Active northeast monsoon over India during 2015 – an assessment of real-time extended range forecast

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Associated with strong El Niño, the southwest monsoon rainfall over India during June to September 2015 was deficit, while the northeast monsoon (NEM) during October to December 2015 over the southern peninsula was very active, particularly during November and early December. Associated with the active phases of NEM, southeast India, especially Tamil Nadu (TN) and Puducherry experienced unprecedented rainfall activity leading to devastating floods over TN, with the megacity of Chennai being the worst affected. The present study discusses the performance of operational extended range forecast (ERF) up to three weeks of this unprecedented NEM rainfall activity over the southern peninsula and TN using the bi-model average (BMA) ERF based on outputs from the Japan Meteorological Agency Ensemble Prediction System and National Centre for Environmental Prediction's (NCEP's) latest version of Climate Forecast System (CFSv.2) coupled model. The BMA forecast captured the likely delay in the onset of NEM over meteorological (met) subdivision TN and associated weak phase of monsoon during October 2015. Similarly, the BMA forecasts also captured the active phases of NEM during November and early December 2015. Although it is difficult to capture the actual magnitude of observed high-rainfall departure over a smaller domain of met-subdivision scale, the BMA-based ERF could capture the active phase of NEM over southern peninsular India, including the metsubdivision TN with a lead time of 1–2 weeks. Quantitatively, the excess NEM rainfall spells during 2015 and particularly that during 5–11 November and 12–18 November 2015 are reasonably well captured in the BMA forecast, although forecast rainfall departure was lower than the actual departure.

Keywords: Bi-model average, climate forecast system, extended range forecast, floods, northeast monsoon.

THE period October to December (OND) is referred to as the northeast monsoon (NEM) season over peninsular India, which was earlier also referred to as 'post-monsoon season' or 'retreating southwest monsoon (SWM) season'. It is associated with the seasonal reversal of surface and lower tropospheric winds from southwesterlies (during the SWM season of June–September) to northeasterlies, which set in over the Indian region in October (India Meteorological Department (IMD) 1973)[1]. In a broader perspective, it is also associated with the northern hemispheric winter circulation dominated by a strong surface high pressure region over Siberia, a primary low over eastern equatorial Pacific region, and secondary shallow lows over the north Indian Ocean. The low-level winds at 850 hPa during September–November indicated the presence of seasonal trough near 20°N in September, which gradually moved southwards to 16–17°N in October and thence to 12–13°N in November[1,2]. The reversal from southwesterlies to northeasterlies in the peninsula in October is a prelude to the establishment of NEM over the southern Indian peninsula. The five meteorological (met) subdivisions of India that received NEM rainfall during OND are shown in Figure 1 *a*, which constitute Coastal Andhra Pradesh (CAP), Rayalaseema (RYS), South Interior Karnataka (SIK), Kerala (KER) and Tamil Nadu (TN); including the Union Territory of Puducherry. The NEM season is the major period of rainfall activity over these five met subdivisions. The onset of NEM takes place first over coastal TN. This is the main rainy season for the state, accounting for about 48% of the annual rainfall. Coastal districts of the state receive nearly 60% whereas the interior districts receive about 40–50% of the annual rainfall. Figure 1 *b* shows the climatological rainfall over the five met subdivisions based on 50 years of data from 1951 to 2000 during OND season. As seen in the figure, CAP receives 1024 mm of annual normal rainfall out of which 327 mm (32%) is contributed by NEM. The normal rainfall over RYS during OND is 219 mm (31% of annual rainfall of 706 mm). SIK receives 1019 mm of annual rainfall and 210 mm during OND (21% of annual rainfall) and most of this is received in October itself. KER receives 478 mm of rainfall during OND, which is only 16% of the total annual rainfall of 2928 mm. Thus, TN is the main meteorological subdivision which accounts for 48% (OND, 438 mm) of its annual rainfall of 914 mm, making this state the major beneficiary of NEM. It is also the only met subdivision of India where rainfall realized during NEM is significantly

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more than that during the SWM season from June to September (317 mm).

Like the variability of SWM rainfall, NEM also shows year-to-year variation. Many researchers have made detailed studies on different aspects of NEM over India[3–8]. Most of these studies propounded a theory of negative relation between Indian NEM and the Southern Oscillation Index (SOI), and positive relation between NEM and El Niño, which is opposite to the relation that ENSO exhibits with the Indian SWM rainfall. The influence of the Indian Ocean Dipole Mode (IODM) on NEM rainfall variability has been examined by Kripalani and Kumar[9]. It has been shown that positive (negative) phase of IODM is associated with enhanced (suppressed) NEM activity. The enhancement of NEM rainfall by the positive dipole phase has been shown to be due to anomalously warm sea surface temperature (SST) in the western Indian Ocean, cold SST in the eastern Indian Ocean and the associated large-scale convergence extending towards South India. The suppression of NEM rainfall activity during the negative phase is due to the anomalously cold SST in the western Indian Ocean and warm SST in the eastern Indian Ocean, and the associated divergent circulation and transport of moisture towards Sumatra, away from southern peninsular India. During 2015, associated with strong El Niño, SWM rainfall over India during June to September was deficit, while NEM during OND 2015 over the southern peninsula was active, particularly during November and early December. Associated with the active phases of NEM, southeast India, especially TN and Puducherry experienced unprecedented rainfall activity during November and early December 2015 leading to devastating floods over TN. The megacity of Chennai was worst affected during the heavy rainfall spells in November and early part of December 2015. The outlook of such active or weak phase of NEM, 2–3 weeks in advance will be useful for various sectoral applications.

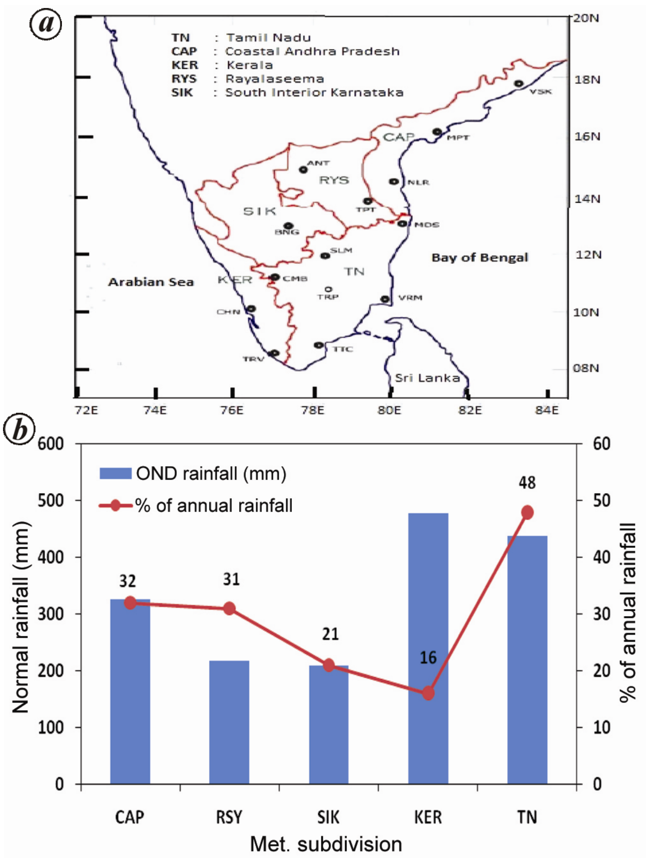

Figure 1. ***a***, Five meteorological (met)-subdivisions of India receiving northeast monsoon (NEM) rainfall during October to December season. ***b***, Normal NEM rainfall over these five met-subdivisions along with its percentage contribution.

The extended range forecast (ERF; forecast up to 3–4 weeks) in the tropics is one of the most challenging tasks in atmospheric sciences. It fills the gap between medium-range weather forecasting and seasonal forecasting, and is certainly a difficult time range for weather forecasting. On the other hand, monthly mean time average is not large enough for the atmospheric signal associated with the ocean anomalies to emerge over the atmospheric noise. At present, several global modelling centres like ECMWF, NCEP, JMA, etc. are running atmospheric general circulation model (AGCM) and coupled atmosphere–ocean models operationally. The latest generation coupled models are found to be useful in providing skillful guidance on ERF[10–12]. The current generation coupled models are also able to provide useful guidance about the active and weak phases of NEM, with a lead time of about 1–2 weeks during the 2010 and 2011 post-monsoon season[13]. Considering the skillful forecast of SWM and NEM rainfall in the extended range timescale, the present study discusses the performance of real-time ERF of active phases of NEM over TN and other met subdivisions during the 2015 post-monsoon season based on the bi-model average (BMA) of two well-known models.

Model outputs used for real-time extended range forecast

Outputs from two well-known models are used for ERF of NEM 2015. The National Centre for Environmental Prediction's (NCEP's) Climate Forecast System version 2 (CFSv2) model and JMA's ensemble prediction system (EPS) are used in the present study. Details of these model forecasts and the methodology of BMA are also given here.

NCEP's climate forecast system (version 2)

From 2004, NCEP was using the coupled model known as Climate Forecast System version 1 (CFSv1)[14]. The atmospheric component of the operational CFSv1 (T62L64/MOM3) is the NCEP atmospheric GFS model. The oceanic component is the GFDL Modular Ocean Model V.3.

CFSv1 is a fully 'tier-1' forecast system. The second version of the Climate Forecast System (CFSv2) was made operational at NCEP in March 2011. This version has upgrades to nearly all aspects of data assimilation and forecast model components of the system. The atmospheric model has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. In operational mode, the CFSv2 runs with 16 members daily[15]. The CFSv2 run based on every Wednesday and valid for the weekly forecast periods of days 2–8 (hereafter called week-1), days 9–15 (hereafter called week-2), and days 16–22 (hereafter called week-3), coinciding with Thursday–Wednesday and for the subsequent Mondays–Sundays are used.

Ensemble prediction system from JMA

The outputs from the other numerical prediction model used here is the ensemble prediction system (EPS) of JMA. Details of the EPS system are available from the website http://ds.data.jma.go.jp/tcc/tcc/news/tccnews35.pdf. AGCM is a low-resolution version (TL159) of the global spectral model (GSM) used for short- and medium-range forecasting at an approximate horizontal resolution of 110 km with 60 levels in the vertical with the topmost layer at 0.1 hPa. Persisted SST (COBE SST) anomalies and climatology of sea ice analysis (at 1.00×1.00 resolution) were used[16]. The model was run with 50 ensemble members every Wednesday, the ensemble members were generated using a combination of breeding of growing modes (BGM) and lagged average forecast (LAF). The JMA EPS model also generates forecast for 32 days based on every Thursday.

Bi-model average forecast

The hindcast mean was calculated from NCEP CFSv2 (23 years' climatology) and JMA (25 years' climatology). Based on the respective hindcast climatology of both models, the weekly anomaly field was calculated from CFSv2 and JMA models with forecast period valid for days 2–8 (week-1), days 9–15 (week-2) and days 16–22 (week-3). The anomaly fields were converted into uniform latitude–longitude grid (0.5° × 0.5°) and BMA prepared giving equal weights to both the models. The BMA forecast was generated for week-1 (Thursday–Wednesday) to week-3 (subsequent Thursday–Wednesday).

Observed northeast monsoon rainfall during October to December 2015

The onset of NEM during 2015 commenced over TN and Kerala and adjoining areas of south Andhra Pradesh (AP) and Karnataka on 28 October, which is a delay of about eight days (the normal date is 20 October). The onset of NEM is associated with the withdrawal of the SWM up to CAP (around 20°N), with the establishment of deep easterlies over TN and of seasonal low in the south Bay of Bengal adjacent to the TN coast. Once these two conditions are satisfied, the first day of fairly widespread rainfall over coastal TN would be the day of NEM onset. However, the onset of NEM is not declared before 20 October, even if the conditions are satisfied. The seasonal rainfall departure over TN during the 2015 NEM season, i.e. OND was about +52%. Also, over the five met subdivisions, NEM rainfall departure during OND was found to be about +30% from its long period average. Figure 2 shows the weekly rainfall during 2015 monsoon season averaged over the entire five met subdivisions along with the met subdivision of TN separately. As seen from the figure, NEM during 2015 showed intra-seasonal variations with the delayed onset of monsoon over TN, followed by weak monsoon rainfall almost during entire October and very active NEM rainfall during November and the first few days of December. Thus, 2015 was very active, whereas during October and December 2015 rainfall activity was subdued. Figure 3 *a–f* shows the spatial distribution of weekly mean rainfall during the main rainfall periods of NEM (29 October to 9 December). As seen from the figure, the active phase of rainfall over TN and adjoining area during the week 5–11 November, 12–18 November and 26 November–2 December 2015, witnessed high rainfall. These active spells of NEM during November 2015 over southeast India, especially TN and Puducherry experienced unprecedented devastating floods over the region, with Chennai being the worst affected. The extremely heavy rainfall over north coastal TN including Chennai occurred in three different spells, viz. 8–10 November, 12–18 November and 28 November–4 December 2015. These three heavy rainfall spells are associated with three different synoptic conditions,

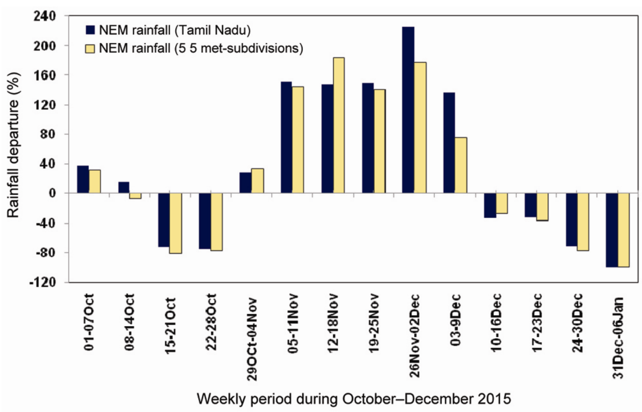

Figure 2. Weekly area weighted (five metsubdivisions shown in Figure 1 *a*) NEM rainfall departure and that over the Tamil Nadu meteorological subdivisions.

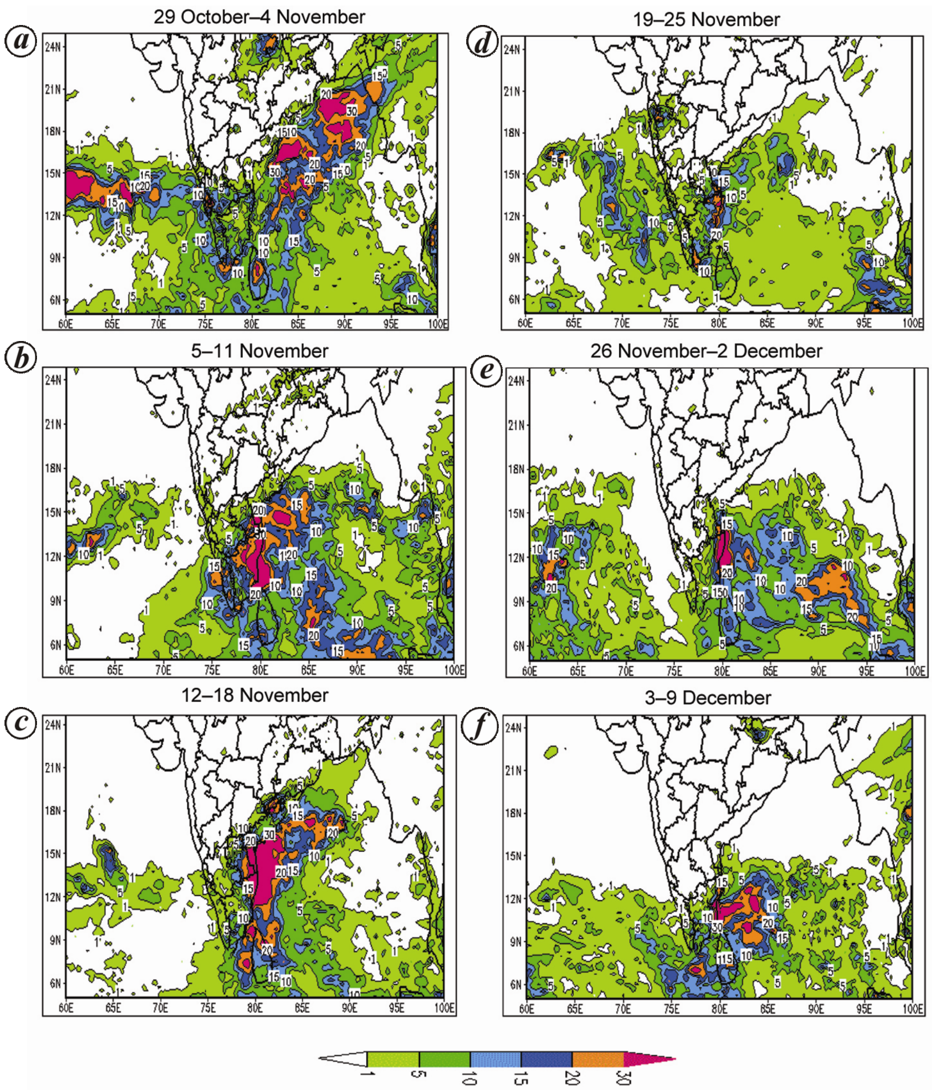

Figure 3 *a–f*. Observed weekly rainfall for six weeks during 29 October–9 December 2015.

viz. (i) deep depression over southwest Bay of Bengal during 8–10 November 2015 crossing north TN coast near Puduchhery in the evening of 9 November 2015; (ii) well-marked low-pressure area over southwest Bay of Bengal during 12–18 November 2015, and (iii) troughs of low with embedded cyclonic circulation extending up to middle tropospheric level over southwest Bay of Bengal during 28 November–4 December 2015 (ref. 17). These synoptic systems on different occasions caused very heavy rainfall (13–24 cm) at a few places, with isolated extremely heavy rainfall (>25 cm) over TN and adjoining districts of CAP. Figure 4 shows the INSAT-3D satellite images and corresponding 24 h accumulated rainfall associated with these synoptic systems for one day each of the three heavy rainfall spells. The INSAT-3D satellite imagery of the system as on 09th/0000 UTC along with the observed one-day rainfall recorded on 9 November 2015 are shown in Figure 4 *a* and *d* respectively. As seen from Figure 4 *d*, north TN and adjoining Rayalaseema received heavy to extremely heavy rainfall during 24 h ending at 0300 UTC of 9 November 2015, with some stations receiving more than 35 cm of rainfall. Even on the subsequent day (10 November 2015), a station (Neyveli of Cuddalore district) in north coastal TN recorded the highest 24 h rainfall amount of 48 cm. The second synoptic system also contributed heavy to very heavy rainfall over north TN and south CAP and Rayalaseema during 16–18 November 2015. Heavy to extremely heavy rainfall occurred along the entire north TN coastal belt during the 24 h ending at 0300 UTC of 16 November 2015, and isolated heavy to very heavy rainfall on the other days. INSAT-3D satellite imagery of the system as on 0000 UTC of 16 November 2015 and one-day rainfall valid for the same day indicated more than 30 cm of rainfall (Figure 4 *b* and *e*). The third spell of heavy rainfall was associated with two troughs of low pressure that

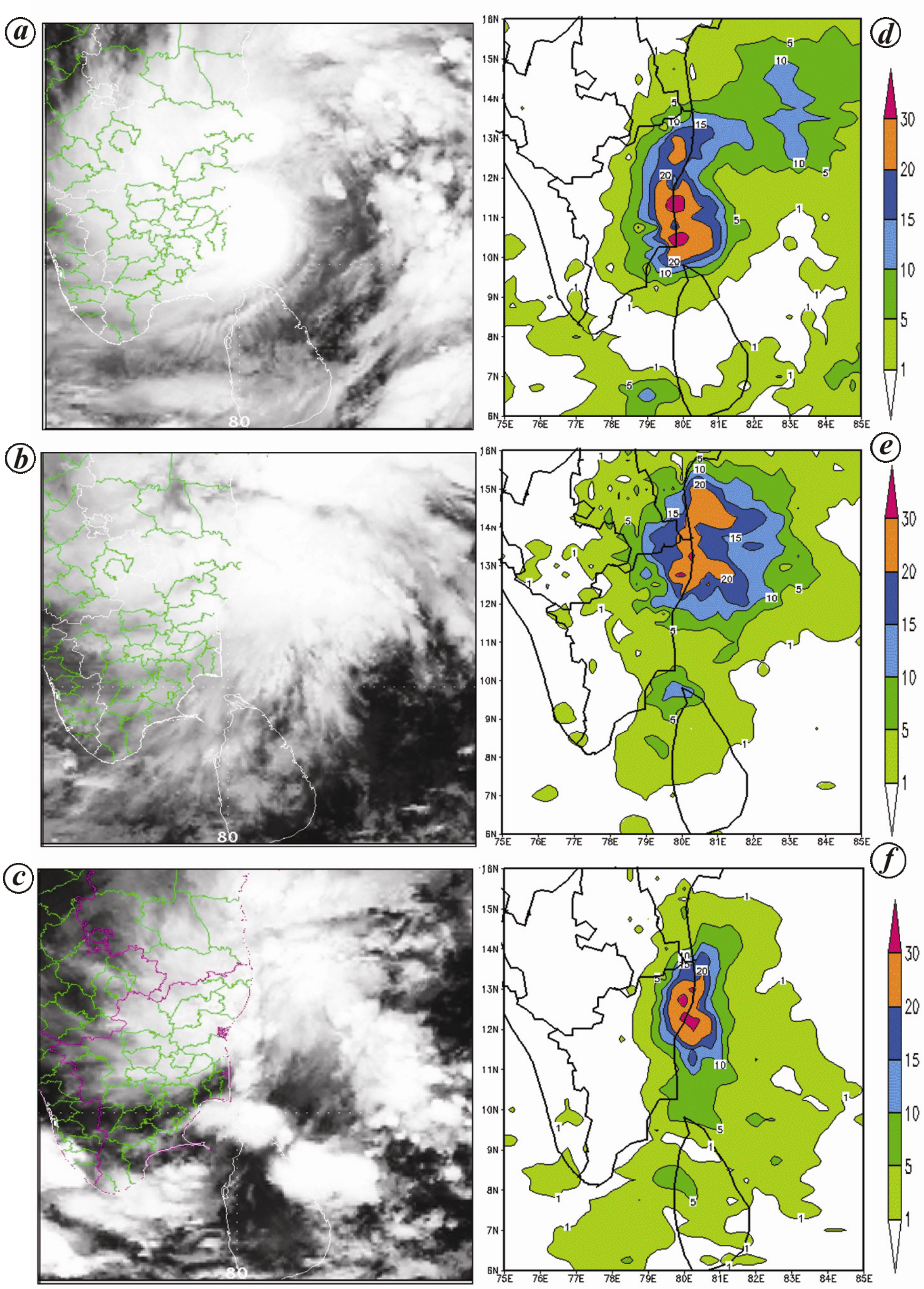

Figure 4 *a*, *b*. INSAT 3D satellite imagery and one-day rainfall on 9 November 2015. ***c***, ***d*** and ***e***, ***f*** same as ***a*** and ***b*** but for 16 November and 2 December 2015.

developed over southeast Bay of Bengal during the last week of November and moved westwards towards TN coast. The INSAT-3D imagery and associated rainfall valid for 2 December 2015 are shown in Figure 4 *c* and *f* respectively, which indicated more than 30 cm of rainfall over parts of TN. Thus, associated with these synoptic systems, excess rainfall was recorded during the weeks 5–11 November, 12–18 November and 26 November–2 December 2015 (as shown in Figure 3 *b*, *c* and *e*).

Performance of bi-model average extended range forecast

As discussed earlier, although the seasonal rainfall over TN and other NEM met subdivisions remained above normal during the 2015 season, NEM during 2015 showed large intra-seasonal variations associated with the delayed onset of monsoon over TN followed by weak monsoon rainfall almost during entire October. This was

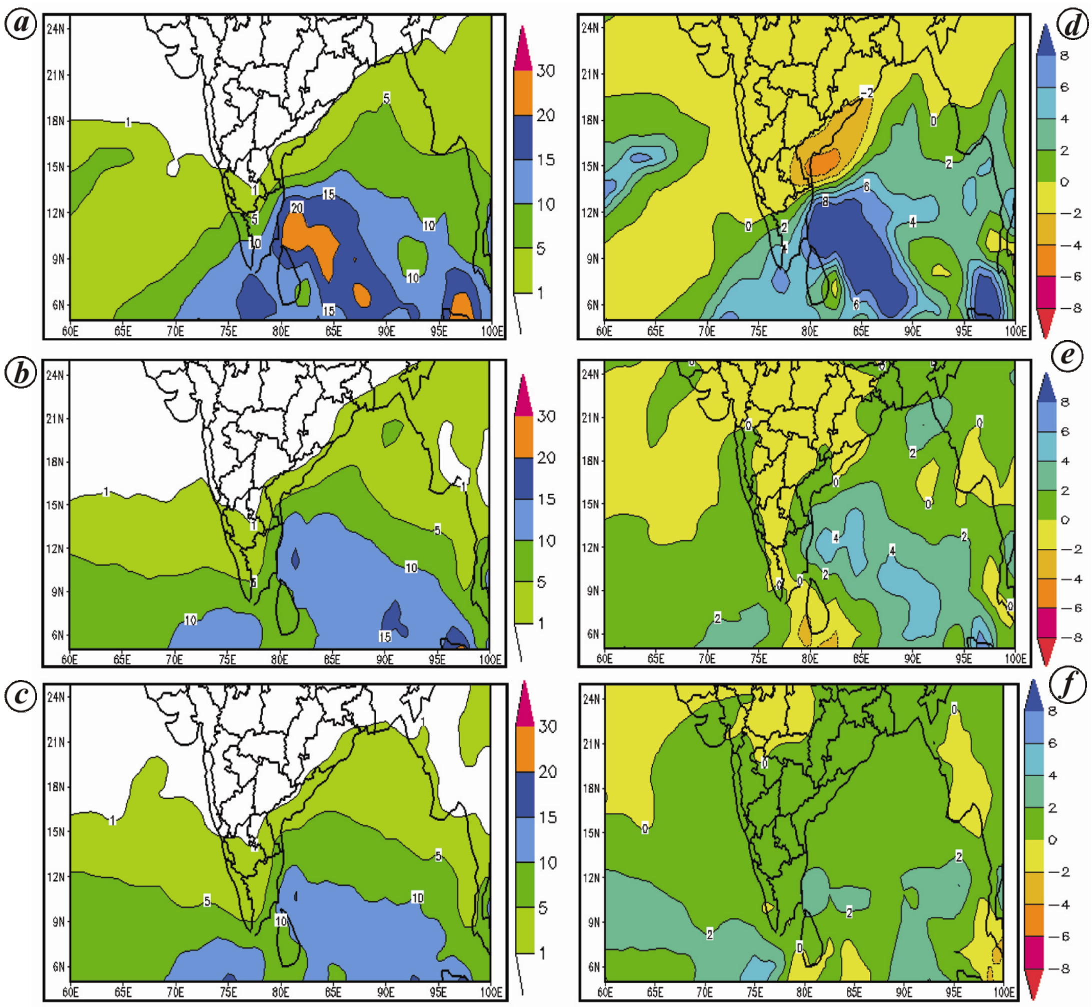

Figure 5. Biomodel average forecast weekly mean rainfall (mm/day) based on the initial condition of 4 November 2015 and valid for three weeks. ***a***, 5–11 November 2015; ***b***, 12–18 November 2015; ***c***, 19–25 November 2015; ***d–f*** same as ***a–c***, but for rainfall anomaly.

followed by very active phase of rainfall during entire November and the first few days of December. In order to study the performance of BMA forecast, particularly for the active NEM phase, Figure 5 *a–f* shows the rainfall forecast for three weeks (mean and anomaly) based on the initial condition of 4 November 2015, and valid for the period from 5 to 11, 12 to 18 and 19 to 25 November 2015. As seen in Figure 5 *a* the BMA week-1 forecast valid for the period from 5 to 11 November 2015, indicated active NEM rainfall over southeast coastal belt of India off TN coast, similar to that seen in observed rainfall valid for the same period shown in Figure 3 *b*. However, the rainfall maximum is underestimated in the BMA forecast compared to the observation. The week-2 and week-3 forecasts (Figure 5 *b* and *c*) based on 4 November 2015 and valid for the period 12–18 November and 19–25 November 2015 also indicate the active phase of NEM. The active phase of NEM during this period can also be interpreted in terms of positive rainfall anomaly over the region as shown in Figure 5 *d–f*. Similarly, based on the initial condition of 11 November 2015, the three weeks' BMA forecast valid for the period 12–18 November, 19–25 November and 26 November–2 December 2015, as shown in Figure 6 *a–f* also indicate active NEM associated with positive anomaly of rainfall. However, quantitatively it is underestimated in the forecasts compared to the observed rainfall. Thus, BMA forecast did capture the active phase of NEM during this period, although the magnitude of the forecast NEM rainfall was comparatively less both over the NEM subdivisions as a whole and over TN. The weak phase of NEM during the later part of December was also captured well in the BMA forecast (figure not shown).

Verification of quantitative rainfall forecast

For quantitative verification the observed weekly rainfall departure of NEM rainfall (area weighted rainfall over the five met subdivisions) and that over TN met subdivision

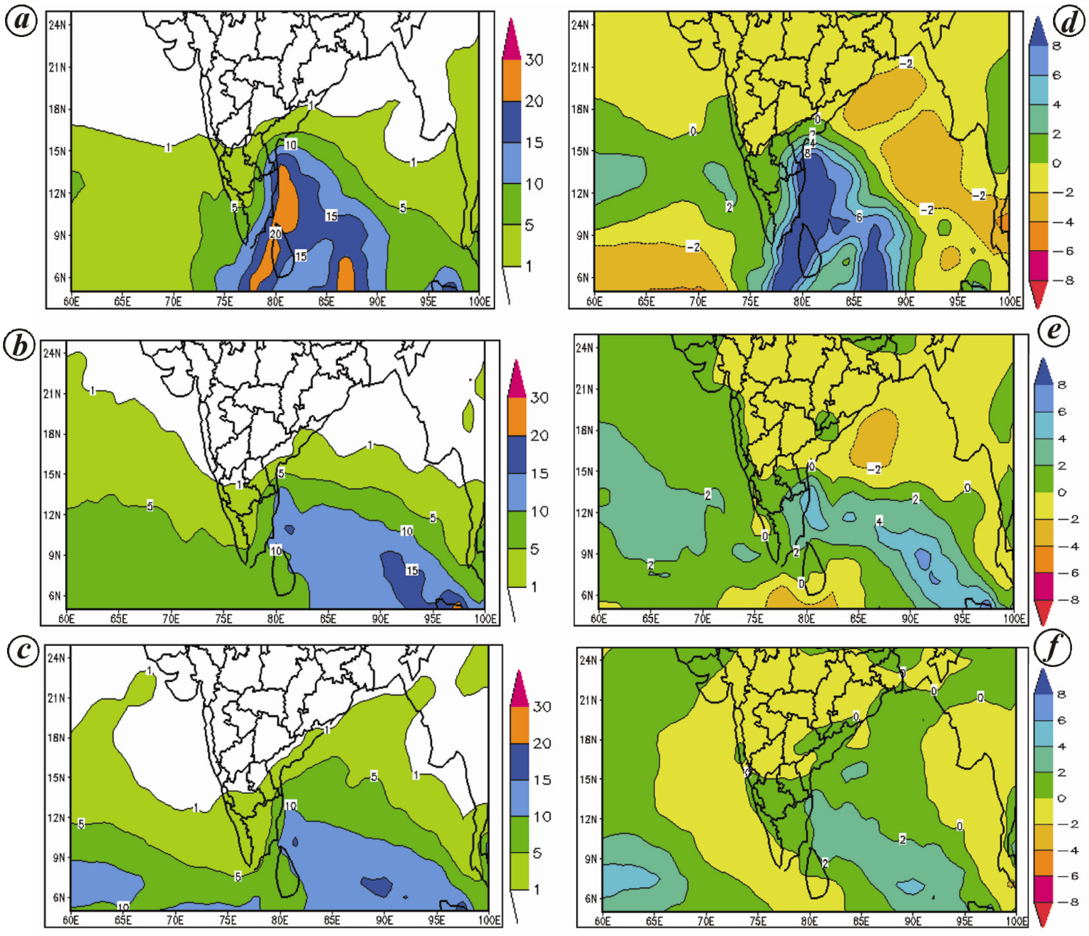

Figure 6. Biomodel average forecast weekly mean rainfall (mm/day) based on the initial condition of 11 November 2015 and valid for three weeks. ***a***, 12–18 November 2015; ***b***, 19–25 November 2015; ***c***, 26 November–2 December 2015; ***d–f*** same as ***a–c***, but for rainfall anomaly.

were calculated (Figure 2). The weekly observed NEM rainfall and rainfall over the met subdivision of TN were compared with the corresponding BMA forecast rainfall for the entire NEM season starting from 1 October to 31 December 2015. The BMA forecast rainfall was compared up to three weeks with the observed rainfall departure. In addition to the BMA forecast, the weekly forecast during the entire NEM season was also calculated for individual models (CFSv2 and JMA), and the same was compared with the observed NEM rainfall departure. Thus, the week-wise observed NEM rainfall departure was compared with the BMA, CFSv2 and JMA model forecast rainfall departure for NEM (averaged over the five met subdivisions) and the TN rainfall as shown in Figures 7 and 8 respectively. As seen from the figures, during the second half of October, NEM rainfall activity was weak associated with delayed onset, which was well captured in the BMA and individual model forecast as indicated by negative rainfall departure up to the week ending 28 October 2015. Subsequently, NEM activity revived over the entire southern peninsular, including TN, as indicated by above normal NEM during the entire six weeks from 29 October to 9 December 2015. The BMA forecast did capture the active phase during this period, although the magnitude of the forecast NEM rainfall was comparatively less both over the NEM subdivisions as a whole and over TN. Similarly, the weak phase of NEM during the later part of December 2015 was also reasonably captured in the model forecast, although it was overestimated in the JMA and BMA model forecasts. It may be mentioned here that the three excess rainfall spells over TN occurred during the weeks 5–11 November, 12–18 November and 26 November–2 December 2015, with observed rainfall departure of 151.9%, 147.6% and 225.2% respectively. The excess rainfall spells during 2015 NEM and particularly those of 05–11 November and 12–18 November 2015, were reasonably well captured in the BMA forecast, although the BMA forecast rainfall departure was lower than the actual rainfall departure (Figures 7 *a* and Figure 8 *a*). When the individual model (CFSv2 and JMA) forecasts were compared for NEM and TN rainfall, particularly during the five active weeks from 5 November to 9 December 2015, the magnitude of the rainfall forecast in the

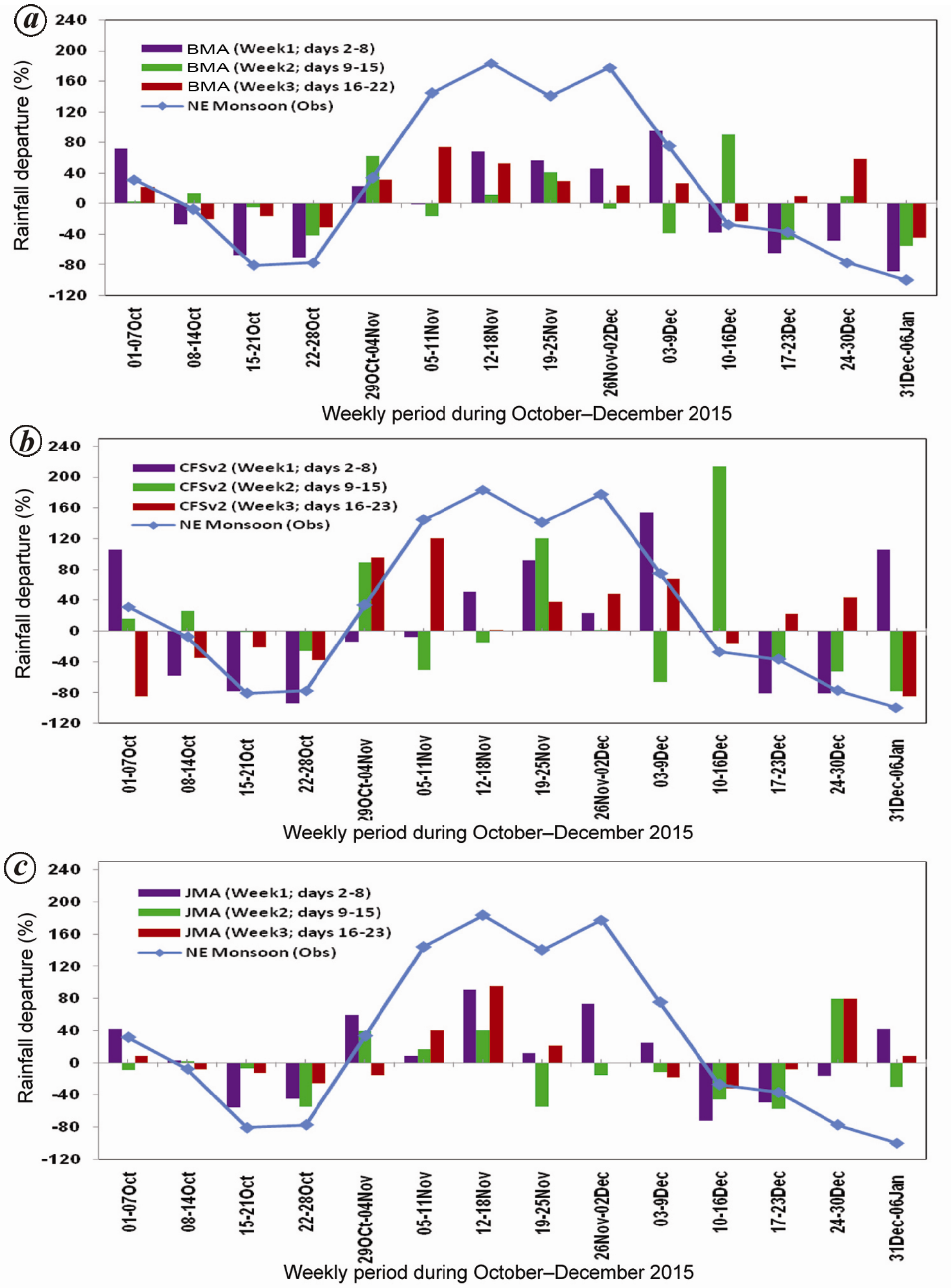

Figure 7. Weekly forecast NE monsoon rainfall departure over five met subdivisions during October–December 2015 along with model forecast rainfall. ***a***, BMA forecast; ***b***, CFSv2 forecast; ***c***, JMA forecast.

CFSv2 model was comparatively better as the departure during this period was much closer to the observed rainfall departure. However, the consistency (having the same sign in week-1, week-2 and week-3) was somewhat better in JMA forecast compared to CFSv2 forecast. To have a reasonable comparison of the forecast performance, the mean absolute forecast error (MAFE) in terms of percentage departure of weekly rainfall was calculated during the 13 weeks period for NEM rainfall as well as TN rainfall; Figure 9 is a plot of the average of MAFE for five active weeks (5 November to 9 December 2015). As observed in Figure 9 *a*, the week-1 forecast shows slightly less MAFE in case of JMA model compared to CFSv2 forecast, whereas for week-2 and week-3 forecasts, CFSv2 has slightly less MAFE compared to that of JMA. Over the smaller spatial domain like the met subdivision of TN, the JMA model forecast has consistently less MAFE compared to that in CFSv2 for week-1, week-2 and week-3 forecasts. Although one season is not sufficient for a comparison between the two models, in the present case the JMA model forecast did perform slightly better compared to CFSv2 for a smaller spatial domain

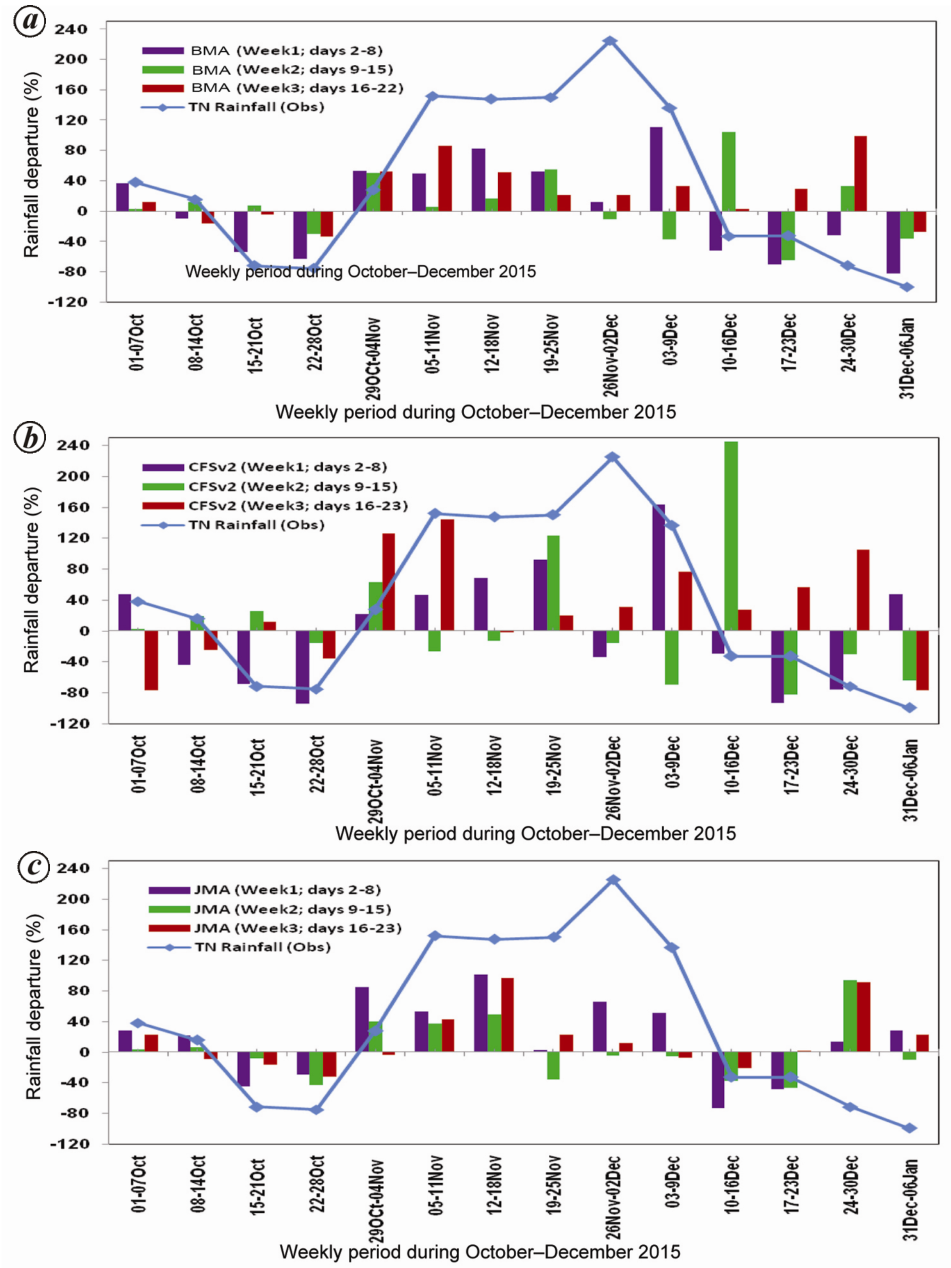

Figure 8. Weekly forecast rainfall departure over Tamil Nadu during October–December 2015 along with model forecast rainfall. ***a***, BMA forecast; ***b***, CFSv2 forecast; ***c***, JMA forecast.

like TN, similar to the case of heavy rainfall forecast event of Uttarakhand during the SWM season in June 2013 (ref. 18).

Conclusions

The 2015 NEM season experienced unprecedented rainfall activity during November and early December over the southeast region of India, leading to devastating floods over TN. The BMA forecast captured the likely delay of onset of NEM over TN. The BMA forecast also captured the active phases of NEM during November and early December 2015. Although it is difficult to capture the actual rainfall departure over a smaller domain of met subdivision scale, the BMA-based ERF was able to capture the large positive rainfall departure over NEM met subdivisions as a whole, and TN separately with 2–3 weeks in advance. The first two heavy rainfall spells covering the period 6–12 and 13–19 November 2015, were reasonably well-captured in ERF in advance. Thus, the excess rainfall spells during the 2015 NEM and particularly that of November 2015, were reasonably well-captured in the BMA forecast, although the forecast

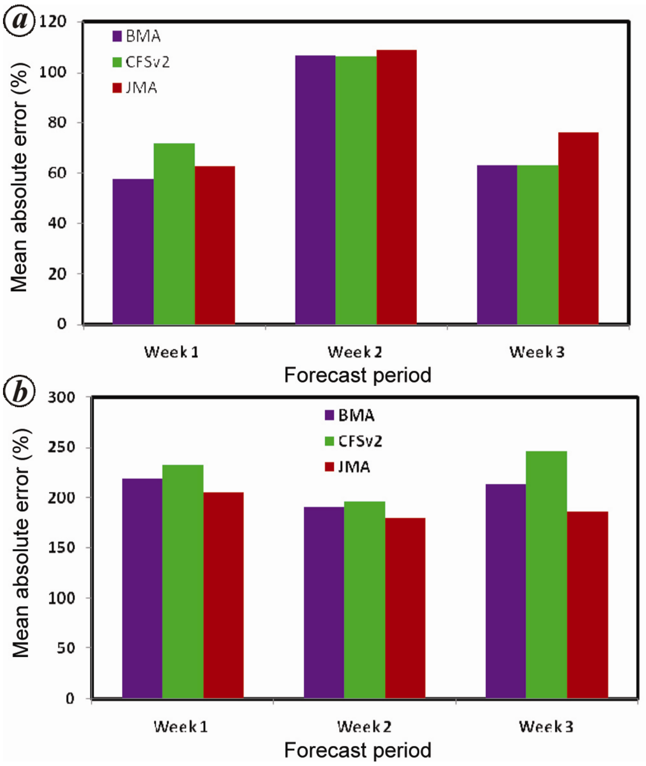

Figure 9. ***a***, Mean absolute forecast errors by BMA, CFSv2 and JMA for weekly forecast of NEM rainfall during the five active weeks from 5 November to 09 December 2015 as shown in Figure 7. ***b***, Same as (***a***), but for the Tamil Nadu rainfall as shown in Figure 8.

rainfall departure was lower than the actual rainfall departure. Although one season is not sufficient for a comparison between the two models, in the present case of forecast of NEM rainfall over TN, the JMA model forecast performed slightly better compared to CFSv2.

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