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Evaluation of forecast skill of GFS T1534 for heavy rainfall events of monsoon 2017 at district level across India

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सार – अत्यधिक वर्षा की घटनाएं प्राकृतिक आपदाएँ हैं जो विशेष रूप से भारत जैसे कृषि प्रधान देश की अर्थव्यवस्था को प्रभावित करते हैं। वर्तमान अध्ययन में, भारत के विशेष मौसम विज्ञान उप-खंडो के तहत जिला स्तर पर भारी वर्षा (>64.5 मिमी) केपूर्वानुमान में वैश्विपक पूर्वानुमान प्रणाली (जीएफएस) टी 1534 मॉडल की अनिश्चितता का मूल्यांकन ग्रीष्मकालीन मॉनसून 2017 के लिए किया गया है। आईएमडी की मदद से वर्षामापी प्रेक्षणों, कुछ भारी वर्षा के मामलों का चयन किसी विशेष मौसम विज्ञान उप-खंडो में किसी जिले में प्रेक्षित की गई वर्षा की उच्चतम मात्रा के आधार पर किया जाता है। गुणात्मक स्थानिक सत्यापन के लिए, प्रेक्षित ग्रिडेड वर्षा आंकडों का उपयोग एक उप-खंडो में किसी विशेष जिले में भारी वर्षा क्षेत्र का पता लगाने के लिए किया गया है। इसके अलावा, जिला स्तर पर विभिन्न वर्षा श्रेणियों के पूर्वानुमान में मापी प्रेक्षणों की तुलना में जीएफएस मॉडल पूर्वानुमान के मात्रात्मक सत्यापन के माध्यम से प्राप्त विभिन्न सांख्यिकीय कौशल अंकों पर भी चर्चा की जाती है। वर्तमान अध्ययन के आधार पर, यह पाया गया है कि मौसम संबंधी उप-खंडो और जिला स्तर पर हल्की से मध्यम बारिश का अनुमान लगाने में मॉडल वर्षा पूर्वानुमान काफी बेहतर है। मॉनसून 2017 के भारी और अत्यधिक वर्षा के मामलों के लिए, मॉडल कुछ मामलों में मौसम संबंधी उप-खंडोस्तर और जिला स्तर पर उचित रूप से अभिग्रहण कर सकता है, लेकिन वर्षा प्रतिरूप के स्थानिक बदलाव के कारण कई मामलों में जिला स्तर पर मॉडल पर अभिग्रहण नहीं किया जा सका। यह सुझाव दिया जाता है कि भारी वर्षा वाले स्थानों के पूर्वानुमान के लिए संभाव्य मार्गदर्शन के साथ एन्सेंपबल पूर्वानुमान का उपयोग करने की आवश्यकता है।

ABSTRACT. The extreme rainfall events are natural hazards; affect the country's economy, especially an agricultural country like India. In the current study, the uncertainty of Global Forecasting System (GFS) T1534 model in predicting heavy rainfall (>64.5 mm) at district level under particular meteorological sub-divisions of India has been evaluated for the summer monsoon 2017. With the help of IMD rain gauge observations, few heavy rainfall cases are selected based on the highest amount of rainfall observed over a district in a particular meteorological sub-division. For the qualitative spatial verification, the observed gridded rainfall data have been used to locate the heavy rainfall area over a particular district in a sub-division. Further, various statistical skill scores derived through the quantitative verification of the GFS model forecast against gauge observations, in predicting different rainfall categories at the district level are also discussed. Based on the present study, it is found that the model rainfall forecast is much better at predicting the occurrence of light to moderate rain at meteorological sub-division and district level. For the heavy and extreme rainfall cases of monsoon 2017, the model could capture reasonably at meteorological sub-division level and district level in few cases; but due to the spatial shift of rainfall pattern model could not capture at district level in many cases. It is suggested that, for the location specific heavy rainfall forecast there is a need to use the ensemble forecast with probabilistic guidance.

Key words – GFS, NWP, Global model, Heavy rainfall analysis, District-level forecast, Indian summer monsoon, Rainfall prediction skill.

1. Introduction

The southwest (June-September) monsoon season is most crucial for an agricultural country like India because more than 80% of the land area gets about 90% of its annual rainfall during this season. Crop failure, drought and more extreme famine cases due to weak or deficient monsoon become very critical to the country. Therefore, it is most important to monitor the rainfall variation (location and intensity) across the country on daily, weekly, monthly and seasonal time scale. India meteorological department (IMD) is providing heavy rainfall warnings regularly as and when it expected. A detailed regional study is practically useful for planners and other users.

Pai *et al.* (2014) opined that an increasing trend in the low-pressure monsoon days in post-1970s, is the main reason for increasing trends in the heavy (HR) and very heavy rainfall (VHR) events over South-central India (SCI) & North-central India (NCI); and decreasing trends in HR events over North-east India (NEI) during 1956-2010. Goswami *et al.* (2006) study, using daily rainfall data (1951 to 2000) shows a notable rising trend in the magnitude and frequency of extreme rainfall events and a decreasing trend in the moderate rainfall events over central India. However, no significant trend observed in the seasonal mean rainfall. One of the recent studies by Guhathakurtha *et al*. (2015) also indicates that the frequency of moderate rainfall events (5 mm ≤ daily rainfall < 100 mm) decreased significantly during the period 1951-2010 over the monsoon core region of India. In contrast, no significant changes observed in the frequencies of heavy (daily rainfall >100 mm) or very heavy rain (daily rainfall > 150 mm) during the southwest monsoon season. An SST variation over the tropical Indian Ocean is one factor for extreme rainfall events over Indian monsoon regions (Rajeevan *et al.*, 2008).

Senroy *et al.* (2007) analyzed hourly precipitation data for 78 stations from 1980 to 2000; found that the diurnal spatial patterns result from the interaction of local orography and convectional processes. The maximum total precipitation time is mostly about half an hour to 1 hour before the maximum frequency. There have been a very few studies on heavy rainfall forecast in terms of spatial and temporal shift during the Indian summer monsoon based on real-time operational NWP models. The success rate of Weather Research and Forecast (WRF) model significantly reduced at higher rainfall categories for localized and non-localized extreme rainfall events (EREs) and the forecast misses the majority of rainfall events (Mohapatra *et al.*, 2017). Decreasing grid spacing in mesoscale models to less than 10-15km generally improves the results' realism but does not necessarily significantly improve the objectively scored accuracy of the forecasts (Mass *et al.*, 2002). The study of western disturbances by Dimri *et al.* (2009) suggested that the model has a systematic easterly bias, though the magnitude is small. It also observed that the advection simulated in the model is not strong enough to advect the system with the observed speed. There is a need to maximize the data ingest in the NWP model with better data assimilation schemes to improve the rainfall forecast skill (Bhowmik *et al.*, 2007).

There had been high demand from farmers for the weather forecast at district, block or even up to village level. In this direction, the India Meteorological Department (IMD) started issuing quantitative district level weather forecast for eight weather parameters on an operational basis up to five days from June 2008. Till 2014 the rainfall forecast is generated based on the Multi-Model Ensemble (MME) technique. At present, the Global Forecast System **(**GFS) T-1534L64 with a horizontal resolution of (0.125° × 0.125°) is utilized for the operational medium-range weather forecast in IMD. So the district and block level weather forecasts are generated up to 5 days by using the GFS T1534 model output. The forecast products are generated by Numerical Weather Prediction (NWP) division, IMD before their value added by the respective Regional Meteorological Centers (RMC's) and Meteorological Centers (MC's). After that, send to 130 Agro meteorological Field Units (AMFU) to prepare district-level advisories. On a particular day, the value addition is done manually by considering the local climatology and prevailing synoptic conditions of a specific region, Satellite/DWR products and NWP model forecast valid for the day. As the quality of agro-met advisory depends on the weather forecast accuracy, the forecast verification plays a vital role in identifying the estimates' accuracy and further improvement. Among the other extreme weather events, the heavy rainfall cause flood conditions mostly during monsoon season and hence there is a need to predict these extreme events well in advance. There are many heavy rainfall episodes during 2017 monsoon season and real-time forecasts have issued to denote them as described above. The performance evaluation of the model forecasts is limited to a few specified heavy rainfall events in this paper, but the study's novelty and robustness are maintained. The details about the data used and methodology followed in forecast generation and its verification result, with discussion and conclusions, are explained in the following consecutive sections.

2. NWP model used in the study

The Numerical Weather Prediction (NWP) model used in this study is a global spectral model with updated dynamics and physics (Kanamitsu, 1989 & 1991; Kalnay *et al.*, 1990; Moorthi *et al.*, 2001; Durai *et al.*, 2010a; Saha *et al.*, 2010) adopted from National Centre for Environmental Prediction (NCEP). This GFS model conforms to a dynamical framework known as the Earth System Modeling Framework (ESMF) and its code restructured to have many options for updated dynamics and physics. The details of the physics and dynamics options of the global model GFS T1534L64 discussed by Sridevi *et al.* (2019). More information about the GFS model is available at http://www.emc.ncep.noaa. gov/GFS/doc.php.

TABLE 1

Rainfall categories based on daily rainfall

S. No.	Terminology	Rainfall range in mm	Nomenclature
1.	Light rainfall (LRF)	0.1-15.5	HR1
2.	Moderate rainfall (MRF)	15.6-64.4	HR2
3.	Heavy Rainfall (HRF)	> = 64.5	HR3

TABLE 2

List of subdivisions and number of districts considered in each region

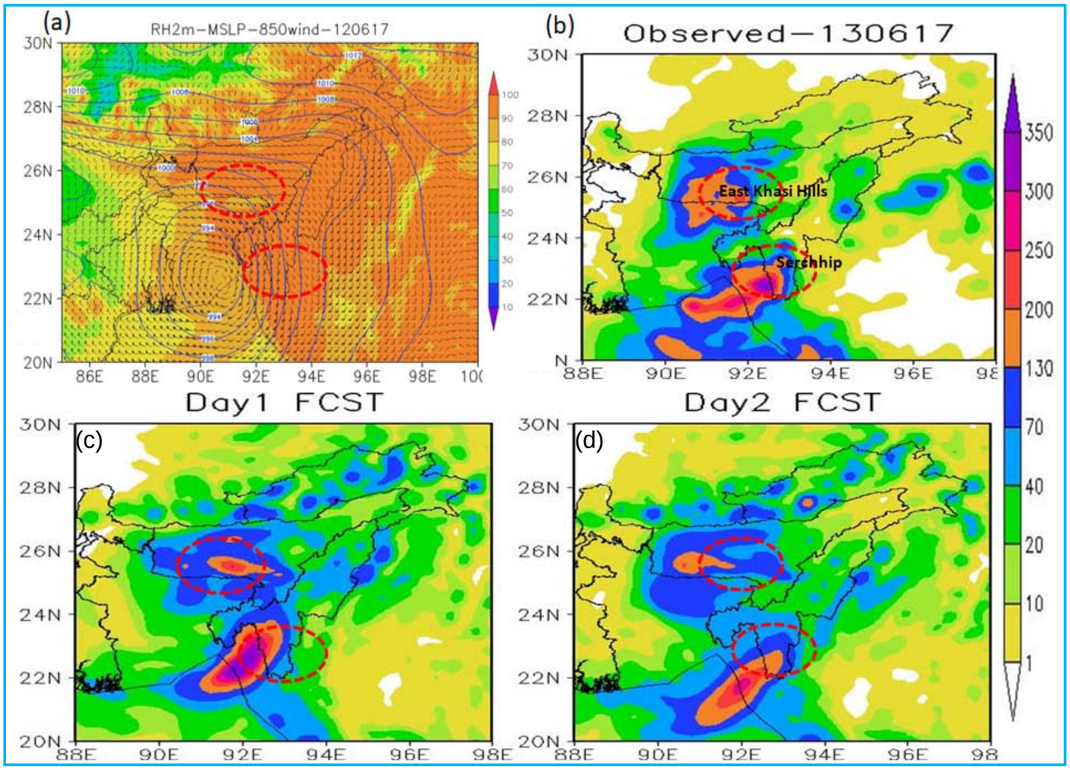
Regions	Sub-divisions	Total number of districts
North India (NI)	Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Punjab, Haryana-Delhi-Chandigarh, West Uttar Pradesh, East Uttar Pradesh	158
North East India (NEI)	Arunachal Pradesh, Assam-Meghalaya, Manipur Mizoram, Nagaland, Tripura, Sub Himalayan West Bengal-Sikkim	54
West India (WI)	East Rajasthan, West Rajasthan, Gujarat, Saurashtra & Kutch, Konkan and Goa, Daman and Diu, Madhya Maharashtra	74
East India (EI)	Gangetic West Bengal, Odisha, Jharkhand, Bihar	114
Central India (CI)	East Madhya Pradesh, West Madhya Pradesh, Chhattisgarh	78
South India (SI)	Coastal Andhra Pradesh, Telangana, Rayalseema Marathwada, Vidarbha, Coastal Karnataka, North Interior Karnataka, Kerala, Tamilnadu & Pondicherry, Andaman and Nicobar Islands, Lakshadweep	120
All India (AI)		608

The GFS-T1534L64 model is operational at ~ 12.5 km horizontal resolution and with 64 hybrid sigma-pressure layers in the vertical reaching top layer at 0.27 hPa. The initial conditions are generated using Hybrid Ensemble Variational (EnVar) Global Data Assimilation System (GDAS), operational at National Center for Medium-Range Weather Forecasting (NCMRWF), India.

3. Data and methodology

The verification of precipitation is an essential part of the model's quality assessment. The daily rain gauge observations for 660 stations (districts) of 36 sub-divisions located across the Indian subcontinent are collected from India Meteorological Department, for the summer monsoon (June, July, August and September) 2017. The GFS T-1534 model outputs have been used to generate the forecast at all the 717 districts. Initially, the outputs extracted for the Indian domain (0° N - 40° N and 60° E - 100° E), then the estimates are obtained for all the 717 districts by downscaling the model forecast. The district-level weather forecasts are obtained by averaging model forecast values of a particular meteorological parameter at the grid points falling within a specific district's boundaries.

The daily forecast data over Indian monsoon region (0 - 40° N and 60° - 100° E) from the GFS T1534 model at 12.5 km resolution for 122 days from 1st June to 30th September, 2017 are used to identify rainfall pattern over a particular district. As per IMD's criteria (IMD, 2015), the heavy rainfall said to occur over a station, if the accumulated rainfall during past 24 hrs as recorded at 0830 hrs (IST) is 64.5 mm or more. The GFS model uncertainty in predicting heavy rain (> 64.5 mm) (HRF) over few districts under specific sub-division during summer monsoon 2017 has been evaluated in this study. Total 943 heavy rainfall days are identified, using rain gauge observations of 660 districts under 36 sub-divisions during the summer monsoon 2017. A few cases selected from these heavy rainfall events based on the maximum rainfall amount observed over a district falling within a particular sub-division. The district-level rainfall forecast has been verified against rain gauge observations up to five days. The spatial verification of heavy rainfall carried out for 0000 UTC model run against daily rainfall observations at 25 km. The daily gridded rainfall observations at 25 km resolution based on the merged rainfall data combining gridded rain gauge observations prepared by IMD Pune for the land areas and Global Precipitation Measurement (GPM) satellite estimated rainfall data for the Sea areas (Durai *et al.*, 2010b; Mitra *et al.*, 2014). The 850 hPa wind, 2 m Relative humidity (RH), mean sea level pressure (MSLP) and Geopotential height from 0000 UTC analysis, are used for identifying the synoptic systems on the particular day of heavy rainfall case.



Figs. 1(a-d). Extreme rainfall (204.8 mm) observed on 130617 over East khasi hills (107 mm fcst) district of Meghalaya Subdivision and for extreme rainfall (242.2 mm) observed on the same day over Serchhip (Mizoram) district of NMMT subdivision, during summer monsoon 2017. (a) Mean sea level pressure (MSLP-contours), 850 wind, 2 m Relative Humidity (RH- shaded) on 12th June from analysis (b) observed rainfall on 13th June (c) GFS model day1 rainfall forecast and (d) GFS model day2 rainfall forecast

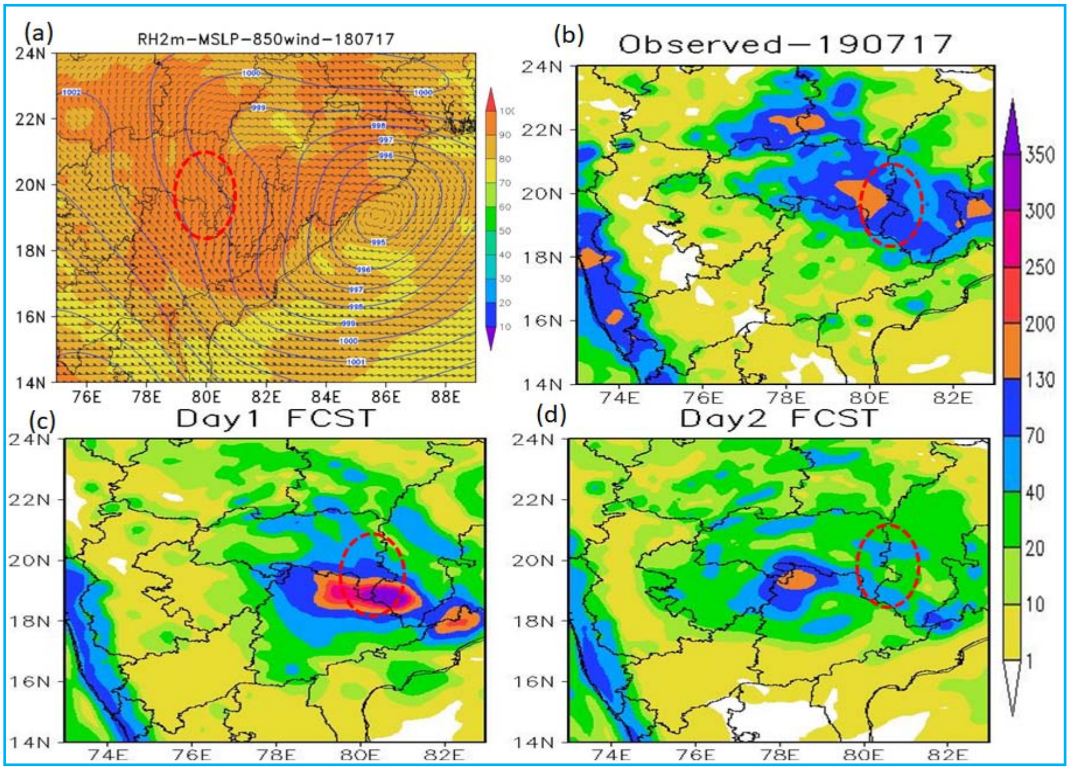
The Frequency Bias Index (FBI) and Percentage of Accuracy (POA) of district-level rainfall forecast computed for three rainfall categories (Table 1), *i.e.*, light (< 15.4 mm) rainfall (HR1), moderate (15.5 - 64.4 mm) rainfall (HR2) and heavy (64.5 - 115.4 mm) rainfall (HR3) based on IMD classification (IMD 2015) for day1 to day5. The FBI measures the frequency of forecast events to the frequency of observed events (http://www.cawcr.gov.au/projects/verification/). The FBI score calculated for the districts is distributed into six homogeneous regions, *i.e.*, North India (NI), North East India (NEI), West India (WI), East India (EI), Central India (CI) and South India (SI) as given in Table 2.

4. Results and discussion

The rainfall is highly variable in space and time and strongly influenced by orographic forcing. The correct rainfall forecast requires a numerical weather prediction (NWP) model of high horizontal resolution. This study's main objective is to identify the possible reasons behind the low skill in predicting heavy rainfall at the location (district level) in day-to-day weather forecast obtained from high-resolution global forecast system (GFS) model during monsoon 2017. A few heavy rainfall cases are selected to examine the heavy rainfall (>64.5 mm) prediction skill of GFS model at district level during summer monsoon 2017, based on the maximum amount of rainfall observed over a district under a particular sub-division. The 0000 UTC analyses show high relative humidity (70 to 100%) over the entire heavy rainfall regions.

4.1. *Case studies*

Case 1 : Extreme heavy rainfall of 204.8 mm observed over East Khasi hills district of Assam-Meghalaya sub-division on 13th June, 2017 [Fig. 1(b)]. The synoptic system responsible for this heavy rainfall event was monsoon depression over south Bangladesh & neighbourhood on 12th June, 2017 [Fig. 1(a)]. In this case, the model successfully simulated the extreme heavy rain of amount more than 200 mm over East Khasi hills district in the day1 forecast [Fig. 1(c)], which is very close to the observed rainfall and the same is better captured in the day2 (130-200 mm) model forecast [Fig. 1(d)] also. Here the model predicted the extreme rainfall two days in advance.



Figs. 2(a-d). Same as Fig. 1 but for heavy rainfall (120.8 mm) observed on 190717 over Gadchiroli district of Vidarbha sub-division

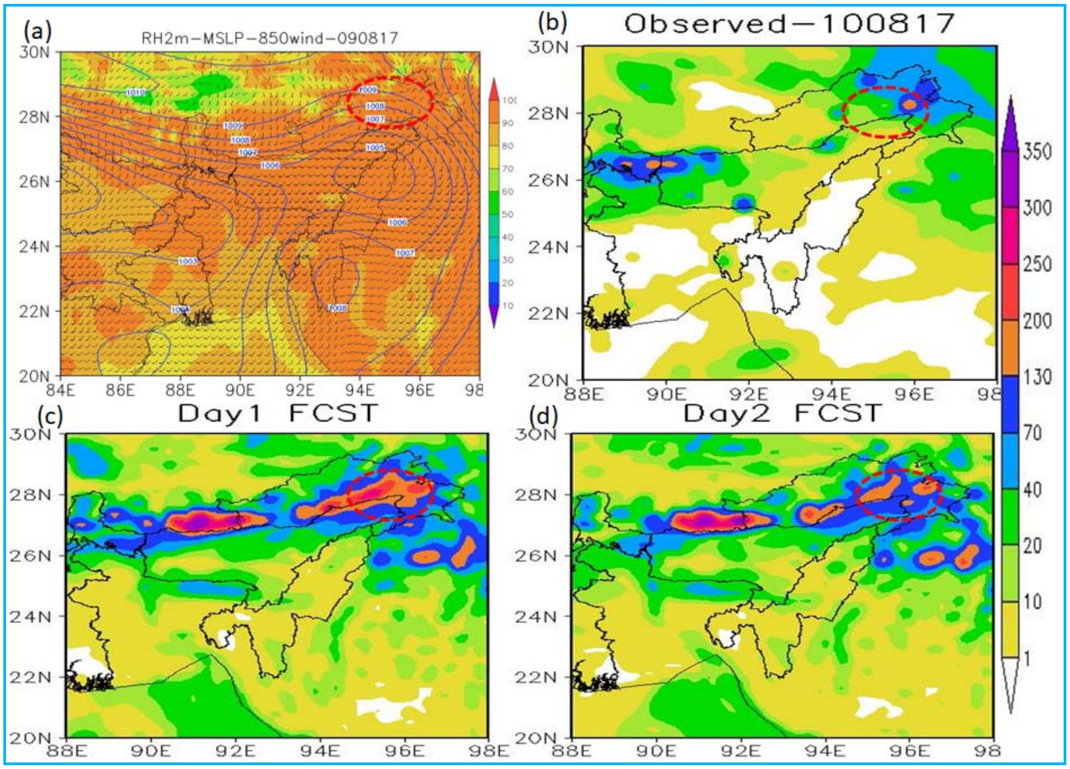
Due to the same synoptic conditions discussed above, an extreme heavy rainfall of 242.2 mm observed over Serchhip district of Mizoram under Nagaland, Manipur, Mizoram and Tripura (NMMT) subdivision on 13th June, 2017 [Fig. 1(b)]. The model predicted the same pattern over the same district on the same day and simulated extreme rainfall pattern and amount (>200 mm) is very close to the observed rainfall in the day1 forecast [Fig. 1(c)], however in the day2 forecast [Fig. 1(d)] intensity (130-200 mm) is slightly underestimated. In this case, the model predicted the Extreme rainfall pattern and amount in the day1 & day2 forecast at sub-division but underestimated the rainfall intensity (89 mm) at the district level in day2.

Case 2 : Very heavy rainfall of 120.8 mm observed over Gadchiroli district of Vidarbha sub-division on 19th July, 2017 [Fig. 2(b)]; model predicted the same on the same day over the same district. This heavy rainfall event occurred due to the formation of the depression over north-west & adjoining west-central Bay of Bengal and coastal areas of Odisha and the adjoining regions [Fig. 2(a)]. In this case, the model correctly predicted the heavy rainfall amount in the day1 [Fig. 2(c)] forecast and slightly underestimated in day2 [Fig. 2(d)] forecast (70 mm).

Case 3 : Extreme rainfall of 261.4 mm observed over Lower Dibang valley district of Arunachal-Pradesh sub-division on 10th August, 2017 [Fig. 3(b)], due to the passage of monsoon trough at mean sea level from Ferozpur, Karnal, Fursatganj, Digha, Daltongang and thence south-east wards to north-east Bay of Bengal [Fig. 3(a)]. The same pattern predicted by the day1 [Fig. 3(c)] and day2 [Fig. 3(d)] model forecast. In this case, the model overestimated the rainfall amount in the day1 spatial (sub-division) estimates.

Case 4 : Very heavy rainfall of 151.8 mm observed over Mumbai district of Konkan-Goa sub-division on 29th August, 2017 [Fig. 4(b)]; model simulated it over the same area on the same day [Fig. 4(c)]. There was an offshore trough observed over this region on 28th and 29th August [Fig. 4(a)], under the influence of this synoptic system the heavy rainfall occurred. The day2 model forecast shows the heavy rainfall intensity in the order of 70-130 mm [Fig. 4(d)]. In this case, model correctly predicted the very heavy rainfall pattern and amount in the day1 & slightly underestimated in day2 spatial forecast.

Case 5 : On 17th July the trough at mean sea level runs from north-west Rajasthan to east-central Bay of Bengal across south Uttar Pradesh, north Chhattisgarh; a



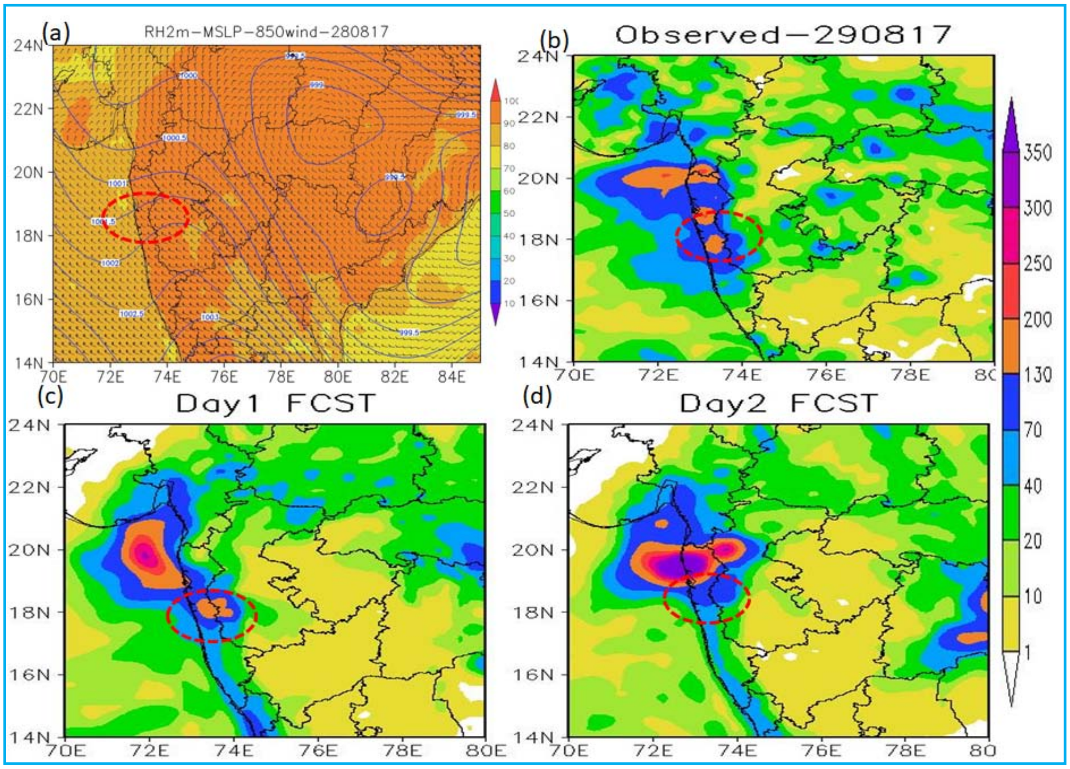
Figs. 3(a-d). Same as Fig. 1 but for extreme rainfall (261.4 mm) observed on 10082017 over Lower Dibang Valley district of Arunachal-Pradesh sub-division

centre of the well-marked low-pressure area formed over north-west Bay of Bengal & coastal areas of Odisha and north Andhra Pradesh [Fig. 5(a)]. Due to this synoptic system, very heavy rainfall of 203.9 mm observed over Balod district of Chhattisgarh subdivision on 18th July, 2017 [Fig. 5(b)]. The model's day1 [Fig. 5(c)] and day2 forecast [Fig. 5(d)] shows moderate rainfall instead of very heavy rainfall over this region and model predicted heavy rainfall to the south-east (Odisha) of the observed rainfall region. In this case, spatial shift (south-east ward) in heavy rainfall pattern was found in the model forecast.

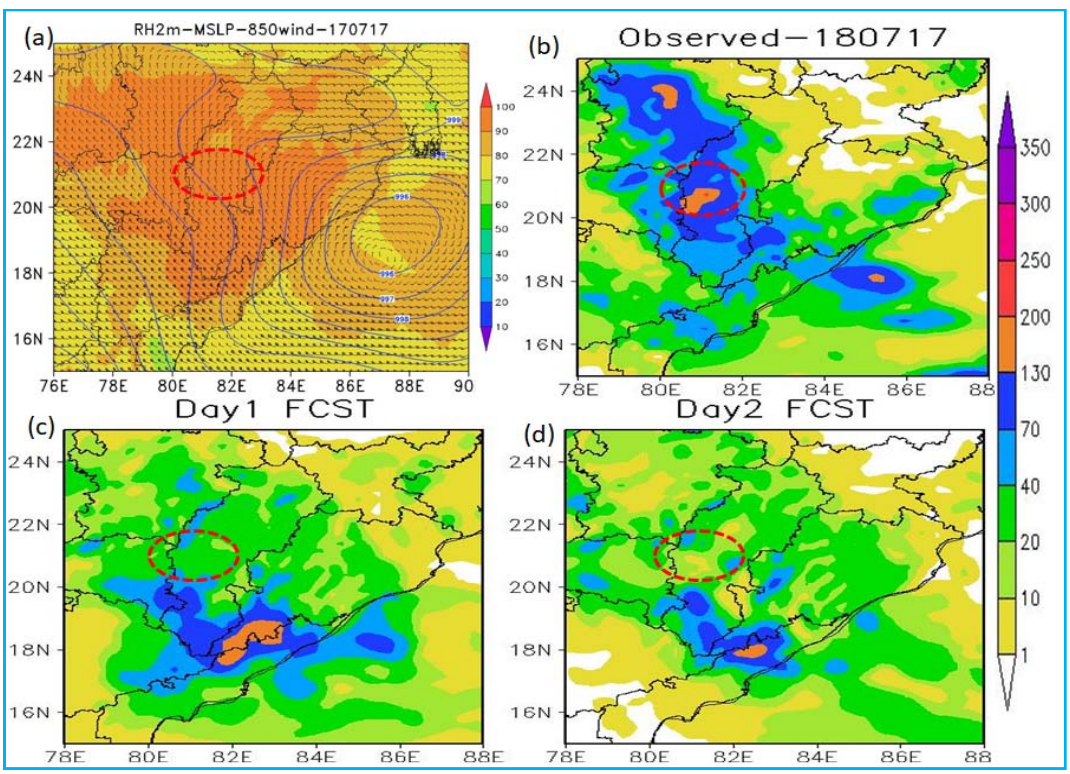
Case 6 : The monsoon trough at mean sea level runs through Jaisalmer, the centre of low pressure persisted over east Rajasthan & neighbourhood on 23rd July [Fig. 6(a)]. Due to this synoptic system, an extreme heavy rainfall of 433.3 mm [Fig. 6(b)] observed over Sirohi district of east Rajasthan subdivision on 24th July, 2017. The day2 [Fig. 6(d)] model forecast correctly predicted rainfall pattern and intensity. In contrast, the day1 [Fig. 6(c)] model couldn't capture the extreme rainfall over Sirohi district; instead, it shows very heavy rain of amounts 130 - 200 mm. In this case, day1 model forecast shows extreme rainfall pattern and intensity to the south-east (Udaipur, Pratapgarh, Dungarpur, Chittaurgarh, Rajasamandi, Bhilwara districts of east Rajasthan) of the extreme rainfall region, so here also spatial (south-east ward) shift observed in the day1 model forecast.

Very heavy rainfall of 130 mm observed over the Jalore district of west Rajasthan sub-division on 24th July, 2017 [Fig. 6(b)], due to a low-pressure system over east Rajasthan & neighbourhood as explained in the above case [Fig. 6(a)]. The day2 [Fig. 6(d)] forecast shows the heavy rainfall amounts, where as the day1 [Fig. 6(c)] model forecast not simulated very heavy rainfall over Jalore district. But, shows heavy rain amounts to the south-east (Udaipur, Pratapgarh, Dungarpur, Chittaurgarh, Rajasamandi, Bhilwara districts of east Rajasthan) and north-east (over Pali district of west Rajasthan) of the observed region. In this case also spatial shift in very heavy rainfall pattern observed in the day1 forecast.

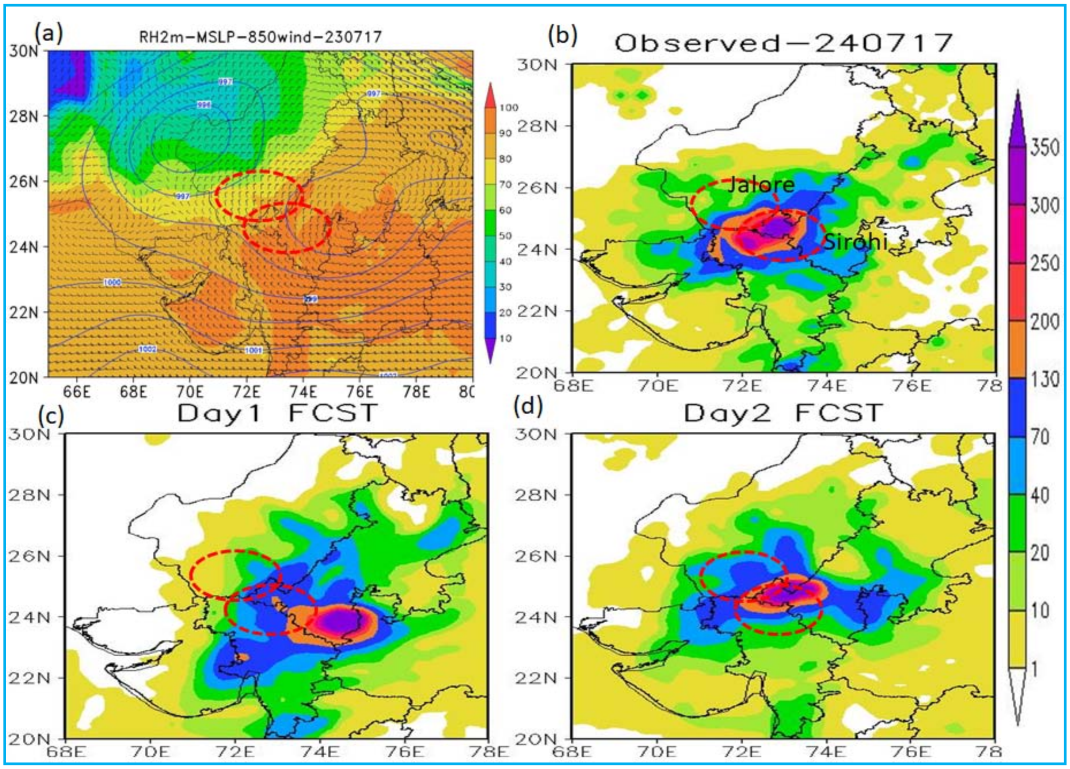
Case 7 : There is a low-pressure system formed over south-east Vidarbha & neighbourhood and the monsoon trough at mean sea level passes through Phalodi, Udaipur and Indore on 20th August, 2017 [Fig. 7(a)]. Due to this synoptic system, heavy rainfall of 107.5 mm [Fig. 7(b)] observed over Ahmed Nagar district of Madhya Maharashtra sub-division on 21st August, 2017. But the same is not predicted by the day1 [Fig. 7(c)] and day2 [Fig. 7(d)] model forecast over the same district. In this



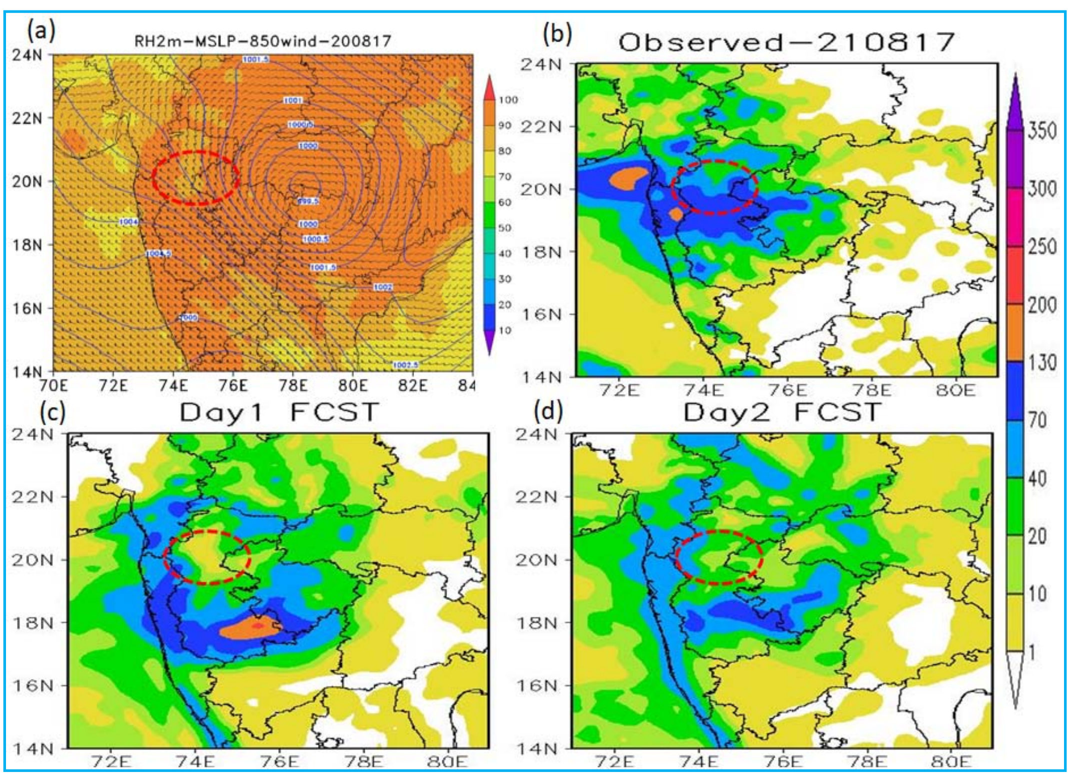
Figs. 4(a-d). Same as Fig. 1 but for heavy rainfall (151.8 mm) observed on 290817 over Mumbai district of Konkan-Goa sub-division



Figs. 5(a-d). Same as Fig. 1 but for heavy rainfall (203.9 mm) observed on 180717 over Balod district of Chhattisgarh



Figs. 6(a-d). Same as Fig. 1 but for extreme rainfall (433.3 mm) observed on 240717 over Sirohi district of East Rajasthan and a very heavy rainfall (130 mm) observed over Jalore district of West Rajasthan sub-division



Figs. 7(a-d). Same as Fig. 1 but for heavy rainfall (107.5 mm) observed on 210817 over Ahmednagar district of Madhya Maharashtra sub-division

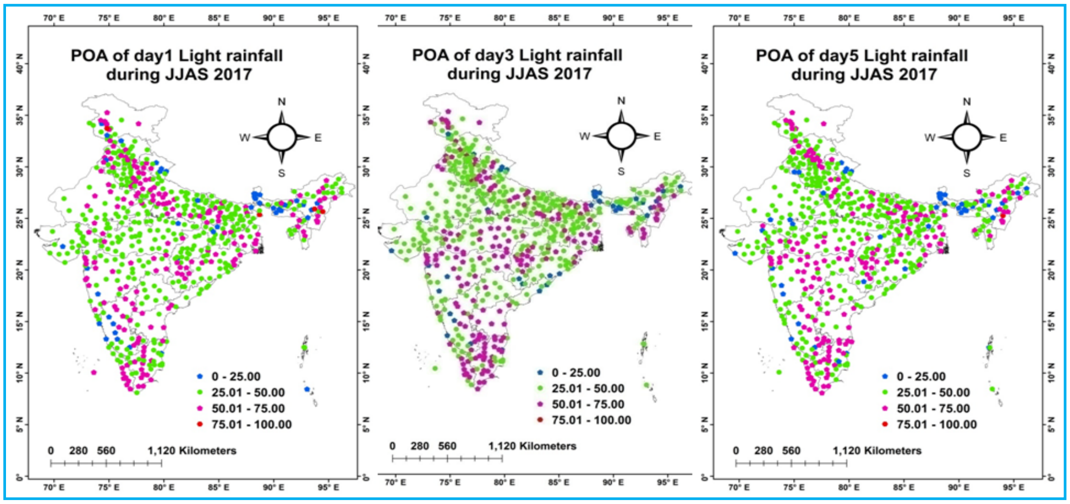


Fig. 8. Spatial distribution of Percentage of accuracy of GFS light rainfall forecast over districts for day1, day3 and day5 forecast

case, day1 and day2 model forecast simulated heavy rainfall amounts to the south of the observed heavy rainfall region. So here also spatial shift (southwards) observed in the model forecast.

In overall, the seven major rainfall events are reasonably well predicted by the model. However, three out of these seven cases showed a spatial shift of rainfall to the south/south-east ward of the observed rainfall location in day1 and day2 model forecast. Due to this spatial shift in the model rainfall forecast, the location-specific forecast over a particular district/block is becoming more difficult on some heavy rainfall events. Although the model could reasonably predict the intensity of these heavy rainfall events, the day2 forecast underestimated in most cases. It is also observed from the previous study (Mcbride and Ebert, 2000), the NWP models rainfall forecast skill falls for the rainfall thresholds greater than 10 mm/day and the models are much better at predicting the occurrence of rain than at predicting the magnitude and location of the peak values.

4.2. *Rainfall forecast skill at the district level*

One of the fundamental ways of validating a model rainfall forecast is comparing the forecasted rainfall with corresponding observed rainfall and assessing forecast skill based on different statistical measures. The percentage of accuracy (POA) and frequency bias index (FBI) in forecasted rain for different rainfall categories computed to validate the model forecast at the district level.

4.2.1. *Percentage of Accuracy (POA)*

Frequency of days falling within different rainfall categories, *i.e.*, light, moderate and heavy rainfall computed from the daily rainfall data of all the available districts (608) for the monsoon season (JJAS) 2017. The POA score is calculated based on the number of rainfall forecast days matching with observed rainfall days in each district under the above three categories. The POA score shows high/low skill, if the POA over the district is equal to '0', there is no skill, if POA<50% low skill and if POA ≥ 50% then high skill.

For the light rainfall (Fig. 8) category high skill observed over 303, 307 and 310 (50%) districts out of 608 districts for day1, day3 and day5 forecast respectively, whereas for moderate rainfall (Fig. 9), high skill observed over 376, 299, 285 (64%) districts out of 590 districts for day1, day3, day5 forecast and the remaining districts shows low skill. Similarly, for heavy rainfall (Fig. 10) category, high skill observed over 27, 20, 9 (8%) districts for day1, day3 and day5 forecast out of 316 districts; low skill found over very few districts and there is no (0) skill over most of the districts.

4.2.2. *Frequency Bias Index (FBI)*

The model bias was further explored by computing frequency bias index (FBI) over the districts. These districts grouped into six homogenous regions under above mentioned three rainfall categories for all day1 to day5 forecast. The FBI measures the ratio of the frequency of forecast events to the frequency of observed events. FBI indicates whether the forecast system tends to under forecast (BIAS<1), over forecast (BIAS>1) or correctly forecast (BIAS = 1) the events. However, the BIAS doesn't give an idea about forecast corresponds to the observations, but only measures relative frequencies (Durai *et al*., 2010b). The FBI scores (number of districts correctly forecasted, under forecasted and over forecasted)

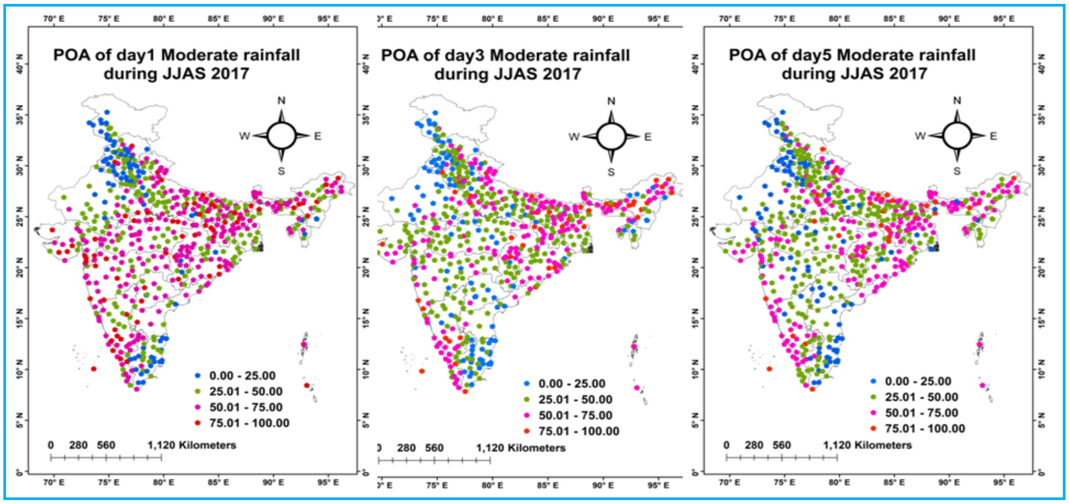


Fig. 9. Spatial distribution of Percentage of accuracy score of GFS T1534 moderate rainfall forecast over districts for day1, day3 and day5 forecast

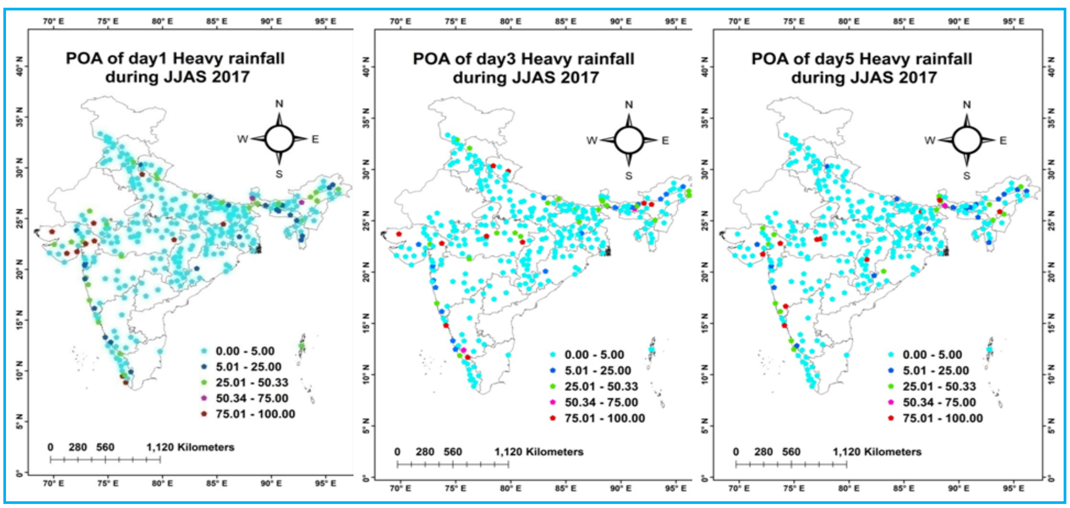


Fig. 10. Spatial distribution of Percentage of accuracy score of GFS heavy rainfall forecast over districts for day1, day3 and day5 forecast

TABLE 3

Frequency bias index (FBI) of day1 forecast of light, moderate and heavy rainfall categories over districts

Region	Day 1 FBI Skill											
	Light rainfall (LRF)				Moderate rainfall (MRF)				Heavy rainfall (HRF)			
	CF*	UF**	OF***	TDIST#-LRF	CF*	UF**	OF***	TDIST#-MRF	CF*	UF**	OF***	TDIST#-HRF
NI	68	34	55	157	15	29	92	136	19	37	8	64
NEI	13	21	20	54	5	1	39	45	4	17	16	37
WI	12	61	1	74	3	4	67	74	4	15	14	33
EI	47	45	19	111	3	0	98	101	16	45	10	71
CI	33	34	10	77	2	0	66	68	8	20	23	51
SI	41	75	13	129	5	8	100	113	12	21	10	43
AI	214	270	118	602	33	42	462	537	63	155	81	299

Note : *CF : Correct Forecast; **UF : Under Forecast; ***OF : Over Forecast; #TDIST : Total Districts

TABLE 4

Similar to Table 3 but for day3 forecast

Region	Day 3 FBI Skill											
	Light rainfall				Moderate rainfall				Heavy rainfall			
	CF*	UF**	OF***	TDIST#-LRF	CF*	UF**	OF***	TDIST#-MRF	CF*	UF**	OF***	TDIST#-HRF
NI	70	27	60	157	14	17	105	136	17	33	14	64
NEI	18	18	18	54	5	0	40	45	6	15	16	37
WI	13	59	2	74	3	6	65	74	5	16	12	33
EI	43	42	26	111	6	0	95	101	10	50	11	71
CI	48	14	15	77	0	1	67	68	12	16	23	51
SI	42	68	19	129	12	9	92	113	1	32	10	43
AI	234	228	140	602	40	33	464	537	51	162	86	299

Note : *CF : Correct Forecast; **UF : Under Forecast; ***OF : Over Forecast; #TDIST : Total Districts

TABLE 5

Similar to Table 3 but for day5 forecast

Region	Day 5 FBI Skill											
	Light rainfall				Moderate rainfall				Heavy rainfall			
	CF*	UF**	OF***	TDIST#-LRF	CF*	UF**	OF***	TDIST#-MRF	CF*	UF**	OF***	TDIST#-HRF
NI	61	27	69	157	15	13	108	136	13	40	11	64
NEI	18	20	16	54	3	0	42	45	6	17	14	37
WI	20	53	1	74	8	4	62	74	3	16	14	33
EI	44	38	29	111	2	0	99	101	10	46	15	71
CI	49	11	17	77	1	0	67	68	11	16	24	51
SI	55	56	18	129	14	8	91	113	14	17	12	43
AI	247	205	150	602	43	25	469	537	57	152	90	299

Note : *CF : Correct Forecast; **UF : Under Forecast; ***OF : Over Forecast; #TDIST : Total Districts

are shown in Tables 3-5 over six homogenous regions under three rainfall categories for day1, day3 & day5 forecast.

In the light rainfall range, *i.e*., 0.1-15.5 mm (LRF), 40-60% of NI, EI and CI districts are correctly forecasted, but for SI, NEI, WI regions 60-80% districts shows underestimation for all day1 to day5 forecast. The moderate rainfall shows overestimation in 70-80% districts of all the six homogeneous regions for all day1 to day5 forecast. Similarly, for heavy rainfall category 40-60% of NI, NEI, WI, EI and SI districts, maximum CI districts show overestimation for all day1 to day5 forecast. In terms of FBI score, the light rainfall correctly forecasted for 40 to 60% of the districts; mostly over forecasting is observed for the moderate rainfall category, but for the heavy rainfall category under forecasting observed over most (70-80%) of the district's and 20% of districts are correctly forecasted.

So, from the above skill scores it is observed that, at the district level model shows a high skill for light to moderate rainfall; for heavy rainfall category, the skill decreases with increasing forecast lead time at the district level. Broadly, the model captures the large scale heavy rainfall distribution over high spatial scales. However, there is a considerable improvement in the NWP model forecast skill over the years by improving model resolution and physical parameterization.

5. Summary and conclusions

In the present study, the heavy rainfall (>64.5 mm) prediction skill of the GFS model at district level under particular meteorological subdivisions of India has been evaluated for the summer monsoon 2017. This study also evaluates the forecast skill for different rainfall categories at the district level. The qualitative analysis shows model reasonably captured the heavy and extreme rainfall over districts in few cases; and spatial change of rainfall in few cases either south or south-east ward of the observed rainfall pattern.

Further verification of GFS model rainfall forecast for different rainfall categories (light, moderate and heavy) has been carried out broadly at the district level. In terms of percentage of accuracy (POA), the light rainfall (0.1 to 15.5 mm) forecast shows high skill over more than 50% of the districts and for moderate rain, 64% of districts show high skill. But for the heavy rainfall forecast, most of the districts show an underestimation of the rainfall amount. In terms of the frequency bias index (FBI), concerning the correct forecast, under forecast and over forecast; the model correctly simulated light rainfall over 40 to 60% of the districts. The model mostly over forecasted the moderate rain, whereas 20% of districts correctly simulated the heavy rainfall category.

This study implies that the light to moderate rainfall at meteorological sub-division and district level well captured by the model. With respect to the heavy and extreme rainfall, the model could reasonably capture at the bigger domains of sub-division level; and at small scales like district level in few cases, but due to the spatial shift model could not capture in many cases. Thus it is suggested that, for the location specific heavy rainfall forecast there is a need to use the ensemble forecast with probabilistic guidance. However, the conclusion drawn here is based on only one season and is not in general. The GFS model's heavy rainfall forecast skill further may improve by incorporating the better analysis scheme and model physics.

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