Extended-range forecast of monsoon at smaller spatial domains over India for application in agriculture

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Abstract
The performance of the operational extended-range forecast (ERF) issued by IMD is evaluated for the southwest monsoon 2020. The normal onset of monsoon over Kerala (the southern tip of India) with subsequent rapid progress northward in covering the entire country is very well captured in the ERF with 2 to 3 weeks lead time. The ERF also captured very well the transitions from normal to weaker phase of monsoon in July and the active phase of monsoon during entire August with a lead time of about 3 weeks. The active monsoon condition in the second half of September associated with delayed withdrawal from northwest India was also reasonably well captured in the ERF. Quantitatively, the ERF shows significant skill up to 3 weeks on all India levels. On smaller spatial domains for 36 meteorological subdivisions (met-subdivisions) over India, the performance of category forecasts is evaluated in terms of above normal, normal and below normal. The spatial distribution of the met-subdivision level forecast skill of predicting above normal, normal and below normal categories for the 36 subdivisions during the entire monsoon season of 2020 in terms of correct (forecast and observed category matching) to partially correct (forecast and observed category out by one category) combined categories is found to be 89%, 83%, 80% and 78% for week 1 to week 4 forecasts respectively. The wrong forecasts (forecast and observed category out by two categories) are found to be between 11% in week 1 and 22% in week 4 forecast. Thus, the met-subdivision level forecast shows useful skill and is being used operationally for agrometeorological advisory services of IMD.

1 Introduction
The forecasting of southwest monsoon rainfall on an extended-range time scale (prediction of active break cycle of monsoon) is vital for issuing reliable advisories to the farming communities of the vast agro-economic country like India, where the agriculture production is directly influenced by monsoon performance (Gadgil and Gadgil 2006). The extended-range forecast (ERF) of monsoon in 3- to 4-week time scale can enable tactical adjustments to the strategic decisions that are made based on the longer lead seasonal forecasts particularly for the farmers. Since 2009, India Meteorological Department (IMD) has been issuing the operational ERF based on multi-model ensemble (MME) from different modelling products viz., National Centre for Environmental Prediction’s (NCEP’s) Climate Forecast System (CFS), European Centre for Medium Range Weather Forecasting (ECMWF) and the JMA’s ensemble prediction model (Pattanaik et al. 2013, 2019; Pattanaik 2014). In the year 2017, IMD implemented a CFS version 2 (CFSv2) coupled model for the operational ERF. As discussed in the recent paper by Pattanaik et al. (2020), the operational ERF during different intra-seasonal episodes of monsoon during 2017 and 2018 including the onset, withdrawal and transition from active to break and vice versa are mostly well captured. Just like every monsoon is different the monsoon of 2020 is also very unique in the sense that the departure of seasonal rainfall over India is found to be close to 109% of its long period average (LPA) of 88 cm, which is subsequent to the excess monsoon year of 2019 having rainfall departure of 110% of its LPA. The end of monsoon season report by IMD (IMD 2020) has shown that the monsoon season 2020 witnessed very heavy rainfall spells over many parts of India leading to flooding conditions over several parts of India. The development of the La Niña is one of the factors which helped to get above normal rainfall activity during the second half of the season.
The importance of Indian monsoon variability on crop production has also been studied by many researchers (Parry et al. 1988; Bhatla et al. 2019 & 2020a, b). Bhatla et al. (2019) have shown that the yearly crop production of Rabi and Kharif shows a clear decreasing trend with India’s monsoon rainfall distribution. Bhatla et al. (2020a, b) have also shown that the influence of El Niño/La Niña on monsoon rainfall directly or indirectly affects the Indian crop over the agro-climatic zones of the Indo-Gangetic Plain. IMD has been using operational medium- and extended-range forecasts for application in agriculture by giving agrometeorological advisories to farmers. Several studies have shown the usefulness of medium-range weather forecast in Indian agriculture (Rathore et al. 2011; Chattopadhyay et al. 2016). The agrometeorological advisories are prepared by IMD based on the real-time weather forecast and it is proved to be useful in the decision-making process in every farm operation, crop planning, rainwater harvesting, irrigation scheduling, control of pests and diseases, etc. (Chattopadhyay et al. 2018). As shown in this study in case of intermittent flash flood during the Kharif season of 2015 over Assam, different situations (flooding period) were created depending on land situation, soil types and nearness of the crop field to the source of the flood. The weather information (weather forecast) available at that time was very much useful in managing the situation arising due to the excess rainfall through real-time agrometeorological advisories. Similar to the agrometeorological advisory in the medium range, a real-time monitoring of intra-seasonal fluctuation of monsoon rainfall in the extended-range time scale can also benefit the farmers through a proper advisory. The operational ERF issued by IMD during the 2009 monsoon season was also quite useful in assessing the extent and gravity of drought conditions of the country (Tyagi and Pattanaik, 2010). Similarly, the dry spells during the recent monsoon seasons of 2017 and 2018 are also very well captured in real time (Pattanaik et al. 2020), which was used operationally for issuing advisories to farmers. A recent study by Robertson et al. (2019) demonstrated the 2-week ERF issued in real time during the June–September 2018 monsoon period for the four districts of one of the eastern states of India, viz., Bihar. These successful forecasts of onset and break phases during monsoon 2018 over Bihar are related to episodes of the Madden–Julian oscillation (MJO), which the model is shown to capture quite well at 1–2 weeks lead. Thus, the agrometeorological advisories based on operational ERF have tremendous economic value for a country like India. A study highlighting the socio-economic benefits of Agrometeorological Services in India was carried out by the reputed National Council of Applied Economic Research (NCAER), Delhi, and found that the farming communities of the country are using agrometeorological advisory service products for critical actions during their farm operations (Sharma, 2015). Considering the significant importance of ERF in providing services to the Agriculture sector, the present paper discusses the performance of ERF up to 3 to 4 weeks during the monsoon season 2020 at smaller spatial scales covering 36 meteorological subdivisions of India.

2 Model used and methodology of the study

2.1 Model used

The current operational ERF modelling system of IMD is based on the CFSv2 coupled model adopted from NCEP (Saha et al. 2014). The CFSv2 has the capability of simulating MJO in a better way compared to that of CFsv1 (Saha et. al. 2014; Pattanaik and Kumar 2014). The present ERF system of IMD was initially adopted at IITM Pune, which has the capability of predicting the active break cycle of monsoon which can be used for various applications (Sahai et al. 2013, 2015). The atmospheric version of the model is the Global Forecast System (GFS) model and the oceanic component is the GFDL Modular Ocean Model V.4 (MOM4). The suite of models consists of (i) CFSv2 at T382, (ii) CFSv2 at T126, (iii) GFSbc (bias-corrected SST from CFSv2) at T382 and (iv) GFSbc at T126 with 4 members each (total of 16 members). The present ERF system of IMD is running operationally once a week based on the initial condition (IC) of every Wednesday and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on. The hindcast runs for 17 years (2003 to 2019) along with the operational run during different phases of monsoon 2020 carried out based on the ICs of every Wednesday (Table 1). The atmosphere and ocean ICs are available from the Global Data Assimilation System (GDAS) and Global Ocean Data Assimilation System (GODAS) run at National Centre for Medium Range Weather Forecasting (NCMRWF) and Indian National Centre for Ocean Information System (INCOIS) respectively. The daily precipitation analysis over the Indian region obtained from merged rain–gauge data with the TRMM TMPA satellite-derived rainfall estimates is used for the verification of the model forecasts (Mitra et al.2009).

2.2 Methodology used for verification

In order to see the forecast skill of ERF over smaller spatial domains of 36 met-subdivisions of India, the observed weekly rainfall departure over each met-subdivision is categorized into five categories like (i) large excess (LE), excess (E), normal (NN), deficient (D) and large deficient (LD) or no rain as per the rainfall departure given in Table 2. For agricultural applications, some of the
categories are merged and formed into 3 broad categories with ‘LE’ and ‘E’ categories combined into above normal and ‘D’ and ‘LD’ into below normal as shown in Table 2. Thus, for the verification purpose over met-subdivision level, the 3 categories (above normal, AN; normal, NN; below normal, BN) are considered for preparing the contingency Table 3. As seen in Table 3, the forecast met-subdivision is considered to be correct (C) if the forecast category matches with the observed category, partially correct (PC) if it is one category out and wrong (W) if it is out by two categories or ‘AN’ becomes ‘BN’ or vice versa. Based on this contingency (Table 3), the verification skill score of the met-subdivision level forecast in terms of correct (C), partially correct (PC) and wrong (W) forecast for the entire monsoon season 2020 is calculated.

3 Observed intra-seasonal activity of southwest monsoon 2020

During 2020, the onset and progress phase of monsoon was associated with interaction with the two cyclonic storms (CSs) viz., the super cyclone ‘AMPHAN’ over the Bay of Bengal during 15–21 May and the CS ‘NISARGA’ over the Arabian Sea during 01–04 June (RSMC 2020). The southwest monsoon arrived over the Bay of Bengal on 17 May 2020, 5 days ahead of its normal date associated with the Super CS, ‘AMPHAN’. However, further progress was delayed and the onset over Kerala (Southern tip of India) was on the normal date of 1 June. The progress of the monsoon was slightly faster and it covered the entire country on 26 June, 12 days before its normal date of 08 July. The CS ‘NISARGA’ over the Arabian Sea helped in bringing the monsoon to Kerala (Southern tip of India) and also in contributing above normal rainfall during the initial period of the season, which can be seen from the daily observed rainfall over the country as a whole along with its normal (Fig. 1).

As indicated at the end of the monsoon season report (IMD 2020) and also reflected in Fig. 1, the monsoon rainfall was above normal during June for many days with faster progression of the monsoon to the north after its onset. However, during the month of July, many unfavourable features of the monsoon appeared resulting in deficient rainfall for the country. The weak monsoon in
July as shown in Fig. 1 was mainly due to the absence of any major monsoon disturbance over the Bay of Bengal and due to the prevalence of a weak cross-equatorial flow in general. The absence of any major systems caused the monsoon trough also to remain in weak condition and was to the north of the normal position or close to the foothills of the Himalayas on many days during the month. It resulted in frequent and prolonged floods over north-eastern India and Indo-Gangetic plains close to the foothills of the Himalayas. At the same time, major parts of central and northwest India received deficient rainfall (IMD, 2020). During the month of August, strengthening of the monsoon flow in the Arabian Sea led to the convergence of strong low-level westerlies along the west coast with most of the days associated with above normal rainfall (Fig. 1). The formation of many low pressure systems in the month of September led to an active monsoon trough which delayed the withdrawal of monsoon from northwest India and it commenced on 28 September from some parts of Northwest India, against its normal date of 17 September.

Thus, the main highlights of intra-seasonal variability of monsoon 2020 are early onset over the Andaman Sea and normal onset over Kerala, relatively faster progress of monsoon to north India, slightly below normal rainfall during July, very active August rainfall and active monsoon in September and delayed withdrawal of monsoon.

4 Verification of ERF during different phases of monsoon 2020

As discussed above, the following intra-seasonal episodes are considered for the verification of ERF forecast during the 2020 monsoon season.

4.1 Early onset over the Bay of Bengal and the normal onset over Kerala

During 2020, the onset and initial progress phase of the monsoon were influenced by two cyclones viz., the ‘AMPHAN’ super cyclone over the Bay of Bengal during 15–21 May and the cyclonic storm ‘NISARGA’ over the Arabian Sea during 01–04 June 2020 (RSMC, 2020). Although the onset over the Bay of Bengal was ahead of normal, the onset over Kerala was on the normal date of 1 June. The cyclonic storm ‘AMPHAN’ over the Bay of Bengal during the period from 15–21 May had resulted in the onset of monsoon over the Bay of Bengal, which can be seen from the positive observed rainfall anomalies over the Bay of Bengal in the top panel of Fig. 2 a. The same can be seen as well in the ERF for the target week of 15–21 May with 2 weeks lead time based on ICs of 13 May and 06 May (bottom panel of Fig. 2 a). However, the week 3 forecast based on the IC of 29 April for the same target week could not capture the convective activity over the Bay of Bengal as indicated with negative rainfall anomalies.

Similarly, the normal onset of monsoon over Kerala (Southern tip of Indian mainland) is also well reflected from the observed rainfall anomalies during the week from 29 May to 04 June 2020, which indicated positive anomalies of rainfall associated with the cyclonic storm ‘NISARGA’ over the Arabian Sea and the western coast of India (Top panel plot in Fig. 2 b). The same is very well predicted with 2 weeks lead time based on the initial conditions of 27 May and 20 May (bottom panel plot of Fig. 2 b) with an indication of normal onset over Kerala. In this case also, the week 3 forecast based on the IC of 13 May could not capture the positive anomalies of rainfall associated with cyclone ‘NISARGA’.

With regard to the onset of monsoon over Kerala, the daily time series of forecast rainfall over the Kerala coast averaged over the region 75–77.5E, 05–7.5 N clearly indicated an increase of rainfall from 29 May onwards compared to
Fig. 2  

(a) Observed weekly rainfall anomaly for the period 15–21 May 2020 and 3 weeks extended-range forecast rainfall anomaly for the same target week based on 13 May, 06 May and 29 April. 

(b) Same as ‘a’ but for the target week of 29 May–04 June 2020 and ICs of 27 May, 20 May and 13 May 2020.
its hindcast mean values shown in Fig. 3. Thus, the forecast based on 20 May clearly indicated the likely onset of monsoon during the week from 29 May–04 June and it may be mentioned here that IMD declared the onset of monsoon over Kerala on 1 June (IMD 2020).

4.2 Relatively faster progress of monsoon to north India

As seen from Fig. 2b above, the onset and active monsoon condition during the week was reasonably well captured for the period from 29 May to 04 June 2020. As seen from Fig. 1, the rainfall increased after the onset during the first week of June; however, it decreased for a few days after that and again increased from 11 of June taking the monsoon to the northern part of the country. During the month of June, apart from the ‘NISARGA’ cyclone, a low pressure area which was formed over the west-central Bay of Bengal (9–12 June) and its associated cyclonic circulation have strengthened the monsoon flow. To see the progress of the monsoon, the ERF of rainfall is prepared for the target weeks of 05–11 June and 12–18 June 2020, with a forecast lead time of 3 weeks (Fig. 4a–b). During the period of 05–11 June, the rainfall activity was decreased as indicated by negative anomaly over most of India (upper panel plot in Fig. 4a) which is reasonably well captured in the ERF at least for week 1 and week 2 forecasts; however, the week 3 forecast based on the IC of 20 May captured the positive anomalies over the southern peninsula but the pocket of positive anomalies over the western coastal region of India could not capture well (lower panel plots in Fig. 4a). The active phase of monsoon over the peninsula and central India during the period from 12–18 June 2020 as represented by positive rainfall anomalies (upper panel plot in Fig. 4b) was well captured in the ERF with week 1 to week 3 leads with ICs of 11 June, 03 June and 27 May respectively (Lower panel plots in Fig. 4b).

4.3 Slightly below normal rainfall during July

During the month of July, many unfavourable features of monsoon appeared resulting in deficient rainfall for the country during the period as shown in Fig. 1; the daily rainfall averaged over India indicates normal to weak spells of monsoon rainfall in many days of the month of July. The weak monsoon in July was mainly due to the absence of any major monsoon disturbance over the Bay of Bengal and due to the prevalence of a weak cross-equatorial flow in general. The absence of any major systems caused the monsoon trough also remained weak with the monsoon trough lay to the north of the normal position or close to the foothills of the Himalayas on many days during the month (IMD 2020). It resulted in frequent and prolonged floods over north-eastern India, met-subdivisions close to the foothills of the Himalayas. At the same time, major parts of central and northwest India received deficient rainfall like typical break conditions (Rajeevan et al. 2010; Krishnan et al. 2000). The Madden–Julian oscillation (MJO) is one of the oscillations in the tropics with a period typically ranging from 30–60 days (Madden and Julian 1971), which can influence the intra-seasonal variability of monsoon. During the northern summer monsoon season, there is a northward propagating component of MJO, which is commonly known
as monsoon intra-seasonal oscillation (MISO) describing the northward propagation of convective band over India (Yasunari, 1979; Sikka and Gadgil 1980; Pattanaik 2003). The Real-time Multivariate MJO series-1 (RMM1) and RMM2 indices proposed by Wheeler and Hendon (2004) are used widely for MJO forecasts. Similarly, the MISO indices proposed by Suhas et al. (2013) have defined two indices MISO1 and MISO2, which are the principal components of extended empirical orthogonal functions (EEOFs) based on a covariance matrix created from 60°E to 95°E averaged rainfall data, which show latitudinal variation in the data and the favourable region of convection. Thus, the capability of numerical models in capturing MISO/MJO signals is very crucial in capturing the active/break cycle of monsoon.

The forecast monsoon intra-seasonal oscillation (MISO) as shown in Fig. 5d based on 08 July IC indicates very weak MISO with practically no northward propagation during the period. In order to see the performance of ERF forecast for this phase of monsoon, the 3-week forecast rainfall anomaly along with the observed rainfall anomaly for the target weeks of 10–16 July, 24–30 July 2020 are shown in Fig. 5a–c respectively. As seen from Fig. 5a, the weak phase of monsoon rainfall over northwest and central India and above normal rainfall over the south peninsula and foothills of India was well captured in the ERF with a lead time of 2 to 3 weeks (Fig. 5b–c).

4.4 Very active August rainfall

The Madden–Julian oscillation of (MJO) conditions showed that it was not very coherent during June and on most days of July. Only towards the end of July up to the middle of August, the signal became active and slight eastward propagation from the Indian Ocean to the maritime continent was seen. The same was also seen in the ERF forecast based on 5 August for a period of 4 weeks as shown in Fig. 6a. As the MJO moved eastwards over the Indian Seas, the Arabian Sea and Bay of Bengal became convectively active in August. The MISO forecast based on 05 August IC also indicated northward propagation from the south peninsula and adjoining central India to central India and northern India (Fig. 6b).

The formation of five low pressure systems over the North Bay of Bengal in succession out of which four of them became well marked (4–10, 9–11, 13–18, 19–26 and 24–31 August) and their west-north-westward movement across central India up to Gujarat and south Rajasthan, active MJO and active monsoon trough mostly south of its normal position during many days in the month led to active monsoon conditions over most parts of the country and caused significantly higher than normal rainfall over central and western parts of India during the month of August (IMD 2020). The active phase of rainfall for three weeks from 07–13 August, 14–20 August and 21–27 August 2020 can
be seen in Fig. 7a–c with most parts of central and northwestern parts of India having a positive anomaly of observed rainfall in the top panel figures. The corresponding forecast rainfall anomaly also clearly captured the active phase of monsoon with 3 weeks lead time for the three consecutive active weeks from 07–13, 14–20 and 21–27 August 2020 as shown in bottom panel plots in Fig. 7a–c).

5 Active monsoon in September and delayed withdrawal of monsoon

The formation of two low pressure areas (on 13 Sept. & 20 Sept.) in the month of September led to an active monsoon trough which delayed the withdrawal of monsoon from northwest India. The withdrawal of monsoon commenced on 28 September from some parts of northwest Rajasthan, against its normal date of 17 September (IMD 2020). One low pressure area formed off north Andhra coast (eastern coastal state of India) on 13 September, which dissipated

Fig. 5 a Observed weekly rainfall anomaly for the period 10–16 July 2020 and 3-week ERF rainfall anomaly for the same target week. b Same as ‘a’ but for the target week of 17–23 July (c) for the target week of 24–30 July and d ERF of MISO phase for 4 weeks based on IC of 08 July, 2020
on 16 September; however, the monsoon trough which was shifted to the north associated with the dissipation of the system regained its near-normal position with the formation of another low pressure system on 20 over Northeast Bay of Bengal and neighbourhood. This low pressure system dissipated over east Bihar and neighbourhood on 26. Apart from the above two low pressure systems in the month, another low pressure system (6–8 September) formed over Southeast and adjoining East central Arabian Sea and in conjunction with an east–west shear zone over south peninsula caused widespread rainfall activity over south Peninsula India, Lakshadweep area and coastal and interior parts of Maharashtra during the first week of the month (IMD 2020). Circulation features favouring convergence of strong moist winds from the Bay of Bengal in the lower tropospheric levels and the alignment of monsoon trough over northeast India and adjoining east India continued to trigger the monsoon activity over the region during the month. The ERF forecast 850-hPa wind for 4 weeks based on IC of 9 September (Fig. 8a) clearly indicated the presence of east–west shear line along the latitude belt of about 18°N and non-establishment of anticyclone over northwest India at least up to 2 weeks (during 11–17 Sept. & 18–24 Sept.) indicated a likely delay of monsoon withdrawal. The weekly observed rainfall anomaly for the period from 11–17 Sept. 2020 shown in the top panel plot of Fig. 8b indicated a positive anomaly over southern and western parts of India as shown in the top panel plot. Similarly, the top panel plot in Fig. 8c also indicated a positive anomaly of observed rainfall during 18–24 September 2020 over parts of central and northwest India leading to the delayed withdrawal of monsoon. The corresponding ERF rainfall anomalies for the target weeks of 11–17 and 18–24 September 2020 also indicated similar patterns of rainfall anomalies 2/3 weeks in advance with likely delay of withdrawal of monsoon from northwest India.

6 Met-subdivision forecast for agricultural applications during 2020 monsoon

6.1 Met-subdivision mean forecast for the monsoon season 2020

Before the met-subdivision forecast skills are analysed, it is useful to see the ERF skill over India as a whole. In order to see the quantitative verification of real-time ERF over the country as a whole, the observed weekly rainfall departure for the country as a whole during the period of 2020 monsoon season is correlated with the corresponding ERF rainfall up to 4 weeks lead time. The observed weekly rainfall departures along with the corresponding ERF rainfall departure for the country as a whole with different lead times are shown in Fig. 9. As seen from Fig. 9, the ERF did capture the observed intra-seasonal variability of monsoon rainfall during different phases of monsoon such as onset, active and break phases, and also, the withdrawal phase in most of the period during the season with significant correlation coefficient (CC) between observed and forecast rainfall departure is found and is skillful up to 2 to 3 weeks.

Though the ERF of monsoon on all India level is very useful, due to the spatial inhomogeneity of the rainfall distribution for agricultural application two factors are necessary to be considered viz., (i) forecast over 36 met-subdivisions of India as shown in Fig. 10a and (ii) the skill in terms of rainfall category will be more useful compared to the actual rainfall departure. Thus, due to increased variability, the forecast skill over smaller spatial domains in terms of actual rainfall departure is not expected to provide meaningful results, particularly for agricultural applications. Thus, for verification at meteorological subdivisions level in place of actual rainfall departure, the category of the met-subdivision based on the observed rainfall departure is compared with the ERF category of the met-subdivision for different lead times. The forecast about the active break cycles of
monsoon 2 to 3 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 ongoing monsoon conditions for providing outlooks to farmers. As discussed by Pattanaik (2014), the met-subdivision-wise category forecasts for monsoon 2012 were very skilful for application in issuing agrometeorological advisories. Similarly, a recent study by Robertson et al. (2019) also demonstrated the 2 weeks ERF issued in real time during June–September 2018 monsoon period for the four districts of the state of Bihar in India (subdivision no. 9 in Fig. 10a) could predict the monsoon onset and break phase forecasts related to episodes of the Madden–Julian oscillation quite well at 1–2 weeks lead.

As discussed in Sect. 2.2, the skill of ERF for smaller spatial domains of 36 met-subdivisions of India (Fig. 10a) is categorized into three broad categories (above normal, AN; normal, NN; below normal, BN) based on the rainfall departure as shown in Table 2 and the contingency table for the verification purpose is shown in Table 3. As seen in Table 3, the forecast met-subdivision is considered to be correct (C) if the category exactly matches with the observed category and will be partially correct (PC) if it is one category out. The wrong (W) is when the forecast category is out by two or ‘AN’ becomes ‘BN’ or vice
versa. Based on this contingency Table 3, the verification skill score of the met-subdivision level forecast in terms of ‘C’, ‘PC’ and ‘W’ forecasts for the entire monsoon season 2020 is shown in Fig. 10b. Similarly, the spatial distribution of met-subdivision level mean forecast skill in terms of correct (C), partially correct (PC) and wrong (W) forecast for the 36 subdivisions during the entire monsoon season of 2020 is shown in Figs. 11a–l.

As seen in Fig. 10b, the correct percentage gradually decreases and is 58% for the week 1 forecast, 45% for the week 2 forecast, 38% for the week 3 forecast and 34% for the week 4 forecast. It may be mentioned here that in the case of normal ERF (when all the met-subdivisions are considered to be of normal (NN) category in the ERF for the entire season), the mean percentage of correct forecast during the 18-week period for 2020 is found to be about 22%. Thus, in terms of statistical score, the ERF at the met-subdivision level forecast is better than the climatology forecast till 4 weeks. It is also seen in Fig. 10b that the partially correct category forecast is 31% of the met-subdivisions in week 1,
38% in week 2, 42% in week 3 and 44% in the case of the week 4 forecast. With regard to the wrong forecast, it is 11% in the week 1 forecast to 22% in the week 4 forecast. Thus, it is very clear from Fig. 10b that the mean percentage of correct to partially correct (one category out) forecast for the total number of met-subdivisions is found to be 89% in the week 1 forecast, 83% in week 2 forecast, 80% in week 3 forecast and 78% in week 4 forecast, which is found to be very skilful for issuing the agrometeorological advisories to farmers.

The corresponding percentage of forecast categories (C, PC and W) at the met-subdivision level in the decreasing order of correct categories percentage are shown in Fig. 12a-d for week 1 to week 4 forecast respectively. In case of week 1 forecast as it is seen from Fig. 11a, most of the met-subdivisions over the south peninsula, central India and north-western parts of India show a higher percentage of correct forecast (>60%) with lower skill (≤40%) over the four met-subdivisions viz., Vidarbha; East Madhya Pradesh; East Uttar Pradesh and Nagaland, Manipur, Mizoram and Tripura (subdivisions nos. 26, 20, 10 and 4 in Fig. 10a respectively) with remaining parts of the correct category are between 40 and 60% (Fig. 11a). The week 1 forecast under the partially correct (PC) categories show the highest value (>50%) for the met-subdivision east Madhya Pradesh (subdivision no. 20 in central India in Fig. 10a) followed by the values between 30 and 50% over the other five met-subdivisions of central India including met-subdivision nos. 19, 22, 25, 26 and 27; three subdivisions over the Northwest India including the subdivisions nos. 10, 11 and 15 and all the 7 met-subdivisions over the Northeast India shown in Fig. 10a. The lower values (<30%) of partial categories are found in the remaining met-subdivisions over the eastern coastal regions, northwest India and western coastal parts of India (Fig. 11b). With regard to the week 1 forecast in the wrong categories (Fig. 11c), it is mainly below 20% over most of the subdivisions except Vidarbha and east Rajasthan (subdivision nos. 26 and 18 in Fig. 10a). The same can also be seen in Fig. 12a with decreasing order of correct percentage categories, which can also be seen from Fig. 11a with 6 met-subdivisions viz., J & K, West Rajasthan, Gujrat, Madhya Maharashtra, Tamil Nadu & Pondicherry and North Interior Karnataka (subdivisions nos. 16, 17, 21, 24, 31 and 33 in Fig. 10a) indicating correct categories of higher than 70% with lowest being the subdivision Vidarbha (no. 26 in Fig. 10a) with 33%.

Similarly, the week 2 forecast as shown in Fig. 11d-e indicated most of the subdivisions with correct to partially correct categories between 30 and 50%, whereas subdivisions over northwest India indicated a slightly lower percentage (<20%). Similarly, the wrong categories in week 2 are up to 30% except for some met-subdivisions over northwest India (nos. 18, 13, 11 and 8 in Fig. 10a) also exceeding 30% (Fig. 11f). It is also seen from Fig. 12b that except met-subdivision J & K and Himachal Pradesh (subdivision nos. 16 and 15 in Fig. 10a), the correct percentage for met-subdivisions is less than 70% with the lowest being the west Uttar Pradesh (subdivision no. 11 in Fig. 10a) with 17%. It is also seen from Fig. 11e and Fig. 12b that in the week 2 forecast, the lower percentage of partially correct categories (<30%) are mainly seen over north, north-western and south-eastern coastal states of India and higher values over the remaining regions. Comparing the week 1 and week 2 forecast in Fig. 11a-b and Fig. 11d-e it is seen that the partially correct percentage in week 1 forecast is indicated identical like the partially correct percentage categories in the week 2 forecast, whereas in week 1 forecast it is dominated with higher values of correct percentage over many subdivisions of India.

Fig. 9 The observed and forecast rainfall valid for 4 weeks during the 2020 monsoon season from June to September
When the week 3 and week 4 forecasts are considered, the higher values are dominated with partially correct categories over most of the met-subdivision followed by the correct categories (Fig. 11g-l and Fig. 12 c–d). It is also seen from Fig. 12c that the correct category week 3 forecasts show much higher values (>50%) over some met-subdivisions of India such as Himachal Pradesh, Arunachal Pradesh, Odisha, Saurashtra & Kutch (subdivisions division nos. 15, 2, 7, 22 and 31 in Fig. 10a respectively). Similarly, in the case of the week 4 forecast, the correct categories show much higher values (≈50%) over the three met-subdivisions viz., Himachal Pradesh, J & K and Saurashtra & Kutch (subdivisions division nos. 15, 16 and 22 in Fig. 10a respectively). Thus, the above analysis indicated that the category forecasts at meteorological subdivisions show skilful results for applications in agriculture planning, where it is not the quantum of rainfall that is important but the category forecast can also give useful inputs for agricultural advisories. It may be mentioned here that the soil moisture along with precipitation and temperature anomalies can play a major role to estimate...
the agricultural and hydrological droughts severity and areal extent (Saha and Mishra 2017; Pattanaik et al. 2019).

6.2 Met-subdivision level forecast for weak to active transition in July–August 2020

The skilful prediction of transitions from active to break and vice versa is very significant for providing services to the agricultural sector. With regard to the excess monsoon year of 2020, there was a relatively weak spell of monsoon during most of July and it revived during August leading to a very active phase of monsoon in August (Fig. 1). The daily average rainfall (mm) over the monsoon zone of India (MZI) as demarcated in Fig. 10a during monsoon season 2020 from June to September along with the corresponding standardized rainfall anomalies over it is shown in Fig. 13a–b. The MZI is defined based on the significant correlation with all India monsoon rainfall and is being used as the active break cycle of monsoon based on the standardized rainfall anomalies (Rajeevan et al. 2010). This is also reflected in Fig. 13a–b with daily rainfall over the monsoon core region indicated below normal rainfall during the last week of July and gradual improvement of rainfall condition in the first week of August and becoming above normal rainfall during the remaining parts of August. Since the met-subdivision level forecasts are being used for agriculture, the observed rainfall departure for 4 weeks (24 July to 20 August) indicating this transition from weak monsoon to active monsoon can be seen from Fig. 14a with many subdivisions indicating below normal rainfall mainly over northwest India and adjoining central India during 24–30 July and gradually becoming above normal rainfall over most parts of India in subsequent 3 weeks (Fig. 14b–d). The 4 weeks category forecast of rainfall from 24 July to 20 August based on the initial condition of 22 July and valid for the same period is shown in Fig. 15a–d also indicated the weak to active transition of monsoon very well. The weak to normal transition of monsoon during 2 weeks period from 24–30 July and 31 July–06 August 2020 is demonstrated for the met-subdivision level forecast. As seen from Fig. 15a–b, most of the meteorological subdivisions in northwest India changed from below normal category in the week 1 forecast to the normal category in the week 2 forecast. Over the southern peninsula, the above normal category in the week 1 forecast remains above normal in the week 2 forecast also. Based on this met-subdivision level forecast, the agro-advisory is issued to farmers, which is found to be very useful for agricultural applications as already discussed by Chhatopadhyaya et al. (2018). The skill in terms of correct (C), partially correct (PC) and wrong (W) forecast for the 36 subdivisions for this episode during the entire monsoon season of 2020 is shown in Fig. 16. As seen in Fig. 16, the correct percentage decreases slightly in week 2 and is 58% for week 1 forecast, 44% for week 2 forecast, 53% for week 3 forecast and 56% for week 4 forecast, which is higher than the mean forecast skill of monsoon 2020 (particularly during week 3 and week 4) shown in Fig. 10b. It is also seen from Fig. 16 that the partial correct category also indicated a much higher value in the week 2 forecast followed by not much variation in week 1, week 3 and week 4 forecasts. With regard to wrong forecasts are about 6% in week 1 and week 2 forecasts and about 11% in week 3 and week 4 forecasts. Thus, the ERF based on this particular initial condition outperformed compared to the seasonal mean forecast during the entire monsoon season. Furthermore, it is to be mentioned here that the district level forecasts will be more useful to farmers considering the size of a met-subdivision as comparatively big. Considering this, IMD has also started preparing the district level category forecasts experimentally both in terms of 3 categories (normal, below normal and above normal based on the rainfall departure as given in the right column in Tables 2 and 3). It is also proposed to prepare the districts level forecast of 2 weeks in near future for the agro-advisory purposes in real time in the category forecast case, which is expected to provide useful services to the farming community over more than 650 districts of India.

7 Conclusions

IMD’s operational ERF based on CFSv2 coupled modelling system has been evaluated at different spatial scales starting from All India to 36 met-subdivision levels for the 2020 monsoon season. The hindcast run for 17 years (2003 to 2019) along with the operational run for 2020 monsoon season has been carried out with every Wednesday initial conditions and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on. The operational ERF could capture the early onset of monsoon over the Bay of Bengal and the normal onset of monsoon over the southern tip of India (Kerala). The ERF also captured different intra-seasonal episodes of monsoon 2020 viz., the fast progress of monsoon northward after the onset, weak monsoon conditions in July, its transition into active monsoon conditions in August and active second half of September associated with delayed withdrawal of monsoon with a lead time of about 2 to
(a) Week 1 forecast skill

Fig. 12 a Week 1 met-subdivision level forecast skill during 2020 monsoon season as per the contingency Table 3 in terms of correct percentage, partially correct percentage and wrong percentage with decreasing order of correct percentage category. b to d same as ‘a’ but for week 2, week 3 and week 4 forecast.
(c) Week 3 forecast skill

![Week 3 forecast skill graph]

(d) Week 4 forecast skill

![Week 4 forecast skill graph]

Fig. 12 (continued)
3 weeks. Quantitatively, over the country as a whole, the ERF forecast provided useful guidance with the CC between observed and forecast rainfall departure is found to be significant till 3 weeks.

The spatial distribution of the met-subdivision level mean forecast skill of predicting above normal, normal and below normal categories in terms of correct forecasts (forecast and observed category matching) for the 36 subdivisions during the entire monsoon season of 2020 is gradually decreased from 58% in week 1 to 45% in week 2 to 38% in week 3 and 34% in week 4 forecasts. When the correct (C) and partially correct (PC) forecasts (when the forecast and observed category is out by one) are combined together, it becomes 89% in week 1, 83% in week 2, 80% in week 3 forecast and 78% in week 4 forecasts. The wrong category forecast (when the forecast and observed category is out by two) is found to be between 11 in week 1 and 22% in week 4 forecasts. Thus, the met-subdivision level category forecast is found to be very skilful for issuing the agro-advisories to farmers.

Considering the encouraging results of the met-subdivision level forecast, the same is being used operationally for agrometeorological services for the farming communities of India for 2 weeks.

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Author contribution All authors contributed to the study. D. R. Pattanaik (D.R.P.) and R. Phani (R.P.) conceptualized the idea for current research and set up the design for the study. Raju Mandal (RM) and Avijit Dey (A.D.) performed the model setup and simulations. Data processing and evaluation were done by Ashish Alone (A.A.) and Praveen Kumar (P.K.). D.R.P. and R.P. wrote the first draft of the manuscript. All authors read and agreed with the final manuscript.

Data Availability The data used in this research will be shared upon genuine request to the corresponding author.

Code availability The code used in this research may be available on request to the corresponding author.
Fig. 14 a to d Observed weekly rainfall departure at a met-subdivision level during the 4 weeks period from 24 July to 20 August 2020. Small figures indicate actual rainfall (mm) in the week and bold figures indicate normal rainfall with percentage departures given in bracket.
(a) Week 1 forecast (24-30 Jul)  
(b) Week 2 forecast (31 July-06 Aug)  
(c) Week 3 forecast (7-13 Aug)  
(d) Week 4 forecast (14-20 Aug) 

Fig. 15 a and b Week 1 and week 2 ERF based on IC of 22 July 2020, at met-subdivision level valid for 24–30 July and 31 July–06 August 2020. c and d Same as a and b but for week 3 and week 4 forecasts valid for 07–13 August and 14–20 August respectively.
Fig. 16  The verification skill score (in %) of met-subdivision level forecast in terms of correct (C), partially correct (PC) and wrong (W) for 4 weeks based on IC of 22 July 2020

Declarations

Ethics approval  This paper is not submitted to any other journal for publication.

Consent to participate  Not applicable.

Consent to publication  All the authors have consented to publish this research.

Conflict of interest  The authors declare no competing interests.

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