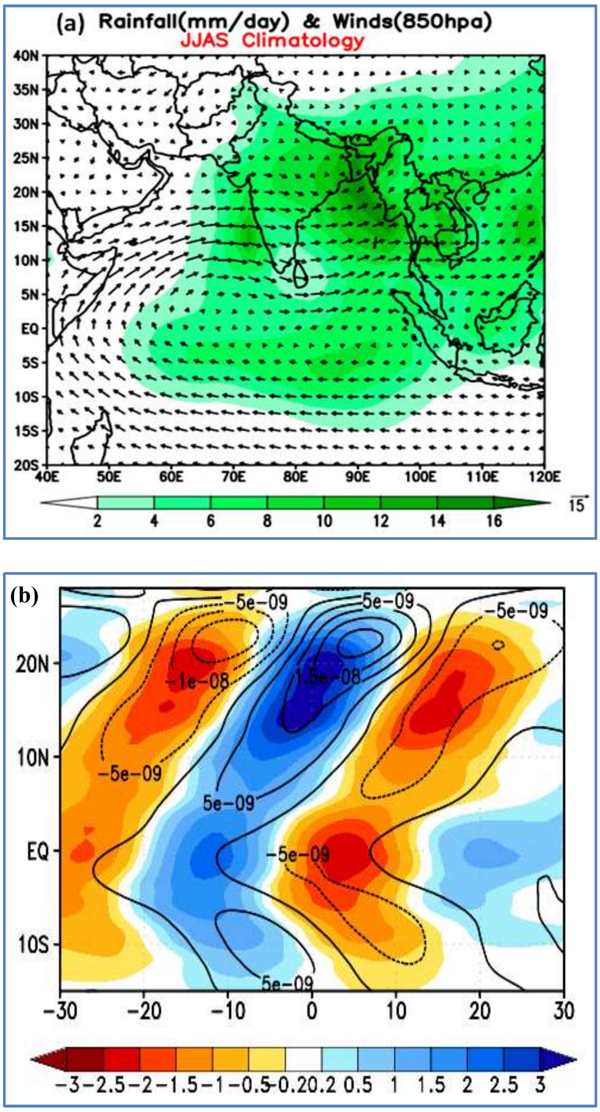
1.1. *Sub-seasonal variability over Indian region*

During ISM, maximum rainfall occurs along the west coast of the peninsula (associated with the orography, *i.e*., the Western Ghats parallel to the coast) and the northeastern regions. The southeastern peninsula is on the rain shadow side of the Western Ghats and hence receives comparatively less amount of rainfall during the season. On a broader spatial scale, the monsoon precipitation has two preferred locations - one over the continental region (between 10°-25° N) and the other over the eastern equatorial Indian Ocean (EEIO). Monsoon intraseasonal variability could be thought of as a manifestation of the fluctuations of the ITCZ, within these two preferred locations. Hence, monsoon intraseasonal oscillation (MISO) is associated with an explicit northward propagation of positive or negative precipitation (or convection) anomalies (Sikka and Gadgil, 1980) [Figs. 1(a&b), Fig. 2(a)], which characterizes prolonged spells of dry and wet conditions, that often lasts for a week or more. The above normal rain spells could be considered as the epochs when the monsoon has been vigorous or "active"; whereas the below normal spells were the epochs when the monsoon took a "break" from its activity (Goswami, 2012). Hence, these spells are termed as "active" and "break" spells respectively. MISO is associated with 30-60 day periodicity and its spatial structure is similar to that of the seasonal mean, strengthening (weakening) the seasonal mean in its active (break) phases and the large scale structure of active/break phases comes mostly from the 30-60 day mode (Goswami, 2012). The ISOs can modulate synoptic activity and cause spatial and temporal clustering of lows and depressions (Goswami *et al*., 2003).

During boreal winter and spring seasons, a strong eastward propagating oscillation called Madden-Julian oscillation [MJO; (Madden and Julian, 1972; 1994)] is active in the equatorial region, with a periodicity of 30-60 days [Fig. 2(b)]. However, during boreal summer, this oscillation is sporadic, complex and weaker in character. At the same time, the MISOs are vigorous. The similarity in the temporal character of the MISOs and MJO has prompted many researchers to investigate the relationship of the two with each other (Yasunari, 1979; Wang and Rui, 1990; Lau and Chan, 1986; Lawrence and Webster, 2002; Joseph *et al*., 2009). Most of them consider MISOs as the pole ward propagating weather anomalies of MJO; and the active/break cycles as manifestations of these ISOs (Yasunari, 1980; Madden and Julian, 1971, 1972, 1994; Gadgil and Asha, 1992; Singh *et al*., 1992; Lawrence and Webster, 2002). The boreal summer intraseasonal variability associated with the 30-60 day mode is represented by the co-existence of pole ward propagation of convection over the Indian and tropical Western Pacific longitudes and eastward propagation along the equator (Annamalai and Sperber, 2005). Till date, it is a matter of debate whether MISO is significantly associated with MJO (Lawrence and Webster, 2001; Lau and Waliser, 2012) or is it a distinct entity with distinguishable feature (Wang and Rui, 1990; Jones *et al*., 2004).

1.2. *Canonical mode of sub seasonal variability, its shades in terms of active break spells*

The active and break spells, as discussed in the last section, is a part of monsoon intraseasonal low-frequency oscillation (MISO), that has a distinct life-cycle as shown in several studies (Goswami, 2012). Several techniques are used to derive the canonical phases of MISO life-cycle. We have used a non-linear method based on Self Organizing Maps [SOM, (Kohenen, 1990)].The canonical mode of MISO is derived based on the SOM technique is known to represent a cyclic oscillation with the movement of rain bands (Chattopadhyay *et al*., 2008). The essential features of active/break cycle associated with MISOs are represented by SOM which shows the systematic increase in rainfall over central India during an active phase with a characteristic decrease of rainfall over the tip of peninsular India near Tamil Nadu coast. SOM also shows the increase in rainfall over foothills of Himalaya and reduced rainfall over the central Indian region during



Figs. 1(a&b). (a) Spatial distribution of precipitation (shaded) and wind (vector) seasonal (JJAS) climatology of Indian Summer Monsoon (b) Time - latitude diagram of lag regressed 20-100 day band pass filtered observed precipitation anomalies (shaded) an surface moisture convergence (kg s^{-1} kg^{-1}, contour) at intraseasonal timescales averaged over 70°-90° E. Here *x*-axis shows days and the y-axis shows latitudes. Day 0 corresponds to the day of rainfall maxima (peak day) over Central India

break phase. The duration and frequency of active/break spells can modulate the interannual variability of ISM. Persistence of active (break) spells for a week, or more can lead to flood (drought) conditions. Joseph *et al*. (2009) showed that long breaks are the underlying mechanism through which monsoon droughts occur. Similarly, the boreal winter MJO features are shown to be captured by SOM-based clustering algorithm (Chattopadhyay *et al*., 2012). The SOM showed the 8 phase canonical MJO propagation in the eastward direction for the MJO. The MISO and MJO, whose spatial structures can be captured by the SOM-based method provided evidence that the canonical phases of MISO/MJO composite can be used for studies related to the comparison of the MISO and MJO phase for future modeling studies.

It is well-known that the MISOs can regulate the seasonal mean states, but it can happen another way also. Sharmila *et al*. (2015a) found that the seasonal mean states during extreme monsoon years can modulate the duration and magnitude of active-break spells associated with MISOs. They noted that the northward propagation of MISOs over the Indian subcontinent shows fast (slow) propagation during the active phase of weak (strong) monsoons, while the situation is just opposite during breaks.

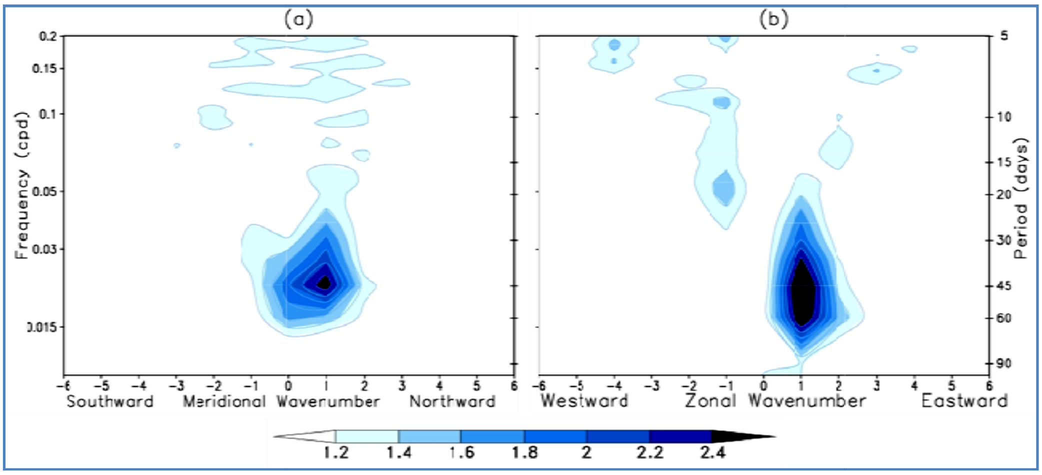
Variability in the slowly varying sea surface temperatures over the Pacific Oceanic regions, termed as El-Niño Southern Oscillation (ENSO), is known to have an impact on the seasonal mean monsoon rains (Walker, 1916, 1925; Rasmusson and Carpenter, 1983; Sikka, 1980). Joseph *et al*. (2011) demonstrated that ENSO has an influence on the duration of MISO phases, which can, in turn, modulate the seasonal mean. They showed that particular MISO phases are preferred during ENSO years such that the period of canonical break (active) phase is more in the El Niño (La Niña) years.

The life cycle of MISO as described in this section is verified further based on model studies and several new aspects have been found out. A few of them are described in the next section.

2. Diagnostics of monsoon ISO

2.1. *Model-baseddiagnostics: Air-sea interaction/ coupled variability using SINTEX/CFS/GFS*

It is well-known that ISM is a coupled phenomenon and hence air-sea interaction can play a seminal role in modulating MISO dynamics. Studies indicate that air-sea interaction can lead to extended breaks and a monsoon drought (Saith and Slingo, 2006; Krishnan *et al*., 2006; Joseph *et al*., 2009). Based on modelling experiments, Sharmila *et al*. (2013) showed that air-sea interaction modifies the mean state in such a way that increased shortwave radiation and reduced latent heat flux induces surface heating, increased SST and leads to unstable atmosphere, which in turn lead to increased convection north of the original convection maximum, thus favoring the northward propagation of MISO. They also affirmed the need of coupled general circulation models in the simulation and prediction of ISM.



Figs. 2(a&b). Space-time spectra illustrating (a) the northward propagating MISO during northern summer and (b) eastward propagating MJO during northern winter. The MISO spectra are calculated from GPCP daily rainfall dataset (1997-2008) and the MJO spectra are calculated using zonal wind at 850 hPa level from NCEP/NCAR reanalysis dataset (1950-2008). For MISO, the analysis is done on the limited domain 65°-95° E; 20° S-30° N; whereas for the MJO, the study is done for all longitudes, but averaged over the latitudinal domain 15° S-15° N

Many studies indicate that SSTs over Indian Ocean region have an increasing trend in recent years and this can have an influence on the strength of ISM through air-sea interaction. Joseph *et al*. (2012) demonstrated that increased warming over the equatorial western Indian Ocean can extend vertically to the upper levels and weaken the meridional tropospheric temperature gradient which in turn leads to a weakening of the moisture gradient as well as the vertical shear of easterlies required for sustained northward propagation of rain band, resulting in weak monsoon circulation.

2.2. *Stratiform/convective paradigm*

The MISO life cycle involves northward propagation of convection. How does the convection get scale organized? This is still a challenging question. It is found out that the stratiform rainfall could be a way to explain the same. The large scale organized rainfall show that the convective component shows weak northward propagation and grows and decays in situ during the evolution of active and break phases. The northward propagation of the monsoon ISO as seen in many studies is largely due to the organized movement of a cloud band that is identified to have a strong non-convective (or stratiform) component. The north-south dipole pattern of total rainfall between the monsoon trough zone and the southern equatorial Indian Ocean also arises largely due to significant contribution from non-convective rainfall anomalies. Several studies show that the northward propagation of the monsoon ISO is due to the anomalous response of the atmosphere to the latent heating in the presence of mean easterly vertical shear. Owing to the different dynamical response of stratiform heating (Chattopadhyay *et al*., 2009; Schumacher *et al*., 2004) the modification of the vertical profile of heating due to a contribution from stratiform rain could influence the dynamics over the monsoon zone and hence could modulate the northward propagation of the monsoon ISO. An example is shown in Fig. 3 which shows a standard composite propagation of non-convective rainfall during active phases. Lag 0 is the day identified as the peak active day from the data. Other lags are calculated accordingly (Chattopadhyay *et al*., 2009).

We tested this hypothesis using a simple global atmospheric circulation model. The dynamical response is calculated to study the response of the convective and stratiform heating profiles on the modification of the mean condition dynamics through a modification of Hadley cells. Results indicate that the presence of stratiform heating favors the northward propagation of the heat source thereby facilitating the positive feedback leading to northward propagation of the convective rain bands. In order to improve monsoon ISO forecast using dynamical models, it is necessary that the vertical profile of heating that leads to positive feedback between dynamics and physics has to be correctly captured.

3. Predictability of sub seasonal variability over Indian region

The sub seasonal variability of Indian summer monsoon has a *low frequency* (10-20 day, 20-60 day) mode and *high frequency* (<10 days) synoptic mode. The evolution of these modes is associated with distinct

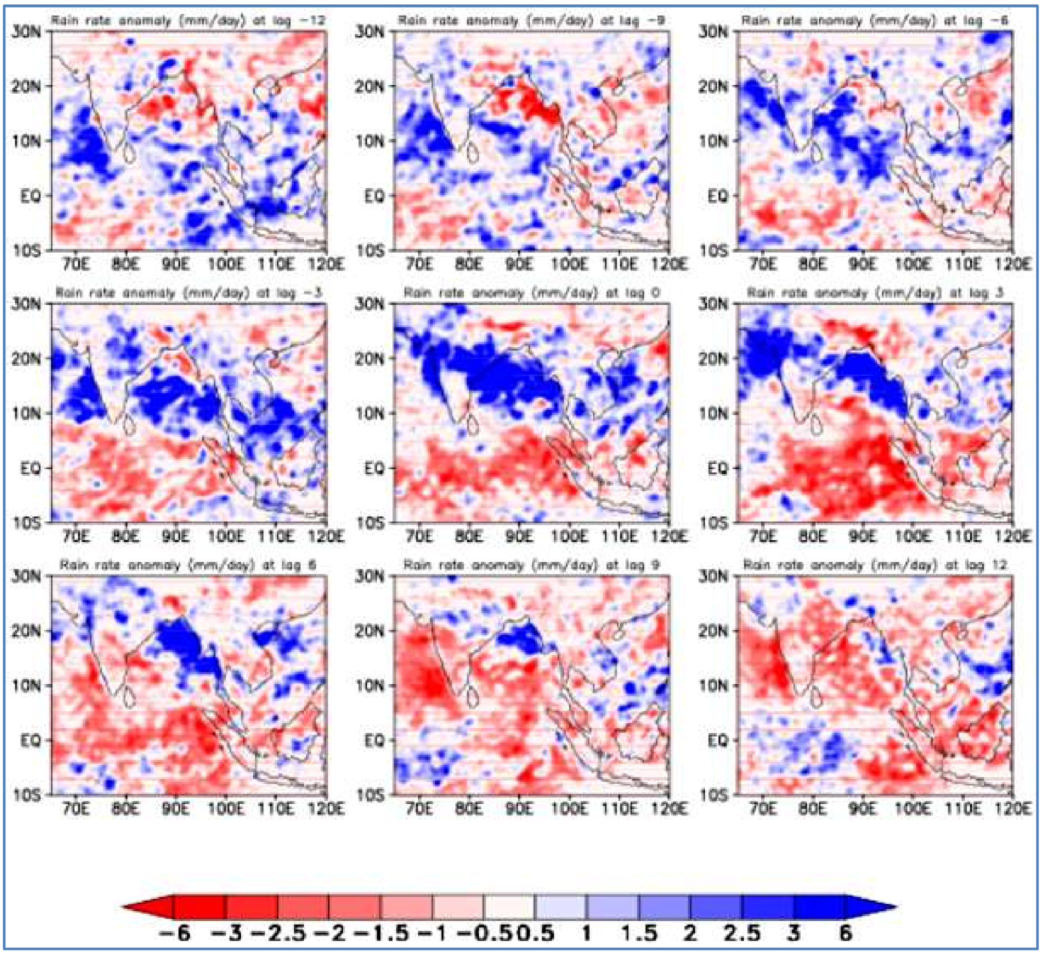


Fig. 3. Non-convective (stratiform) rain rate composite evolution during active phase from TRMM 3G68 data (Chattopadhyay *et al*., 2008)

dynamical features and spatiotemporal distribution of rainfall and other fields. The low-frequency mode evolves in a way that it provides a low-frequency background and hence has better predictability. This hypothesis (van Den Dool and Saha, 1990) is used as a background in developing a statistical and dynamical forecast system for the monsoon intraseasonal oscillation. The predictability of the low-frequency mode is higher and hence extended range forecast in the 2-3 week scale was seen to be useful in predicting the active and break spells. The predictability of monsoon active and break periods differ (Sahai *et al*., 2017) though both statistical and dynamical model confirm that the operational predictability could be extended to 2-3 weeks (Sahai *et al*., 2019).

4. Future climate and monsoon sub-seasonal variability

Global warming associated with anthropogenic forcings is indisputable. However, how these changes affect the ISM and MISO characteristics is largely uncertain. Mandke *et al*. (2007), from the thorough analysis of the Coupled Model Inter-comparison Project Phase 3 (CMIP3) multi-model dataset, found that the break spells may intensify and spatially and temporally extend in the future. Recently, based on the analysis of CMIP5 datasets, Sharmila *et al*. (2015b) proposed that severity and frequency of extreme (strong/weak) monsoons will increase in future climate. They also indicated that (*i*) the precipitation anomalies would become more intense and regionally extended over Indian land during active/break cycles in future climate, (*ii*) longer active spells will be more frequent, while breaks will be fewer and shorter, leading to wetter strong monsoon in future and (*iii*) weak monsoons will be drier due to the high propensity of extended breaks and short active spells in response to enhanced global warming, thereby increasing the risk of both the floods and drought-like conditions over Indian subcontinent in future climate.

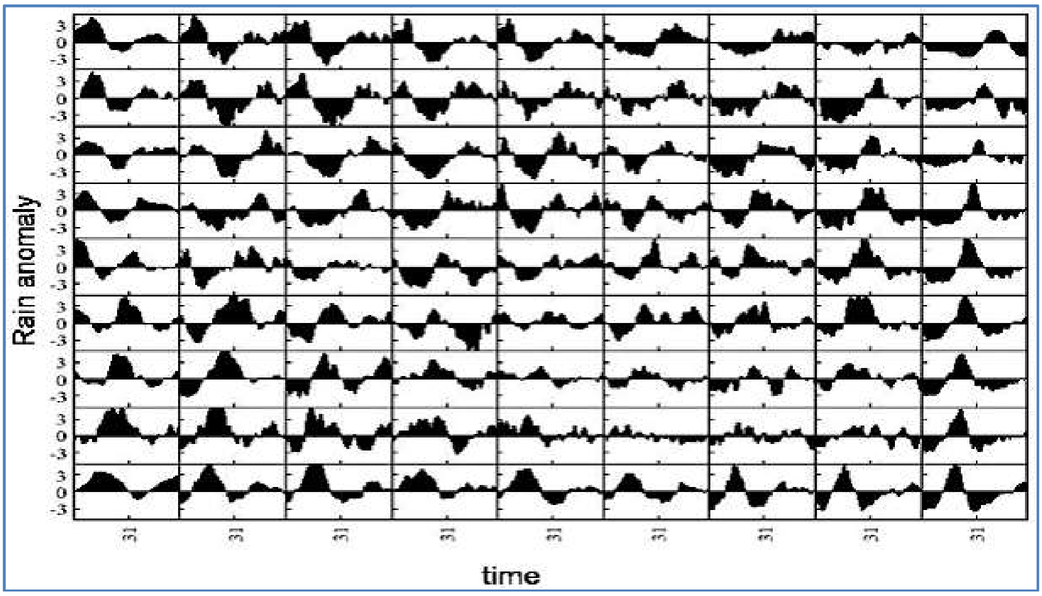


Fig. 4. Temporal evolution of different shades of monsoon active and break phases. These active and break phases are obtained from self organizing map based cluster analysis (Chattopadhyay *et al*., 2008)

In the backdrop of the above-projected scenarios of CMIP3 and CMIP5, MISO prediction is going to be important and the uncertainty arising due to climate change drives the requirement of improved prediction.

5. Statistical prediction models of MISO in a nonlinear approach

5.1. *Deterministic approach*

The most important aspect is that the active spells of rainfall do not remain spatially similar in all cases neither its temporal evolution follows a very systematic coherent pattern. A statistical model is developed to capture the different shades of spatiotemporal evolution of rainfall. These different shades are shown in Fig. 4. It may be noted that such different progressions indicate complexity in the evolution of rain bands. Therefore in order to understand or predict these spells, a statistical method is required to be formulated which can be used to predict these shades of oscillations. Similarly, different patterns of spatial shades also can be constructed based on the compositing of data clustered in each node.

The statistical prediction using a non-linear approach is developed based on a nonlinear analog technique using Self Organizing Maps (SOM). Forecasting is done for pentad (five-day average) rainfall over central India and is done four pentads (~20 days) in advance. The technique works on the following premise. It is shown that the different shades of monsoon ISOs can arise from northward propagation of rain bands or Tropical Convergence Zones. Since the active break phases evolved to have different shades, these shades are shown to be different realizations of nonlinear convectively coupled oscillations. It is shown that different phases of rainfall oscillation identified by SOM are uniquely related to a unique combination of large scale three-dimensional circulation parameters. Reversing the argument, if we could locate unique (distinct) nonlinear patterns (relationship) amongst the large scale circulation parameters and relate it with rainfall patterns, they may be linked to one of the nonlinear phases of the rainfall oscillation associated with active break cycles. This is achieved by SOM nonlinear pattern recognition (Kohenen, 1990) using six large scale indices of monsoon ISO without directly involving rainfall. Using a past library of data in defining the SOM vectors, the evolutionary history of different shades of monsoon phases are saved first. Then an analog technique is defined based on the identification of current data and its closeness with past data using a Euclidean distance criterion. The evolutionary history of the current data (*i.e.*, is the state to be predicted) is defined as an average temporal evolution of all the identified *similar* states based on past data. The plot is shown in Fig. 5. The plot shows that, the predicted rainfall has captured many spells over central India.

5.2. *Probabilistic extension of the deterministic forecast*

It is also found that the probabilistic forecast based on an ensemble of SOM model can give a better representation of ISO forecast in pentad 1 to pentad 4 lead-time (Borah *et al*., 2013). The Relative operating characteristic (ROC) plots and deterministic plots are shown in Fig. 6. The plot shows that the probabilistic information could be used for probabilistic prediction of MISOs.

6. Dynamical prediction experiments with CFSv2 as the standard prediction model

Deterministic forecasts from dynamical General Circulation Models (GCMs) show continued improvement in skill in short andmedium-range forecasts. However, an extended range dynamical forecast over India remains a challenging problem. On the other hand, several studies demonstrated that statistical models show significant skill in predicting precipitation evolution over 2-4 weeks lead time (Webster and Hoyos, 2004; Xavier and Goswami, 2007; Chattopadhyay *et al*., 2008). However, these skills in forecasts are on area average precipitation and not on the spatial distributions on which decisions are made. The fact that MISOs are modulated by air-sea interactions (Fu *et al*., 2003; Waliser *et al*., 2003; Sengupta *et al*., 2001; Wang *et al*., 2009) and are convectively cupled oscillations (Jiang *et al*., 2004; Lau and Waliser, 2012; Goswami, 2012; Goswami *et al*., 2011; Abhik *et al*., 2013) necessitates the use of coupled ocean-atmosphere general circulation models (CGCMs) for predicting active-break spells onthe extended range.

Extended range prediction (ERP) skill is mainly determined by the model's ability to represent the MISO and the associated air-sea interaction, as revealed by various studies using ocean-atmosphere coupled models (Rajendran and Kitoh, 2006; Sharmila *et al*., 2013; Kim and Kang, 2008; Fu *et al*., 2007). With improved model physics and incorporation of interactive air-sea coupling, some global models show useful skill even beyond 2-3 weeks and the predictability limit is comparable to or even better than the skill of current empirical models (Waliser *et al*., 1999; Jones *et al*., 2004; Jiang *et al*., 2008; Seo *et al*., 2009). Recently Fu *et al*. (2013) have pointed out that empirical and dynamical models show comparable skill and a combined dynamical-empirical ensemble technique extends the ISO prediction skill of rainfall to 3 weeks.

The intraseasonal prediction skill of the Climate Forecast System (CFS) model by National Center for Environmental Prediction (NCEP) has been analyzed by several researchers. A recent work by Fu *et al*. (2011) has investigated the intraseasonal prediction skill of CFSv2 over Southeast Asia and global tropics. They have shown that the MJO prediction skill measured with RMM index (Wheeler and Hendon, 2004) reaches 14 days and the actual rainfall prediction skill over Southeast Asia can be

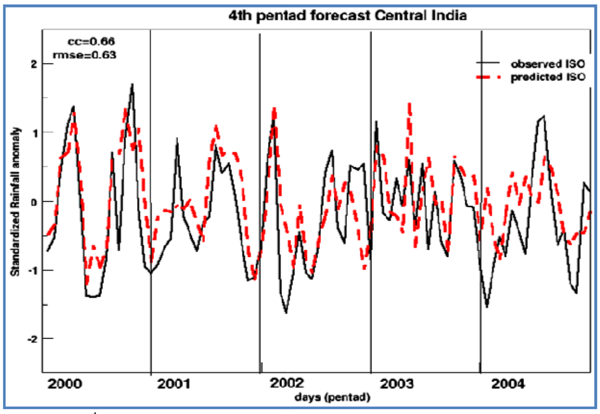


Fig. 5. 4th pentad (5-day average) lead-time forecast of rainfall intraseasonal oscillation (ISO) over central India (Chattopadhyay *et al*., 2008)

extended by 2-4 days compared to the 1-week forecast skill using NCEP Reanalysis 2 and ERA-Interim as initial conditions. However, their analysis is limited only to 5 years of hind cast from 2004 to 2008 during summer monsoon season. Zhang and Van den Dool (2012) have compared the ISO prediction skill of both CFSv1 and CFSv2 and reported that CFSv2 shows significant improvement over CFSv1 in predicting MJO with a skill of 2-3 weeks. They believe that these improvements might be coming from the improved model formulation and better initial conditions from the CFS reanalysis (CFSR). CFSv2 simulates the northward propagating MISOs reasonably well (Sharmila *et al*., 2013) and has useful skill in predicting the MISO indices up to a lead time of 20 days (Suhas *et al*., 2013). Further, the model well-simulates the observed lead-lag relationship between sea surface temperature (SST) and precipitation over the Arabian Sea, Bay of Bengal as well as in the South China Sea from 20 days before to 20 days later (Roxy *et al*., 2013). As a result, this modeling system has been taken as the base model for further improvement of the seasonal prediction of ISMR and ERP of active-break spells under the National Monsoon Mission project of the Ministry of Earth Sciences, Government of India.

6.1. *Development of an indigenous method for generating initial conditions(IC)*

Considering the time scales involved in ISO forecast, it is expected that the predictability on this time scale is controlled both by initial conditions and boundary forcing (Krishnamurti *et al*., 1992; Fu *et al*., 2008). Uncertainty in the dynamical ERP mainly arises from the uncertainty in the initial conditions, boundary forcing as well as from the incomplete representation of the model physics. Ensemble approach is usually used to sample these errors (Palmer, 1993; Harrison *et al*., 1999).

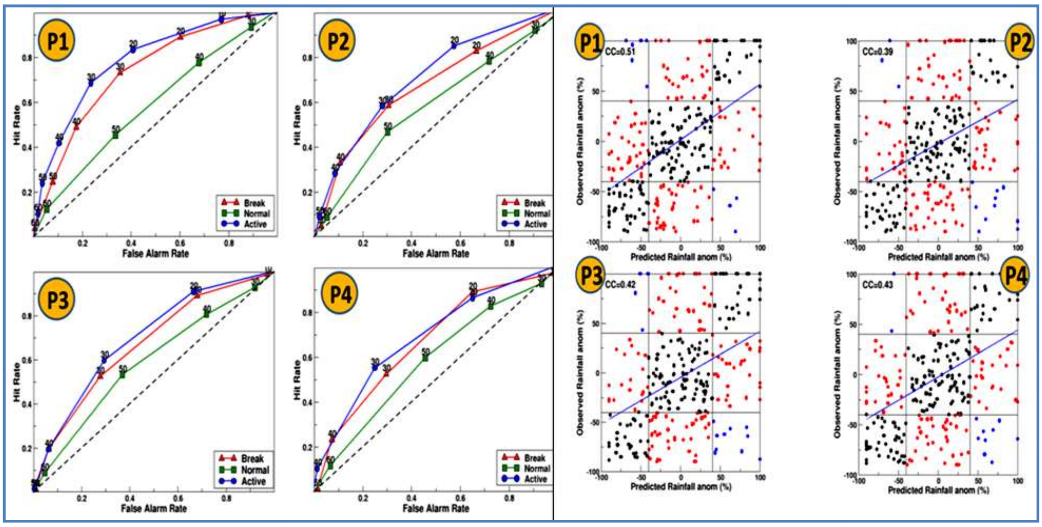


Fig. 6. Pentad lead-time forecast of statistical SOM model with multiple ensembles (Borah *et al*., 2013)

Extended Range Prediction group at Indian Institute of Tropical Meteorology (IITM) is issuing a real-time experimental forecast of the active/break spells of ISMR up to 4th pentad lead using an indigenously developed EPS based on the dynamical model NCEP CFSv2. A perturbation scheme has been introduced indigenously to develop a reliable and flexible Ensemble Prediction System (EPS) in CGCMframework. Without depending on external data encoding, the EPS can be used for real-time operational as well as research purpose. At IITM, as part of National Monsoon Mission Project, we carried out the initial testing of the in-house developed EPS system based on the CFS in different versions of the model (Pattnaik *et al*., 2013). There are various approaches to ensemble perturbation techniques. The EPS of ECMWF evolved from 50 initial perturbations generated using singular-vector technique and an unperturbed control run (Buizza and Palmer, 1995). At NCEP, the ensembles of initial perturbations are created in a similar way as at ECMWF, but breeding vectors (Toth and Kalnay, 1993) are used instead of singular vectors. At Meteorological Service of Canada (MSC) an Ensemble Kalman Filter (EnKF) with perturbed observations and different combinations of parameterization schemes is used to generate an ensemble of initial conditions for their medium range prediction (Houtekamer *et al*., 2005). Buizza *et al*. (2008) classified the different ensemble generation strategies into three groups. Although there are several approaches to generate ensembles of different initial conditions, we use an approach which is similar to the 'complex-and-same-model environment group' as classified in Buizza *et al*. (2008).

An ensemble of 10 perturbed atmospheric initial conditions were developed in addition to one actual initial condition. Each ensemble member was generated by slightly perturbing the initial atmospheric conditions with a random matrix (random number at each grid point) generated from a random seed. In order to make the perturbation size consistent with analysis variance of each variable, the amplitude of perturbations is adjusted to ensure sufficient spread in the forecast fields and also to ensure that amplitude of perturbation varies in accordance with the uncertainty in the analysis. In order to make the ensemble mean to be centered around the unperturbed study, the fraction of the tendency of different model variables are added to or subtracted from the unperturbed analysis with random perturbation between −1 and +1 times the tendency so that the perturbations follows a Gaussian distribution. We perturb the wind, temperature and moisture fields and the amplitude of perturbation for all variables are consistent with the magnitude of the variance of each variable at a given vertical level. In the present formulation, there is an option to select the perturbation variable, where X can be any variable from u-component of wind (u), v-component of wind (v), temperature (t) and humidity (q). This approach also helps to study the individual impact of perturbing each variable on the final forecasts. More details about the formulation of the EPS and its initial testing can be found from (Abhilash *et al*., 2015, 2013).

6.2. *Role of SST bias correction*

CFSv2 has considerable cold SST bias of about 2-3 °C over the tropical Indian Ocean (IO) (Roxy *et al*., 2013) as well as the remarkable colder Tropospheric temperature (TT) bias over the Asian continents (Sharmila *et al*., 2013). There may be a possibility to link up the dry bias over the Indian land to the TT and SST biases, which in turn is responsible for the underestimation of both mean and variability of ISMR in CFSv2 (Sharmila *et al*., 2013). It is likely that the SST bias could prevent us from attaining the potentially achievable skill of ERP of MISO. With the cold bias, the CFSv2 forecasted SST may lead to poor amplitude and organization of convective precipitation. In order to correct the SST cold bias, we carry out a series of ERP experiments with the GFSv2 forced by forecasted SST from CFSv2 with the same initial state. The forecasted SST is corrected for its bias in the CFSv2 forecasts derived from a large ensemble of hindcast. Recently, Fu *et al*. (2013) have demonstrated that atmosphere-only model forced with forecasted SST from CFSV2 without any bias correction shows similar skill as that of the coupled model and skill is improved further by forcing theatmosphere-only model with observed SST. On the basis of the above findings, we assume that the skill of the atmosphere-only model, forced with bias-corrected forecasted SST, will be between the above two experiments.

For the observed SST climatology, we have used NOAA optimum interpolation SST (OISST). Bias correction in daily forecasted SST from CFSv2 for each lead time has been done by removing the daily mean bias for corresponding lead time (model climatology-observed climatology) from forecasted daily SST and is provided as the boundary forcing for the GFSv2 (hereafter known as GFSbc, with '***bc***' indicating bias correction). Bias correction technique is detailed in Abhilash *et al*. (2014a&b).

6.3. *Implementation of high resolution*

Studies (Jung *et al*., 2006; Kinter *et al*., 2012; Lin *et al*., 2012) have shown that increase in resolution of GCMs can improve the simulation and prediction of ISM, owing to the better representation of small spatial scale physical processes. With this background, the high resolution (T382) version of CFSv2 was implemented for ERP and compared with the low-resolution version (T126) by Sahai *et al*. (2015a). They showed that T382 version had provided a better basic state for MISO along with large reduction in climatological biases in monsoon rainfall, compared to T126. However, area-averaged forecast and the temporal evolution of MISO show statistically similar skill for both resolutions. Therefore, there is no significant improvement in the prediction skill from increased horizontal resolution, in terms of computing resources.

7. Development of CFS based Grand Ensemble Prediction System (CGEPS)

Forecasts are more useful if the uncertainty is quantified. In the extended range especially, beyond the weather scale (~3 weeks), a single deterministic rainfall forecast is not sufficient; the user community also should be given probabilistic forecasts that quantify the uncertainty. One chronic problem in numerical ensembles is under-dispersion, leading to overconfidence errors in the resulting statistical forecast distributions. Single-model ensemble (SME) prediction systems are especially prone to under-dispersion since they do not represent all sources of forecast error (Buizza *et al*., 2008). Uncertainties in the initial conditions (ICs) are bracketed by creating IC ensembles, using various methods as surveyed in Buizza and Palmer (1995) for example. A straight forward way is to slightly perturb the original atmospheric or oceanic states as described in (Abhilash *et al*., 2013, 2014a). Imperfect model uncertainties are known to be challenging. In a posterior approach, ensemble predictions from different models are pooled to produce a final forecast probability distribution. In any multi-model approach, the independent skills of the participating models are combined in a judicious manner to reinforce the total skill of the multi-model ensemble (MME) mean (or other statistics).

The present MME derived from multi-version, multi-resolution and two-tier extended range forecasts computed in one center based on CFSv2. It's atmosphere component, the Global Forecast System (GFS) has been subsequently improved in ways that have not yet propagated to the coupled system. We run different versions of CFS/GFS to generate their SMEs and then pool them to form the MME. In doing this, we have followed the approach for ensemble prediction described by Houtekamer *et al*., 1996. The versions of CFS/GFS are diverse in resolution as well as in model physics. Specifically, the MME includes both coupled CFS integrations and "two-tier" integrations with stand-alone atmospheric GFS forced by bias-corrected CFS-forecasted SST, *i.e.*, GFSbc. Integrations also utilize the perturbed parameter approach (Pellerin *et al*., 2003) in which the same model is run several times with different settings. In this way, this forecast system addresses the prime goal of the National Monsoon Mission Project, initiated to improve the monsoon prediction capabilities of the CFS system.

The idea to combine these versions arose from detailed analysis of the SMEs of CFS and GFSbc (Abhilash *et al*., 2014a; Borah *et al*., 2015; Sahai *et al*., 2015b; Abhilash *et al*., 2013, 2014b) forecasts, which showed that although in many cases forecasts from CFS and GFSbc are similar in skill, sometimes one model outperforms the other. The same is found to be true for the skill in forecasting individual spells of active and break phases (Sahai *et al*., 2013). This complementary nature of these variants motivated the development of the presently described CFS based Grand Ensemble Prediction System (CGEPS), for ERP of active/break spells of Indian summer monsoon rainfall. Another operational reason to combine SMEs into an MME (rather than disseminating each variant separately) arises from the difficulties to communicate the measure of uncertainties and the associated reliability estimations of multiple forecasts valid for the same lead time. The consensus forecast based on the MME is thus significant from the users' point of view in an operational set-up. More details about the configuration of MME is presented in (Abhilash *et al*., 2015).

It is found that the CGEPS MME provides multiple benefits. It not only expresses the errors in ICs and forecast model well but also provides better probability forecasts from the users' perspective (measured by increased reliability). Most of the overconfidence penalty involved in SME is partly overcome in MME. This approach further adds value to both of the deterministic and probabilistic forecasts. The better probabilistic skill is probably contributed to the improved spread-error relationship (SER). The results encourage us towards a comprehensive adaptation of this broadened NCEP-CFSv2 framework for the operational ERP of the Indian summer monsoon.

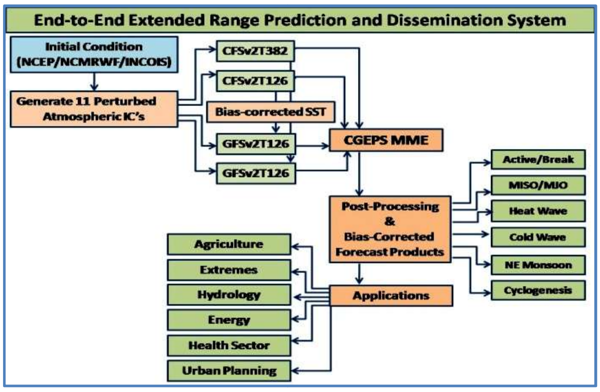


Fig. 7. Schematic of the end-to-end forecast and dissemination system implemented for ERP

8. Development of customized forecast products

Various customized forecast products are being disseminated from this ERP which includes prediction of active-break spells of the Indian summer monsoon, monsoon onset, progression, withdrawal, heat-cold wave, monitoring of MISO and MJO, cyclogenesis and many other. Now this ERP system is capable of generating an extended outlook for various sector-specific applications such as agriculture, hydrology, energy, insurance, re-insurance, urban planning, health, etc. Fig. 7 shows schematic of the end-to-end forecast and dissemination system developed and implemented for operational ERP.

8.1. *Monsoon onset criteria*

The onset of ISM over Kerala marks the first active spell of MISO. Although the date of Monsoon Onset over Kerala (MOK) does not have any bearing on the subsequent progression and strength of ISM, it has important implications on agricultural productivity. Therefore, the prediction of MOK is essential for the economy of the country. Joseph *et al*. (2015b) proposed an objective criterion for the real-time operational dynamical prediction of MOK in extended range time scale, based on the CGEPS developed at IITM. The criterion was developed in such a way that it successfully eliminates the possibility of bogus onsets and that the predicted MOK dates should largely match the IMD-declared MOK dates for the past data. For the criterion, three indices were formulated-one based on rainfall over Kerala and the other two based on the strength of low-level jet and depth of westerlies. It is found that the evolution of various model-predicted large-scale and local meteorological parameters corresponding to the predicted MOK date is in good agreement with that of the observation, signifying the robustness of the devised criterion and the appropriateness of CGEPS for MOK prediction.

8.2. *Monsoon progression and advance*

After its onset over Kerala around 1 June, ISM makes northward progression and covers the entire country by around 15 July. During some years, the progression is very fast and during some years, it is very slow. In 2013, ISM covered the entire country in 16 days and it was predicted by the EPS well in advance (Joseph *et al*., 2016, 2015a). When this prediction was given in real-time, there were speculations that the EPS has some bias in predicting the ISM progression very early. However, in the very next year, the ISM progression was delayed and this was also well-predicted by the model well in advance (Joseph *et al*., 2016). This proved that the EPS is capable of predicting the distinct progression phases of MISO.

8.3. *Monsoon withdrawal*

ISM generally starts withdrawing from the northern parts of the country by 1 September. However, during some years, low-pressure systems form in the Bay of Bengal and move northwestwards, thus delaying the withdrawal process. Such an incident happened in 2013. IMD started giving withdrawal from the northwestern states by September first week of 2013. The real-time prediction from EPS based on 8th September, 2013

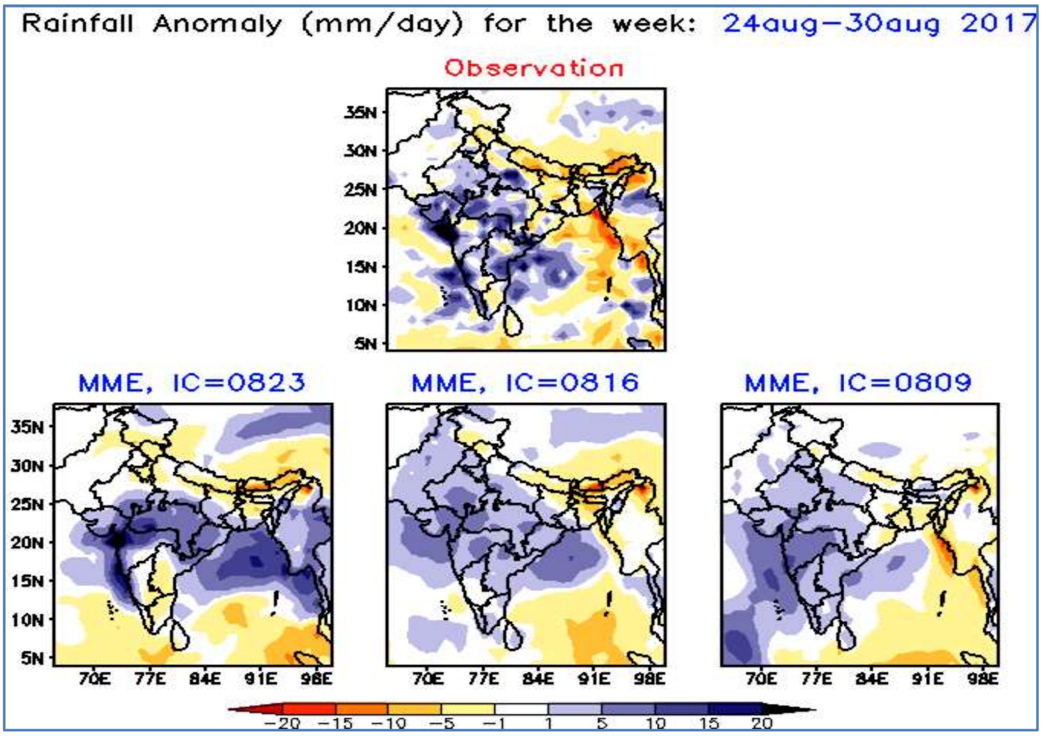


Fig. 8. Observed as well as predicted rainfall anomaly during 24-30 August, 2017

indicated that monsoon would revive by mid-September with the formation of a low-pressure system in the Bay of Bengal, which will give good rainfall activity over northwestern parts as well and this turn of events actually happened as foreseen. This prediction helped IMD to revise the declaration of withdrawal from the northwestern states and additional operational leverage is gained.

During other years also, the EPS could successfully predict the MISO fluctuations during the withdrawal phase of ISM.

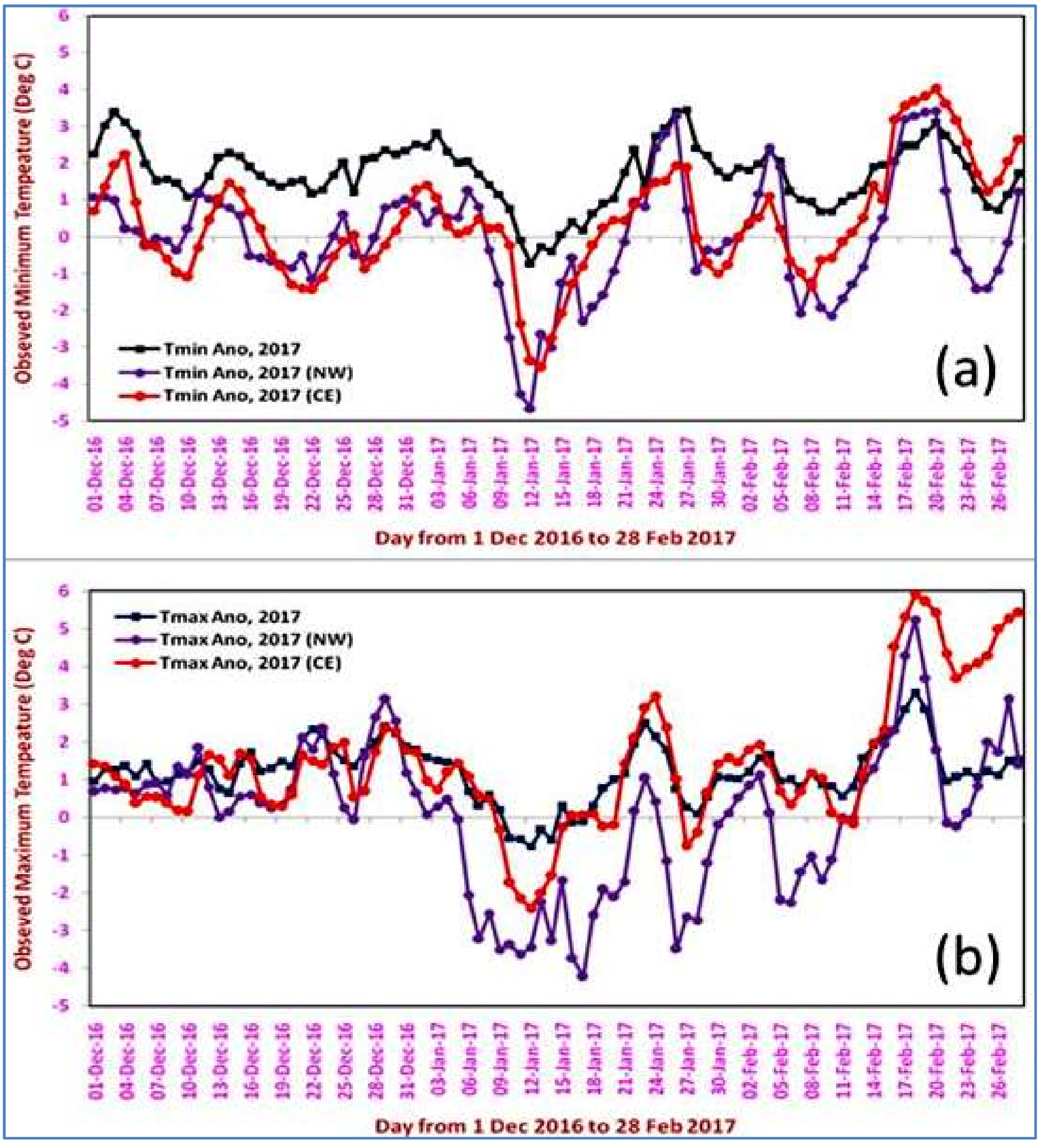
8.4. *Extremes in monthly rainfall*

As mentioned earlier, the ISM rainfall progression phase was quite distinct during 2013 and 2014. This resulted in the extremes in June rainfall during these years. The June rainfall was highly excess during 2013 (+34%), whereas it was highly deficit (-43%) during 2014. Such extremes were noted during June 2001(2009) when the June rainfall departure was +35% (-47%). The large scale conditions were also distinct during these extreme years. Joseph *et al*. (2016) have shown that the EPS was successful in predicting these observed contrasting behaviour of ISM. They also noted that the EPS not only forecasted the observed discrepancy but also predicted the influential role of the large-scale meteorological conditions prevalent during June 2013 (2014), thus demonstrating the remarkable skill of the EPS in predicting June extremes.

8.5. *Heavy rainfall events*

Goswami *et al*. (2006) and many other studies thereafter indicated that the frequency and the magnitude of extreme rain events are increasing and frequency of moderate events are decreasing in recent years. Heavy rainfall events can result in loss of life and property due to hazards like floods and landslides. Therefore the prediction of such events on the extended range time scale is beneficial to the society.

The capturing of an extreme event is a rather difficult task. The CFS model captures extreme events with different skills in different resolution (Chattopadhyay *et al*., 2018b). It is observed that there is marked dissimilarity in simulating high-intensity rain events in these models. The model run at high and low resolutions capture intensity and frequency differently. It is found that (a) the low-resolution version, CFST126 free run, gives better estimates of the frequency of rainfall events compared to the high-resolution version, *i.e*., CFST382, (b) on the contrary, the CFST382 free run gives better estimates of the intensity of high-intensity rainfall events compared to CFST126. These discrepancies indicate that the statistics of the extreme event may be dependent on



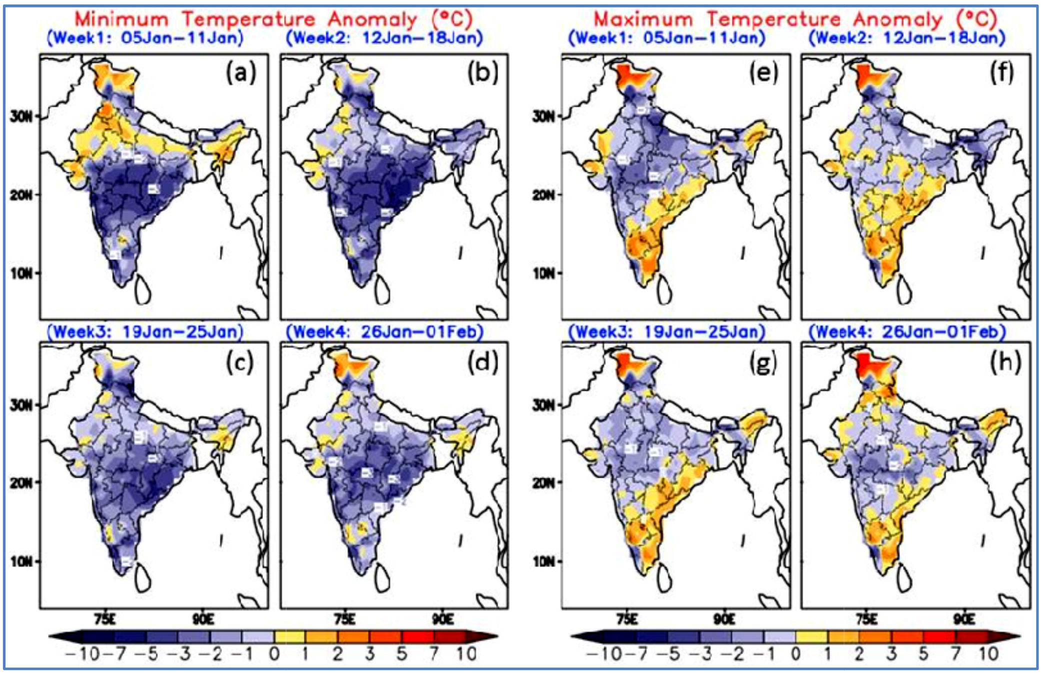
Figs. 9(a&b). Area averaged observed daily time series of (a) minimum and (b) maximum temperature anomalies from 1 December, 2016 to 28 February, 2017. Black, purple and red colors indicate whole country, north-west India and central India respectively

model resolution (Chattopadhyay *et al*., 2019). Several studies have shown skill of the multi model ensemble forecasts based on CFSv2 model in predicting the Uttarakhand rainfall event (Joseph *et al*., 2015; Pattanaik *et al*., 2015). Joseph *et al*. (2015a) also indicated that the high resolution version has better skill in predicting heavy rainfall events over Indian region. Any bias in the forecast, thus, should be statistically corrected and a multi-resolution ensemble version runs of CFSv2 has to be used for operational outlooks of the extreme events.

Based on this hypothesis, the multi-ensemble EPS system is deployed to give outlooks of these events. The skill of the CGEPS in predicting the Mumbai heavy rainfall event happened in August 2017 is shown in Fig. 8. It is clear from the figure that an indication of the impending event was given even 3 weeks in advance.

9. Application of extended range forecast for other seasons: Heat/cold wave

Extended range forecasts are quite general in principle and the method can be applied to other weather and climatic incidents as well. Extremes of heat and cold have a broad and far-reaching set of impacts on the nation. These include significant loss of life and illness, economic



Figs. 10(a-h). Week-1 to Week-4 Tmin anomalies (a, b, c and d) and Tmax anomalies (e, f, g and h) from 4th January, 2017 initial condition

costs in transportation, agriculture, production, energy and infrastructure.

In India, cold waves (CWs) occur during boreal winter months from November to February. Earlier studies showed that CWs occur mostly due to the intrusion of cold air from northern latitudes into the northwestern parts of India. The CW conditions over the northern parts of India are often associated with the passage of western disturbances (Bedekar *et al*., 1974). On the other side, the heat waves (HWs) over India generally occur during March to June with high frequency over north, northwest, central and the eastern coastal regions. The favorable conditions for HWs are different for different regions. The HWs over India is linked with the climate mode such as ENSO (De and Mukhopadhyay, 1998). HWs over India are found to be influenced by anomalous sub-tropical persistent high with the anti-cyclonic flow, lacking soil moisture and SST anomalies over the tropical Indian and central Pacific Oceans (Rohini *et al*., 2016). Ratnam *et al*. (2016) identified that HWs over north-central India and over coastal eastern India are associated with anomalous blocking over the North Atlantic Ocean and anomalous baroclinic Matsuno-Gill response to the anomalous cooling in the Pacific respectively. Sometimes, HWs may develop *in-situ* (Ray *et al*., 2013).

The CWs are known to increase mortality rate owing to the socio-economic conditions of people of the northern parts of India. For example, the CW that occurred in January 2003 resulted in the death of about 900 people (De *et al*., 2005). During 1978-1999, a total number of 3264 deaths were reported due to CWs in the northern parts of India (De and Sinha Ray, 2000).

It appears that the causal mechanism for cold related mortality is not so much a single cold snap as it is a longer-term chronic exposure. Research indicates that those at risk are the homeless people staying under the open sky during cold snaps, people primarily engaged in the outdoor activity and the elderly who are chronically exposed to colder indoor temperatures.

9.1. *Case study: Cold wave event: 5-18 January, 2017*

Figs. 9(a&b) show the observed time series of minimum temperature (Tmin) and maximum temperature (Tmax) anomalies respectively. From this figure, it can easily be identified that there was a sudden drop in Tmin as well as Tmax during 6-18 January, 2017.

This CW spell was well predicted by the multi-model ensemble (MME) prediction system in sufficient lead time. Figs. 10(a-h) shows the weekly averaged forecasted Tmax and Tmin anomalies up to 4 weeks lead time from 4th January initial condition (IC).

On the other side of the coin, HWs can be more devastating than all other weather-related disasters and the severe heat waves have caused catastrophic crop failures, thousands of deaths. The Indian HW of 1988 caused an estimated number of 1300 deaths (De and Mukhopadhyay, 1998; De *et al*., 2004) and likewise, the HWs of 1998 and 2003 caused deaths of about 2042 people (Jenamani, 2012) and 3054 people (Bhadram *et al*., 2005), respectively. According to the international disaster database, EM-DAT (Guha Sapir *et al*., 2016), the HW of 2015 caused deaths of 2248 people in various parts of India. The total impacts of temperature extremes are not fully documented and known. Much of the documentation of temperature impacts combine other meteorological events and uses climatological scales of space and time. The nature of seasonal impacts is more cumulative and complex than the impacts of cold snaps and heat spells. Weather forecasting must take into account the hazards and impacts of temperature extremes to provide useful, understandable and timely information for the nation to reduce natural disasters.

Since our focus is over Indian region, keeping in mind the criteria developed by IMD (which is based on station data) to predict the HWs over India, a modified HW criteria has been defined (Joseph *et al*., 2018) based on maximum and minimum temperatures that can be applied not only on the gridded observation data but also for the real-time prediction of HWs using the dynamical coupled models as well. This ERP system is providing real-time predictions of heat waves in theform of probability of Occurrence for Extreme Heat such as HOT condition, Heat Wave (HW) and Severe Heat Wave (SHW) conditions in 2-3 weeks in advance.

9.2. *Case study: Heatwave event: 19 May-1 June, 2018*

The central and northwestern parts of India experienced a HW event during the second half of May 2018. Fig. 11 depicts how the ERP system has predicted this spell from the two nearest ICs (9th and 2nd May) using the newly developed criteria. This HW spell was very well predicted by the ERP system 2 weeks in advance.

10. Madden Julian Oscillation (MJO)

Since MJO is one of the dominant modes of subseasonal variability, MJO prediction at medium to extended range time scales has got huge attention. In the long past, MJO signal has been isolated through the Empirical Orthogonal Function (EOF) analysis of band-pass filtered data (Lau and Chan, 1985; Knutson and Weickmann, 1987). However, the major challenge in MJO monitoring and prediction was the extraction of its

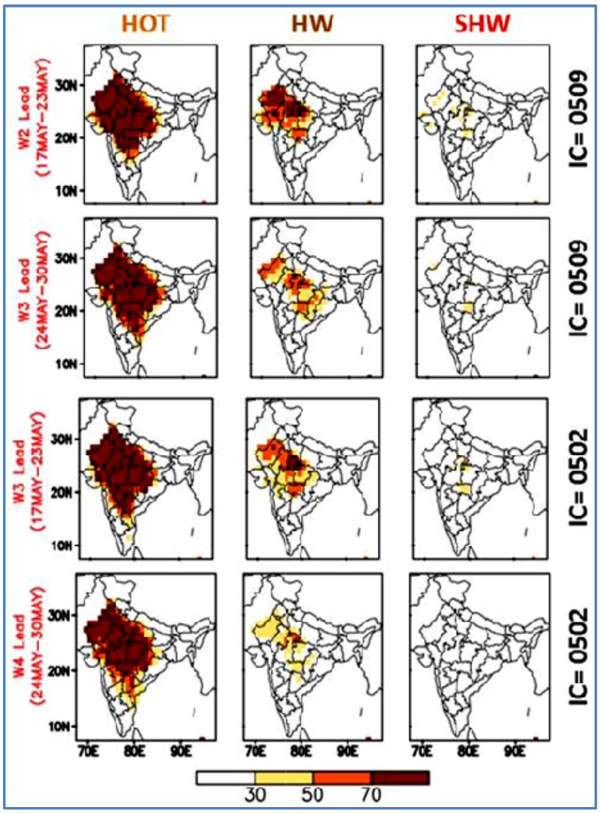
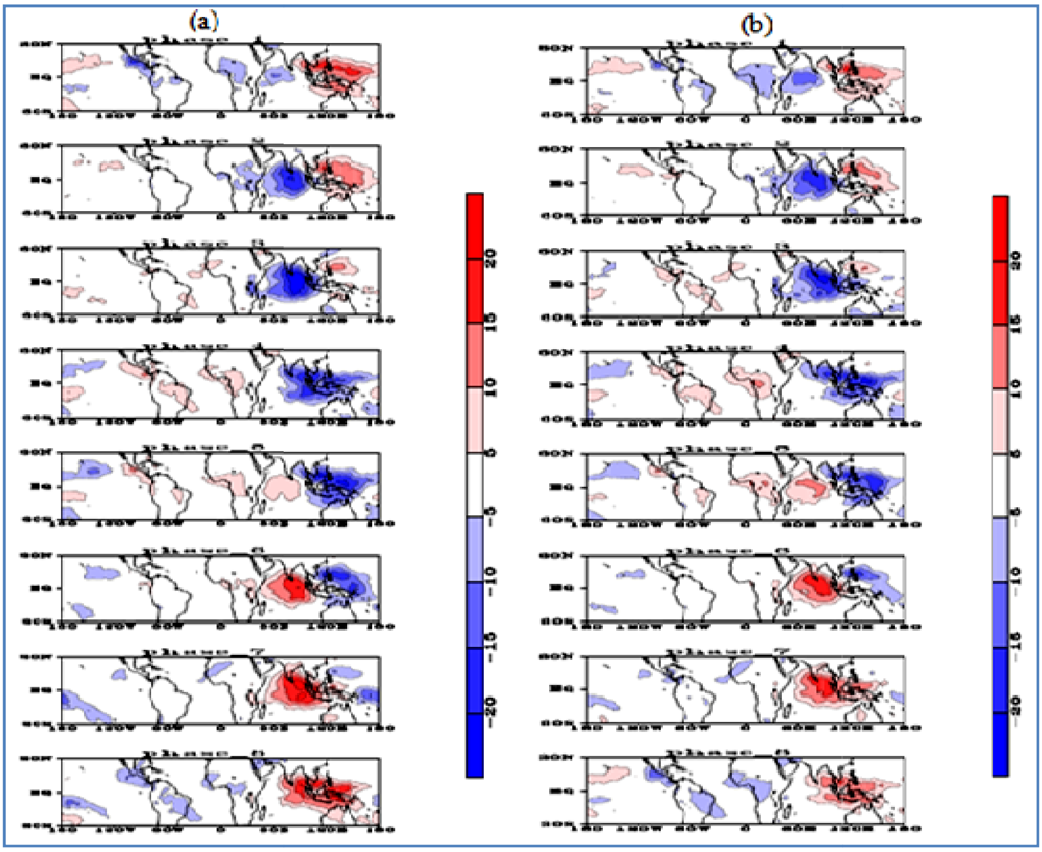


Fig. 11. Weekly averaged probabilistic forecasts of HOT, HW and SHW conditions for different lead time for HW spell 19 May-1 June, 2018

frequency limited signal without using any kind of band-pass filter. Since the band-pass filter requires data beyond the end of time series, it cannot be used in real time application. Lo and Hendon (2000) have shown that much of the MJO associated signal can be isolated simply by the projection of high-pass filtered daily data onto the spatial pattern characteristic of the MJO. Spatial projection removes a large portion of the variability on the other space-time scales, which are not associated with MJO. To define the spatial pattern of MJO, Lo and Hendon (2000) use EOF analysis of OLR/Stream function in the global tropics. Later Wheeler and Hendon (2004) (hereafter WH04) used EOF analysis of the combined field of OLR, zonal wind at 200 hPa (U200) and zonal wind at 850 hPa (U850). WH04 noted an improvement in the signal to noise ratio by using multiple fields. Similarly SOM clustering method yields a large scale global pattern based on these indices (Chattopadhyay *et al*., 2012). A very recent study by Ventrice *et al*. (2013) noted improvement in MJO prediction by replacing OLR component of WH04 index with velocity potential at 200 hPa level (Chi200).

Keeping this literature survey in mind, a method for real - time MJO monitoring is proposed by



Figs. 12(a&b). OLR anomaly (W/m^2) composite of eight phases (period 1979-2013) in the sequential pattern each showing the life cycle of canonical MJO: (a) WH04 method (left column) and (b) EEOF method (right column)

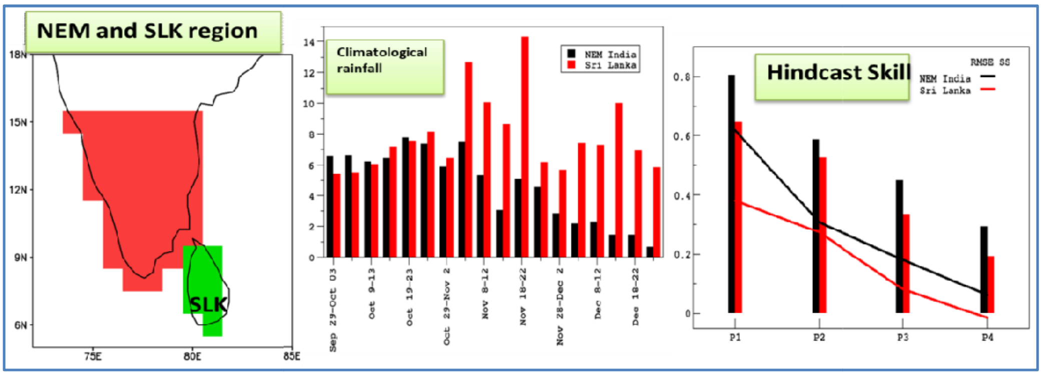


Fig. 13. Plot showing the northeast monsoon domain, climatological rainfall cycle and current skill in predicting the northeast monsoon in the extended range scale. The skill is calculated from IITM EPS system based on 10 years of hind cast data

Dey *et al*. (2018). We normalized each input field (*i.e.*, U850, U200 and Chi200) at every grid points, apply 10° averaging of data along longitude in addition to the equatorial averaging (averaging over 15° S-15° N) and replace OLR with velocity potential at 200 hPa (chi200) after that we performed Extended EOF (EEOF) analysis. For EEOF analysis we use lag up to six days (day 0 … day 5), *i.e*., past six days data is appended to the covariance matrix. This filters out synoptic scale high-frequency variability. Phase composite based on this EEOF method shows similar eastward propagation like WH04 method [Figs. 12(a&b)]. In this EEOF method, temporal propagation in the phase space (defined by the leading pair of PCs of EEOF) is much smoother. Leading

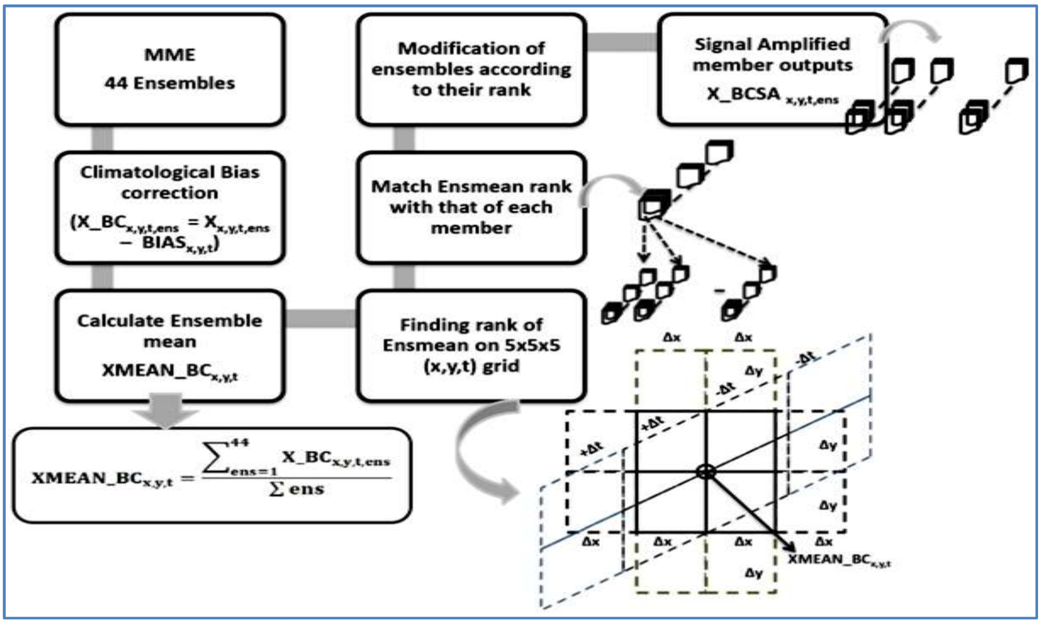


Fig. 14. A schematic flowchart of bias correction and signal amplification technique

pair of PCs of EEOF isused to introduce seasonally varying regression coefficients and hence to reconstruct the fields. These fields are then utilized for linking the bidirectional phase propagation (northward moving MISO and eastward moving MJO) during boreal summer. EEOF based method captures the life cycle of MISO and MJO with equal confidence. The proposed EEOF method is tested during TOGA-COARE, DYNAMO period MJO and also during few strong MISO events and it is found that the method is capable of capturing most of the events.

11. Northeast (NE) monsoon

The northeast monsoon plays a significant role in maintaining the hydrological cycle in the peninsular tip of India around the Tamil Nadu coast and Sri Lankan Island. A study is initiated to improve the skill of northeast monsoon. An example of extended range prediction skill for northeastern region is shown in Fig. 13. The plot shows that the skill is modest beyond two weeks as of now and it is a research challenge to improve this forecast beyond weather scale.

12. Operational applications of extended range forecast

12.1. *Bias Correction and Signal Amplification (BCSA) technique*

BCSA Technique is a post-processing tool introduced by Saranya *et al*. (2018) for improving the MME-track forecasts of tropical cyclones at longer leads which can be applied to any number of MME outputs. Flowchart for this method is shown in Fig. 14. MME comprises four variants of NCEP CFSv2 and GFSv2 at T126 (100 × 100 km) and T382 (38 × 38 km) resolutions with 11 ensemble members each (44 ensembles). For storm-track forecast improvements, the variables subjected to this technique include zonal and meridional winds at 850 hPa, mean sea level pressure, temperature at 500 and 200 hPa and geopotential height values at 200 and 1000 hPa, the variables used for track prediction in the GFDL-objective tracking algorithm (u850, v850, MSLP, T200, T500, Z200, Z1000). The first step involves the calculation of observed and model climatology of the variables for the past years, to calculate and eliminate the climatological biases in the raw-MME outputs. During the signal-amplification procedure, each bias-corrected member undergoes a two-point space-time correction of latitude (2° N and S), longitude (2° E and W) and time (2 days before and after) with respect to the corresponding ensemble mean of the group. Ensemble spread of each member is optimized by comparing the member-ranks with the rank of Ensemble mean and thereby obtain the amplified or dampened to obtain BCSA outputs. Results from Saranya Ganesh *et al*., 2018 show that track errors of BCSA forecasts are much lower compared to the raw-MME forecasts.

12.2. *Dynamical downscaling using WRF*

Under the development of different strategies, dynamical downscaling of ERP system is another attempt to refine the prediction of extreme weather events on the

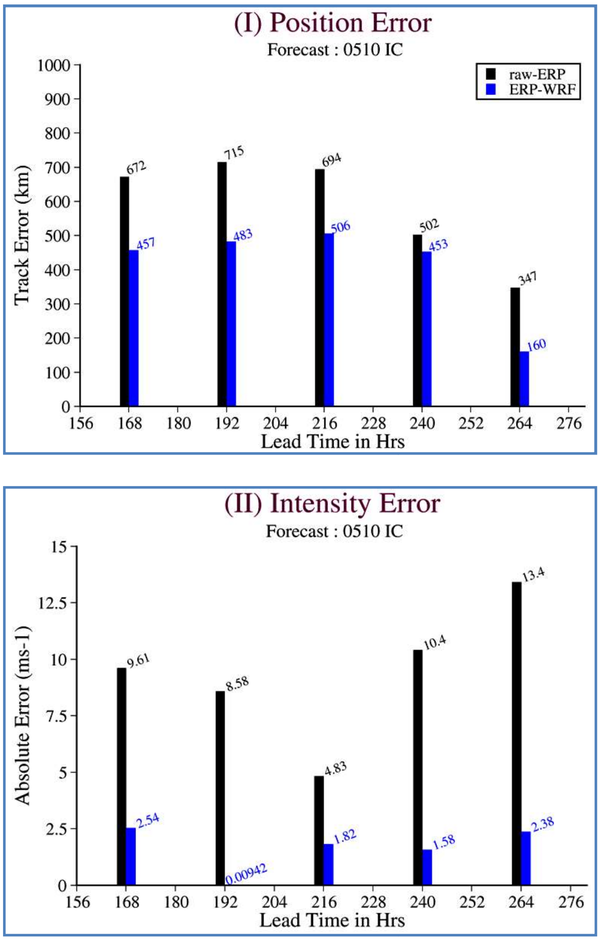


Fig. 15. Raw-ERP and ERP-WRF track errors for cyclone Roanu

sub-seasonal scale. ERP system has good skill, but the model's resolution is still coarser and therefore underestimates the regional orographic features and sub-grid scale process. These overlooked processes play an important role in the genesis of weather systems causing extreme downpours. Weather research and forecasting (WRF) model is used to downscale individual members of ERP fed as initial (ICs) and lateral boundary conditions (LBCs). WRF model resolution is 9 km and domain centered at India has 1001 × 944 points which covervast surrounding region to include air-sea interactions. WRF simulations are inclined towards large scale forcing from raw-ERP. ICs and LBCs from parent ERP model components are corrected for restricting migration of biases to WRF domain. Initial downscaling attempts for Roanu cyclone case that happened during 17-22 May, 2016 has been tested with 10 May initial condition almost a weak ahead of the system formation. It has been found that bias-corrected downscaled ERP (ERP-WRF) shows better intensity and track of the system compared to raw-ERP. Tracks errors from raw-ERP and ERP-WRF (Fig. 15) shows that ERP-WRF simulated cyclone intensity is substantially improved and the position errors are reduced. Initial results are encouraging for more focused work headed for development of downscaling strategy in the near future.

12.3. *Applications in the health sector*

In India, large number of population (mainly children and older people) die due to two types of preventable infectious diseases such as vector-borne and water-borne diseases. There are various complex ways in which climatic factors (e.g., temperature, precipitation, humidity, extreme weather events and sea-level rise) can directly or indirectly affect the appearance of those diseases. Changes in local climate alter the ecological conditions which can affect vector ecology and then indirectly impacting human health (Luber *et al*., 2014).

For example, health impacts of HWs are not only affected by peak temperatures but also by the extended length of a heat wave, high day time and night time temperatures and high relative humidity. So, using the ERF products such as maximum/minimum temperatures, HW conditions for next 2-3 weeks can be forecasted and thus the health warning system can be monitored. Also, the probabilistic forecasts (e.g., maximum and minimum temperatures for different temperature ranges) can be used to provide the forecast of the different types of diseases which are strongly linked with these climatic variables (for a particular range) over different parts of the country, mostly over those disease-prone areas. Figs. (16&17) show, the temperature probabilistic weekly forecasts up to 4 weeks, lead time for a particular temperature range, here it is 33-39 °C and 16-19 °C for maximum and minimum temperatures respectively.

12.4. *Applications in agriculture*

In India, the cropping season is classified into two main seasons namely, Kharif (June-October) and Rabi (October-March) depending upon the monsoon rains. All the climate variables (rainfall, temperatures, humidity, soil moisture etc.) have significant contributions to the yield and cropping area. Kharif crops require hot and wet climate whereas cold and dry climate is suitable for Rabi crops. Rainfall plays a significant role in the yield of crops. Rain is good for Kharif crops while the same may spoil the yield of Rabi crops. Prolonged hot weather condition may cause moisture stress in the soil and adversely affect agriculture, especially during summer time. Therefore, there is a need to understand the impacts of climate change (*viz*., changes in maximum temperature, minimum temperature, rainfall, humidity etc.) on the yield and cropping area in different cropping seasons.

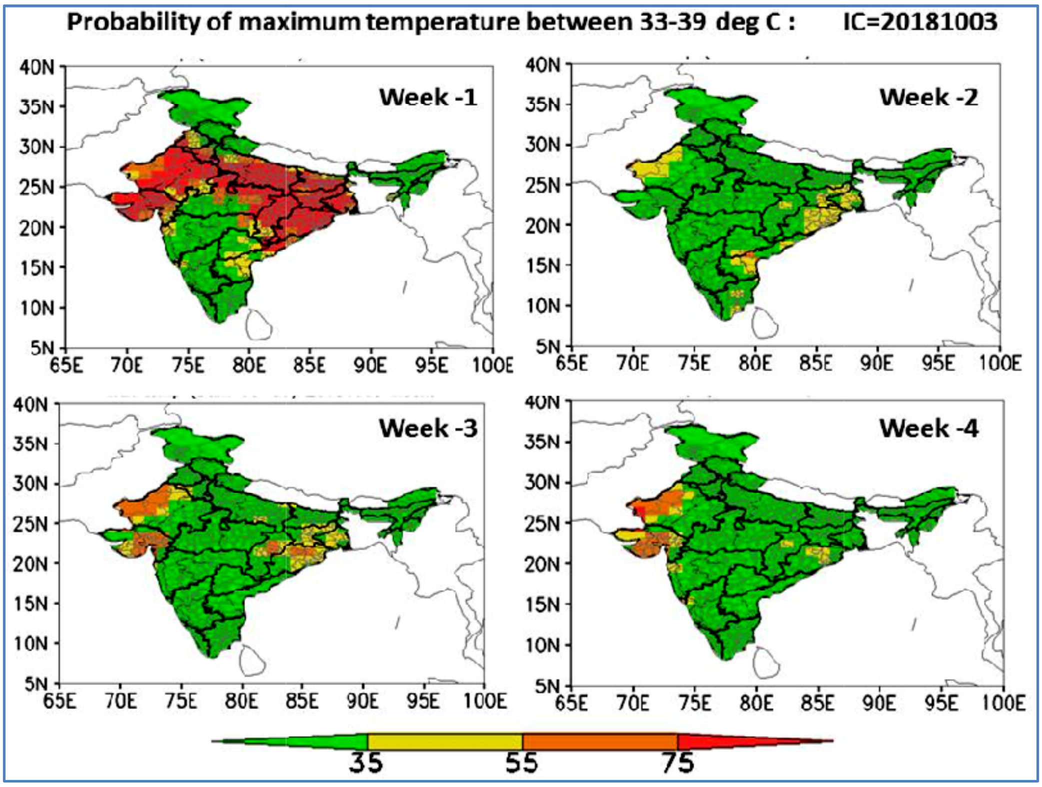


Fig. 16. Probability of maximum temperature between 33-39 °C for week 1-4 from 3rd October, 2018 initial condition

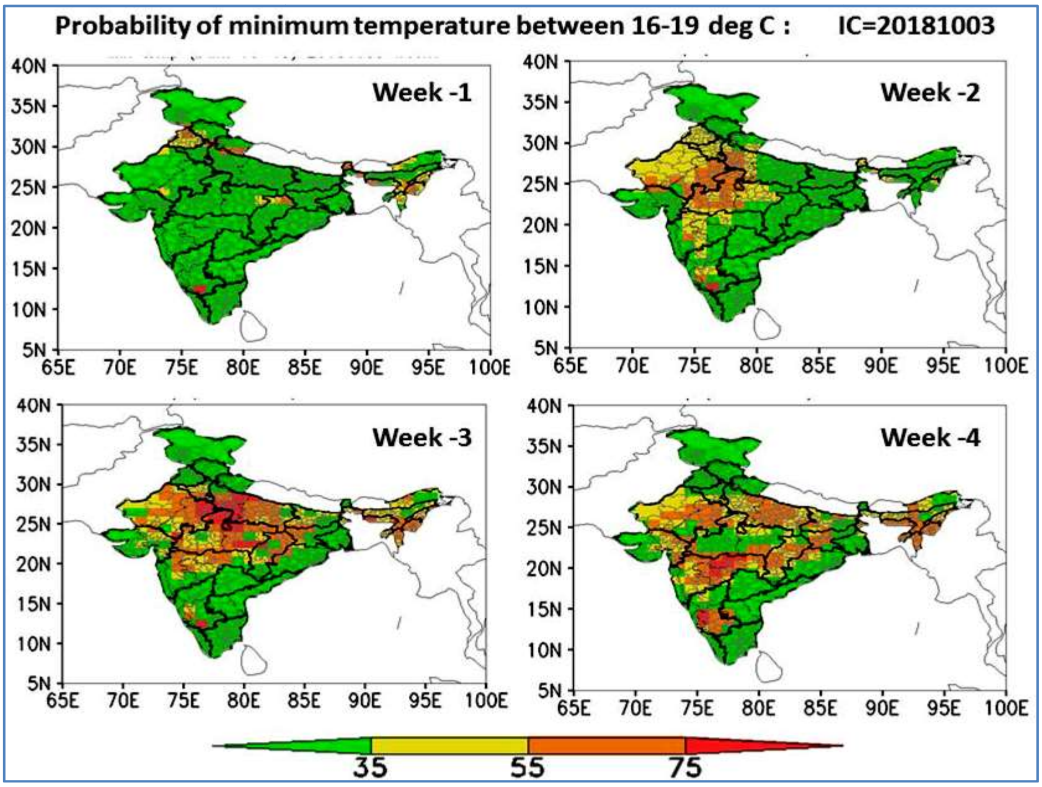
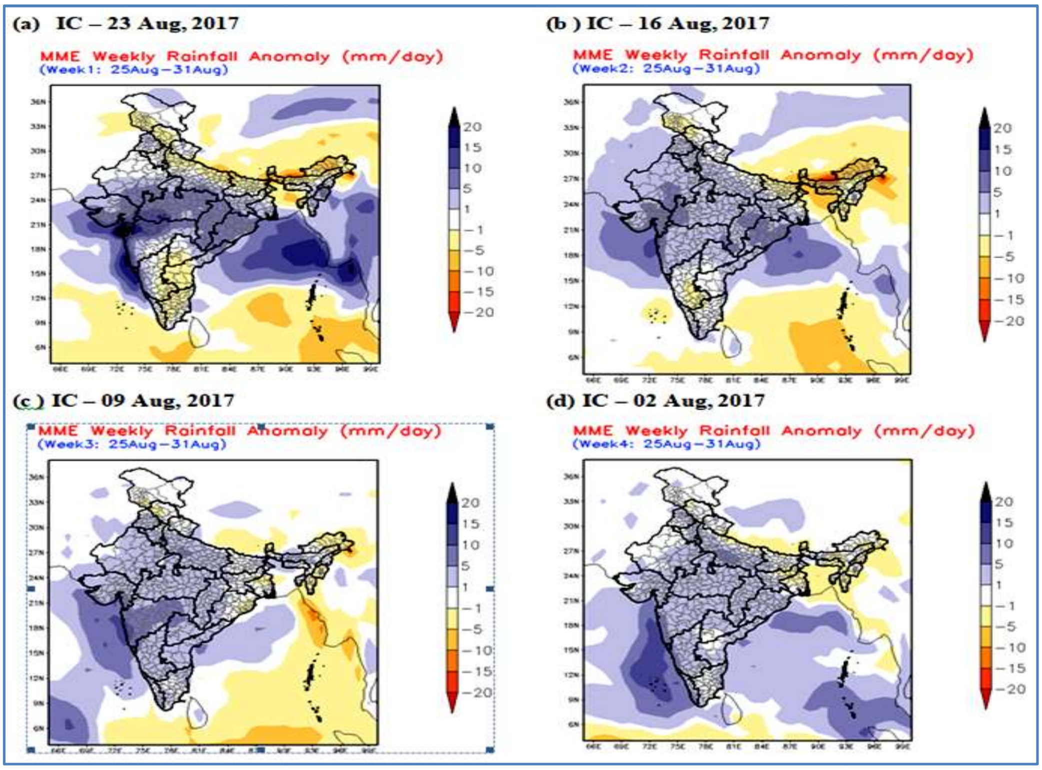
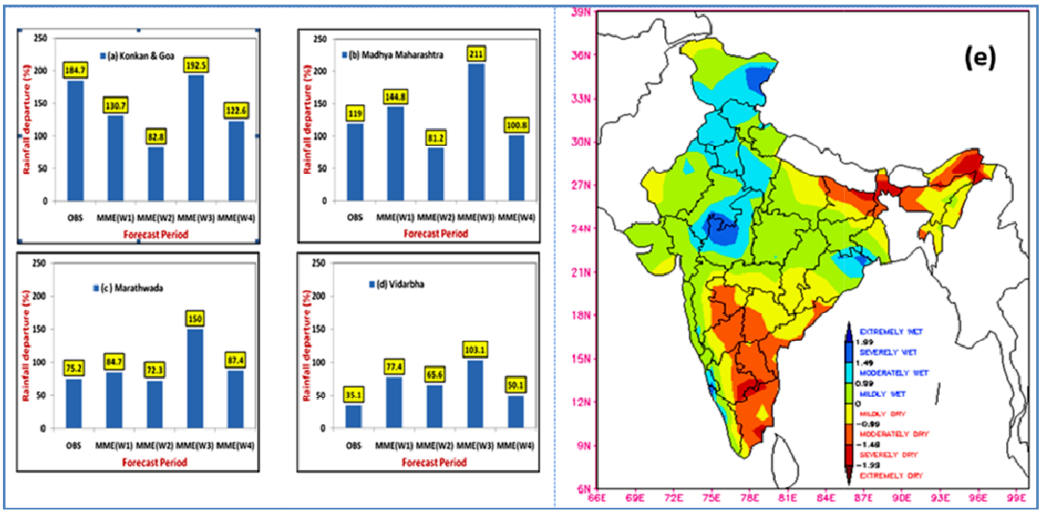


Fig. 17. Probability of minimum temperature between 16-19 °C for week 1-4 from 3rd October, 2018 initial condition

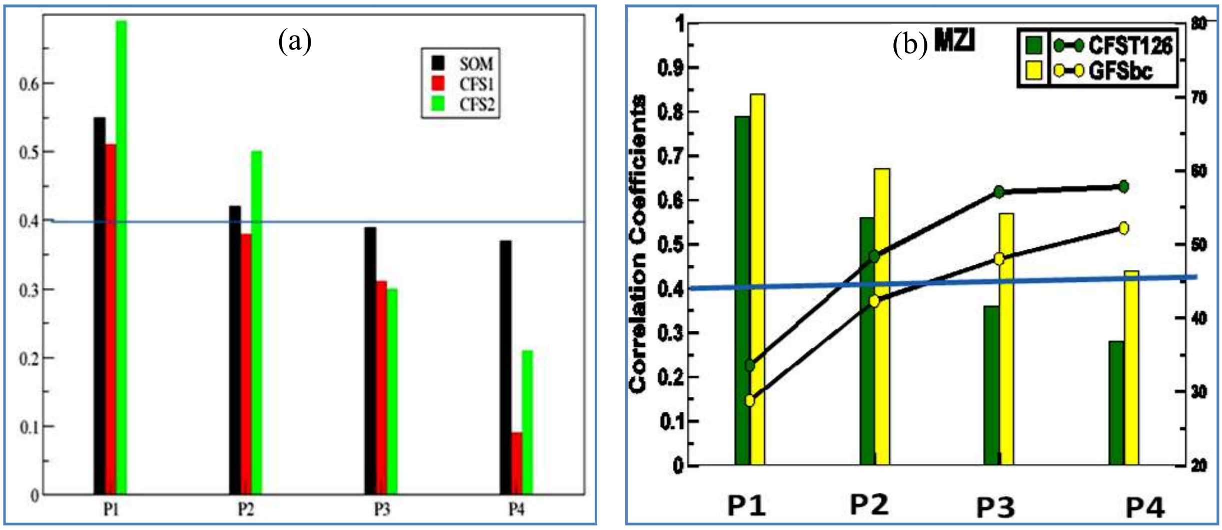


Figs. 18(a-d). Week 1 to week 4 forecast rainfall anomaly valid for the period from 25-31 August, 2017 based on IC of 23rd August, 16th August, 9th August and 2nd August respectively



Figs. 19(a-e). ERF forecast rainfall valid for the period from 25-31 August, 2017 with different lead time over 4 meteorological sub-divisions of Maharashtra, (e) Standardized Precipitation Index (SPI) outlook based on the 4 weeks extended range forecast of 11th July, 2018 and valid for the period from 12 July to 8 August, 2018

During the recent years, the focus has been made on helping small farmers in their endeavor to get better returns from farming through an improved package of practices, crop diversification according to the weather condition and increasing irrigation facilities through water conservation etc. by the Agriculture Department, Government of India. To fulfill the above goal the ERP can play a significant role by providing the real-time forecast of rainfall, temperatures, humidity and other variables in 2-3 weeks in advance. From the year 2017,



Figs. 20(a&b). (a) Plot showing the pentad (5-day average) lead-time skill for CFS model version 1 (CFS1), version 2 (CFS2) and the self-organizing map (SOM) based model for different lead times over grids averaged for monsoon zone of India (MZI). Lead time P1 indicate the skill for lead day 1-5 average, P2 indicate lead day 6-10 average etc. and (b) Plot showing improvement in skill due to SST bias correction run using GFS model (GFSbc) as compared to CFS model run at T126 resolution (CFST126). The left ordinate is for correlation coefficient and the right ordinate is for root mean square error (RMSE)

the weekly ERP products are being used by India Meteorological Department (IMD) for the preparation of Agromet Advisory Service Bulletin in every week. These Agromet advisories include the Strategic Agricultural Planning for different sub-divisions of Maharashtra state based on ERP products during the next two weeks from each forecast date. This helps the farmers to organize and activate their own resources in the best possible way to increase the crop production (Chattopadhyay *et al.*, 2018a).

12.5. *Applications in hydrology*

During monsoon season, some studies have highlighted the importance of the extended range forecasts that can have various hydrological applications (Pattanaik and Das, 2015; Sahai *et al.*, 2019). For example, the probability of excess rainfall could be given an operational outlook to hydrological forecasters. A case study for hydrological application is described below:

The real-time extended range forecast valid for an active phase during the 25-31 August, 2017 with different lead time as shown in Figs. 18(a-d), indicated large positive anomaly of rainfall over Maharashtra region**.** The quantitative forecast over the 4 homogeneous met-subdivisions of Maharashtra valid for the period did capture the active phase of monsoon over the region **[**Figs. 19(a-d)**].** Over the Konkan & Goa, which received the highest rainfall departure during the week, the ERF forecast did capture the heavy rainfall departure over the region at different lead time except for week 2 lead (IC of 16 August, 2017), where the forecast rainfall departure was less than 100% compared to the observed rainfall departure of more than 300%.

This information can be used by the city or regional planners to give quantitative precipitation forecast for a city or a block. This rainfall forecast in different lead-times could be used for quantitative flood forecast based on hydrological models.

Another product, that can be used for the hydro-meteorological application is the Standard Precipitation Index (SPI) to monitor the dry/wet condition. IMD has started preparing these products from the monsoon season of 2018 in the real time based on the extended range forecasts. The SPI outlook based on the 4 weeks extended range forecast of 11th July, 2018 and valid for the period from 12 July to 8 August, 2018 is shown in Fig. 19(e).

13. Way forward

The extended range forecast in the 2-3 week time scale based on the CFSv2 has improved our understanding of the monsoon system in general. Specifically, this technique has optimized the skill of the monsoon prediction system by improving the monitoring and prediction of tropical intraseasonal oscillations. The dynamical models reflect our knowledge of the physical system and therefore their improvement (by improving various parameterizations) indicates an overall improvement in our understanding of the various physical processes.

Dynamical models are the most sophisticated and most expensive tools with limited prediction skill in subseasonal to seasonal scale variability. Even with the limitations that several high-frequency synoptic scale events could come in the way of dynamically extended range prediction using CFS (Abhilash *et al*., 2018), it is the best tool to provide the scientific outlook beyond the weather scale. With the incorporation of a new understanding of various physical process into the model, such synoptic scale systems are better captured and the skill in the extended range forecast is increasing but with a slow rate. The community needs to accelerate improvement in the skill of forecasts. Therefore statistical correction of dynamical model forecasts using suitable techniques can lead to improved skill.

An example of how statistical corrections have improved the skill in the dynamical model is shown in Figs. 20(a&b).

The CFS model is undergoing continuous improvement in forecast skill. The skill of CFS version2 (latest one used as IITM model) is better than CFS1, but still, the skill is less than the SOM statistical model used as a benchmarking tool. However, if we do bias correction of sea surface temperature, the skill of CFS2 improves and the multimodel ensemble improves the skill over the monsoon zone (MZI) as shown in right-hand side of Figs. 20(a&b). Similarly downscaling of forecast product would be useful to enhance the skill of block-level forecast. Thus, a combination of models with multiple physics, multiple resolutions and running the model with the removal of statistical bias could potentially improve the skill in the future extended range forecast models.

In the backdrop of climate change effects on the seasonal and subseasonal variability (Sharmila *et al*., 2015b), applications of extended range prediction can be useful for farmers, dam managers and several other stakeholders. With erratic rainfall pattern and unpredictable trends, new stakeholders are showing interest and the number of potential users of this forecast are increasing every day. Several new climate sensitive stakeholders related to artificial ground water recharging (Chattopadhyay *et al*., 2019), rainwater harvesting, crop insurance, crop planning, urban planning are showing interest in this forecast as this would help the to mitigate the uncertainties arising due to projected erratic behavior of rainfall in the near future. In the coming years, effective implementation of extended range forecast should be serving as a backbone of economic growth over India.

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